Use of bacterial cellulose in the textile industry and the wettability challenge—a review

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Abstract  Bacterial cellulose (BC) has been studied as an alternative material in several segments of the food, pharmaceutical, materials and textile industries. The importance of BC is linked to sustainability goals, since it is an easily degradable biomaterial of low toxicity to the environment and is a renewable raw material. For use in the textile area, bacterial cellulose has attracted great interest from researchers, but it presents some challenges notably to its hydrophilic structure. This integrative review article brings together studies and methods related to minimizing the hydrophilicity of bacterial cellulose, in order to expand its applicability in the textile industry in its dry state. The databases consulted were Scopus, ScienceDirect, ProQuest and Web of Science, the documents investigated were scientific articles and the time period investigated was between 2015 and 2021. The results showed that although there are methods to make the BC membrane more hydrophobic, future studies in this regard and on other properties must continue so that bacterial cellulose can be commercially introduced in the textile sector.

Keyword  Textile industry · Bio-textile · Sustainability · Bacterial cellulose · Wettability

Introduction

The textile industry is associated with numerous environmental problems. Large amounts of harmful waste are generated at all stages of clothing manufacturing, with negative environmental and social impacts, such as landfill consumption, low resource efficiency and air/soil pollution (Chan et al. 2018; Correia and Silva 2019; Sandvik and Stubbs 2017). Although the garments are used for a relatively long period, even by several consecutive users, studies have demonstrated that the manufacture of cotton garments, for example, is extremely polluting.

To obtain 1 kg of cotton fiber, 29 tons of water are consumed. In total, 25% of all insecticides and more than 11% of pesticides used globally in agriculture are applied to cotton crops. The amount of material that requires disposal presents a real challenge for the
fashion industry. This quantity has increased notably in the past 50 years, with around 15 million tons of used textile waste currently being generated each year in the USA (Domskiene et al. 2019).

The quest to make the fashion industry more sustainable has increasingly directed designers and scientists to focus on biomaterials such as bacterial cellulose (BC), and their biocompatible properties. BC is environmentally friendly, safe for the human body and considered a renewable raw material and one way to obtain it is through the kombucha fermentation process (Domskiene et al. 2019). It is a natural, non-woven material, with a firm structure, with an aspect that resembles leather when dry (Chan et al. 2018; Domskiene et al. 2019; Sederavičiūtė et al. 2019).

Biomaterials are mixtures of natural substances that offer biocompatibility and they can improve the quality of life of individuals and increase longevity and comfort (Costa et al. 2019). Domskiene et al. (2019) noted that the use of biomaterials in the fashion trade is very promising, since the material can be grown as required from waste food and used clothing can be easily decomposed and biodegraded (Domskiene et al. 2019). Cellulose is one of the most abundant polymers on Earth and most of it is plant cellulose (PC), however, bacterial cellulose (BC) offers an interesting alternative, such as biomaterials (Costa et al. 2019).

BC was first reported in 1988 by Brown, who identified a structure chemically equivalent to PC, through the growth of an unbranched film (Costa et al. 2019; Römling and Galperin 2015; Sederavičiūtė et al. 2019). The most effective sources for the production of BC are Acetobacter xylinum (also called Gluconacetobacter xylinum), Acetobacter hansenii and Acetobacter pasteurianus. Of these, A. xylinum has been most used for the production of commercially-available BC due to the high levels of productivity attained (Naeem et al. 2018; Wang et al. 2019).

One of the ways to produce BC is in the production of kombucha, a probiotic drink which, according to the earliest records, originated in northeastern China in mid-220 AD. It appeared during the Chin dynasty, when a Korean doctor called “Kombu” used the “che” for treatments, thus originating the name Kombuchá (Amarasekara et al. 2020). After the Second World War, the use of Kombucha became popular in Western countries due to its multiple functional properties, and the drink subsequently spread worldwide (Dim et al. 2017; Dutta and Paul 2019).

Fermentation is considered to be one of the oldest methods for obtaining drinks and involves a low cost energy conservation system (Dutta and Paul 2019). BC fermentation is carried out during the tea fermentation process, generating a cellulose-based biofilm at the air–liquid interface. This is generated by the symbiotic culture of bacteria and yeasts (SCOBY) and is considered as a waste product, but it represents an important potential source of BC (Dutta and Paul 2019; Kamiński et al. 2020; Leal et al. 2020; Villarreal-Soto et al., 2018).

Some authors have reported the applicability of bacterial cellulose for different purposes. Lin et al. (2020), in a recent review, address cellulose in the food industry, while Volova et al. (2019) suggested BC-based biotechnological dressings for the health sector. Furthermore, Costa et al. (2019) stated that BC is able to play a role as a substitute for other materials in the textile area and Araújo et al. (2015) developed a hydrophobic BC material which may have interesting applications for use in textile materials, clothes, flooring and other interior design materials (Araújo et al. 2015; Costa et al. 2019).

In the case of the textile industry, materials for the production of clothing must provide a required set of properties, such as strength, body fit and comfort. Scientists working in the textile field have recently become interested in BC, but this material presents challenges to be overcome before it can be widely applied as a new type of textile fabric for the fashion industry (Domskiene et al. 2019). Despite offering excellent hydrophilicity for some sectors, such as biomedicine and cosmetology, due to its porous structure, this characteristic poses a problem for some uses in the textile industry (Domskiene et al. 2019; Halib et al. 2019; Kamiński et al. 2020).

In this context, the objective of this article is to present an integrative review of the academic literature, understanding its hydrophilic property and the treatments available to make it hydrophobic. Despite numerous studies on hydrophobicity and bacterial cellulose membranes in several areas, research directed at the textile industry or on the dry BC membrane was selected. Thus, some potential applications of BC in the textile sector and the importance of future research with biomaterials are discussed.
Methods

Since the research question seeks to understand the wettability properties of bacterial cellulose and its applicability in the textile industry segment, an integrative literature review is conducted. An integrative review is a specific review method that summarizes past empirical or theoretical literature to provide a more comprehensive understanding of a particular phenomenon (Whittemore 2005). An integrative literature review also is defined as a form of research that reviews, critiques, and synthesizes representative literature on a topic such that new frameworks and perspectives on the topic are generated (Torraco 2005, 2016).

To conduct this integrative review, the databases chosen for the searches were: Scopus, ScienceDirect, ProQuest and Web of science. Thus, to perform the literature review, 3 combinations of search terms were selected for writing the topics. Figure 1 exemplifies the method used to select research articles for this review.

As seen in Fig. 1, it should be noted that the peer reviewed articles were selected by opting for a timeframe between 2015 and 2021. Thus, inclusion and exclusion criteria were employed, which were the readings of the title, abstract and keywords, selecting only those articles that were compatible with the research theme.

Therefore, the results and discussions of this review article are structured as follows:

(a) “3. Results and Discussion”: presentation of the quantitative results for the realization of the integrative review article;
(b) “3.1 Analysis of databases”;
(c) “3.2 Final selection and analysis of articles”;
(d) “3.3 The hydrophilicity properties of bacterial cellulose”: Description of the high hydrophilicity of bacterial cellulose. In this section, it is not just articles focused on the textile sector, but research that specifically describes the natural properties of bacterial cellulose.
(e) “3.4 Studies and alternatives for hydrophobic bacterial cellulose”: Description of methods for making bacterial cellulose more hydrophobic. In this section, only articles focused on the textile industry or experiments with dry bacterial cellulose that could contribute to the sector were included.
(f) “3.5 Bacterial cellulose applications for the textile industry”: Finally, in this section, the application possibilities, advantages and disadvantages of bacterial cellulose for the textile industry were described and discussed.

Results and discussions

Analysis of databases

For each database, two groups of search terms were used: (“bacterial cellulose” AND hydrophobic AND textiles) and (“textile industry” AND bacterial
cellulose). Figure 2 shows the final results of the search, including the filters used, which were the search terms, timeframe and type of document.

As shown in Fig. 2, a higher number of documents was identified in the ScienceDirect database, followed by ProQuest, using the search terms, document type and timeframe filters. The first group of terms (“textile industry” AND “bacterial cellulose”) collected a total of 663 articles. The second group of terms (“bacterial cellulose” AND hydrophobic AND textiles), on the other hand, brought together 231. This data shows the small number of studies directed mainly at the second group of terms.

Final selection and analysis of articles

The final selection of the articles considered for the writing of this review was carried out in two stages. Stage 1 involved the reading of the title, abstract and keywords of each article. Those that were aligned with the search theme, that is, the articles that mentioned bacterial cellulose, its hydrophobicity and its use in textiles were selected. In step 2, the articles were read in full and based on the content only those that would aid the construction of the integrative review were selected.

In this process, the number of articles excluded from the first group of terms (“textile industry” AND “bacterial cellulose”) was 641 among the four databases: ScienceDirect, ProQuest, Web of Science and Scopus. The number of articles excluded from the second group of terms (“bacterial cellulose” AND hydrophobic AND textiles) was 216 among the four databases. The exclusion criteria involved articles repeated between the databases and articles that were not compatible with the proposal of the present review article. Thus, 37 articles were considered for the review and the details of this final selection process can be seen in Fig. 3.

From the process applied in this research, as shown in Fig. 3, it was possible to select a set of articles that contributed to a better understanding of the natural properties of bacterial cellulose. In addition, the main focus of this article was the methods of obtaining more hydrophobic bacterial cellulose and its application in the textile industry.
The hydrophilicity properties of bacterial cellulose

Bacterial cellulose (BC), in addition to its mechanical resistance, has several attractive physical properties. It has higher purity compared to cellulose of plant origin, along with greater flexibility, greater hydrophilicity, tensile strength, biodegradability and transparency (Dima et al., 2017; Martins et al., 2020; Naeem et al., 2018). It should be noted that to review the literature on methods of hydrophobization of bacterial cellulose, it is necessary to understand the natural hydrophilic state of BC.

Researchers have reported that hydrophilic nature and water retention capacity of BC are influenced by the arrangement of the fibrils and the high surface area per unit of mass (Naeem et al. 2018; Shim et al., 2019a, 2019b). According to Paximada et al. (2020) and Sederavičiūtė et al. (2019), BC material has a high moisture content, since water binds to the OH groups of the material, making it hydrophilic. The moisture content results from the microstructure of the BC material and affects both the physical and mechanical properties, such as density, thickness, tensile strength and plasticity.

According to García and Prieto (2018), BC can store over 90% of its own weight of water. In studies reported by Halib et al. (2019), BC molecules lead to a highly swollen three-dimensional (3D) network and pore structures that are capable of holding a maximum of 99% water, resulting in BC as a promising material for obtaining highly biocompatible tissue structures. The authors emphasize that the properties of BC can be altered by different chemical changes which can be used to improve the properties according to different applications.

According to Sederavičiūtė et al. (2019) and Martins et al. (2020), due to the hydrophilic nature of BC, the search for stability of the material dimensions is relevant, because during drying the sample can shrink. Domksiene et al. (2018) also describes in his research that although BC film has properties which attract great interest, studies show that it can undergo deformation and it is difficult to guarantee a uniform structure, thickness and porosity, and therefore the material is not durable.

As an example of these changes in relation to BC instability, in the research by Dima et al. (2017) and collaborators, a hydrophilicity of approximately 1 g of bacterial nanocellulose (BNC) was found: 100 ml of water, after samples of a stable aqueous suspension had been dried in an oven at 70 °C for 3 days. Although the hydrophilicity is an interesting property for some sectors, without hydrophobic treatment, it limits the use of this material.

In addition, the BC water retention capacity can be varied by using different combinations of culture
media, which can alter its structure and thus modify its properties (Bagewadi et al. 2020). Recent research on hydrophilicity found that when this feature of BC is desirable, there is potential for increasing this property. Jiang et al. (2020) reported the biological modification of bacterial cellulose (BC) using various alginates with different molecular weights as a carbon source in the fermentation medium.

According to Jiang et al. (2020), the presence of sodium alginate (SA) had a strong influence on the microstructure of the components resulting from bacterial cellulose incorporated with sodium alginate (SA-BCs) and results indicated that the hydrophilicity of SA-BC was strengthened and suggested the presence of a carboxyl group.

Li et al. (2020) manufactured polymer-modified carbonization bacterial cellulose (CBC) electrodes using varying amounts of cation exchange polymers (glutaric acid (GA) and sulfosuccinic acid (SSA)). The polymer-modified CBC electrodes showed good wetting, due to the addition of oxygen-containing groups that increase the hydrophilicity of the CBC. The high content of the hydrophilic group contributes to the excellent electroosorption performance of the electrodes prepared.

These are some notes from the vast existing literature on the hydrophilicity of bacterial cellulose. Despite the extremely hydrophilic characteristic of BC, Wood (2019) noted that this property is not suitable for use under conditions of high humidity, which can increase with proximity to human skin. Thus, for the production of textile fabrics, the thickness and uniformity of the material are priorities of great importance in the drying process, but the BC dimensions change and it becomes highly hydrophilic during the drying step (Domskiene et al. 2019).

Studies have also shown that the material properties need to be altered prior to biosynthesis (in situ), which changes the intrinsic biophysical properties, in the case of cellulose fibers through the incorporation of bioactive molecules, modifying the porosity and/or crystallinity of BC (Fernandes et al. 2019a, b). Also, the application of chemical finishing can reduce the hydrophilicity of the BC film surface, potentially allowing its application under different conditions. In this way, properties similar to those of clothing fibers can be produced, depending on the parameters of the fermentation process, the application of which is growing in the fashion industry (Domskiene et al. 2019).

Studies and alternatives for a hydrophobic bacterial cellulose

Regarding its application in the textile and footwear sectors, the first proof of concept of the use of BC as an alternative to leather emerged in the 1990s, in the Philippines. In the last decade, the designer Suzanne Lee has expanded the possibility of using BC in the manufacture of clothing and footwear, by resorting to the handmade production of BC (Fernandes et al. 2019a, b). Bio-couture is a project that is being carried out to explore and experiment with different textile biomaterials or the production of textiles. It is based on the idea that minimal resources and chemicals are needed for production and are biodegradable (Lavanya et al. 2021).

Since then, other studies have mainly focused on comfort and appearance, overlooking important properties such as breaking strength, elongation at break or hydrophobicity (Fernandes et al. 2019a, b; Rathnamoorthy and Kiruba 2020; Song and Kim 2019). The inherent wettability and liquid-absorbing capacity of BC are beneficial in some applications, but are crucial drawback in shoe manufacture (Garcı´a and Prieto 2018). In the textile industry, a hydrophobic cellulose is required because it has a wide range of applications, not only in conventional applications, such as in functional applications like in clothing, waterproof textile stain resistant (oils), among others (Arau´jo et al. 2015; Song and Kim 2019).

However, some living organisms possess superhydrophobic surfaces that are being imitated by polymer chemists, and these may be bonded to BC to generate materials with super-antiwetting and even self-cleaning properties. Covalent functionalization, which generally involves reactive hydroxyl groups on the BC surface, is a favoured strategy. Melt processing, such as extrusion or injection moulding, may also be viable at the industrial level. However, the inherent incompatibility between hydrophilic cellulose and generally hydrophobic polymer matrices, as well as thermal stability issues, needs to be addressed (Garcı´a and Prieto 2018).

The use of exogenous molecules in BC production, through the in situ method, leads to different results for the BC properties. In situ modification is less
commonly applied, since the application of hydrophobic matrices can result in weak interfacial bonds with cellulose (hydrophilic) and chemical compatibility is therefore a prerequisite (Fernandes et al. 2019a, b). According to Fernandes et al. (2019a, b), application is suitable only for cases of polymerization in liquid solutions, where cellulose can be distributed in the polymerization medium. Figure 4 shows the methods of the authors found for the writing of this review article and which will be detailed throughout this section.

Methods hydrophobic through commercial products

According to Fernandes et al. (2019a, b), through a simple and cost-effective process, hydrophobized, robust, malleable and breathable nanocomposites based on BC were obtained, featuring promising properties for application in the textile and shoe industries. Hydrophobic surfaces may be obtained through the creation of hierarchical roughness or through the control of the surface chemistry, decreasing the surface energy. Samples were oven dried (WTC binder oven) at 25 °C for 48 h, followed by a curing step for 30 min at 120 °C. To avoid shrinkage of the samples during drying and curing, the composite BC membranes were attached to a zinc-plated wire support.

The research aimed at producing malleable, breathable and water impermeable bacterial cellulose based nanocomposites, by impregnating bacterial cellulose (BC) membranes with two commercial hydrophobic polymers used in textile finishing, Persoftal MS (polydimethylsiloxane) and Baygard EFN (perfluorocarbon), by an exhaustion process. The water contact angle (CA) was measured on BC (± 63.8°). After incorporation of the polymers, overall, higher contact angles were obtained (± 105°), indicative of more hydrophobic surfaces (Fernandes et al. 2019a, b).

Araújo et al. (2015) and collaborators used commercial hydrophobic products from DyStar textile that were given to obtain the hydrophobic cellulose and the hydrophobic finishing agent is EVO Wet Fest. The hydrophobic finishing process, where used two different methods. The first method employed was that is customarily used in the textile industry, 6 BC samples were placed in a bath of 0.5 ml softener, and then placed in a bath with hydrophobic finishing agent.

These hydrophobic finishing baths were composed of distilled water, acetic acid 60% and hydrophobic product with two concentrations 1.5 ml/l and 6 ml/l. The second method is the opposite of the first, the 6 samples were placed initially in a hydrophobic finishing bath and finally in a softener bath (followed the same amounts mentioned above for the various finishing hydrophobic baths). The different samples were dried in an oven at 120 °C for 1 min (Araújo et al. 2015).

The test of the contact angle achieved proves that it is possible to obtain hydrophobic BC with minimal quantities of hydrophobic finishing agents. According to the authors, the control sample reached an angle of approximately 43°, while samples that passed through the hydrophobicity processes reached an angle of

Fig. 4 Hydrophobization methodologies for bacterial cellulose

1. Acrylated epoxidized soybean oil (AESO) and Polyethylene glycol (PEG)
2. Beeswax
3. Electrospinning
4. EVO Wet Fest
5. Glycerol and Plant-based proteins
6. Lauryl gallate
7. Oxygen plasma and trichloromethyl silane
8. Persoftal MS (polydimethylsiloxane) and Baygard EFN (perfluorocarbon)
9. Polyfluoroteflon
10. Polyaniline (PANI)
11. Polyvinylpyrrolidone – carboxymethylcellulose
12. Poly(lactic acid) (PLA)
approximately 108°. With these results we can see that besides the added value to make BC a hydrophobic material it can be also obtained a more homogeneous surface morphology with a more uniform fiber surface (Araújo et al. 2015).

Hydrophobic methods using plant products

According to Fernandes et al. (2019a, b), vegetable oils (OVs) were used. Vegetable oils (VOs) are abundant renewable resources with an increasing number of industrial applications. Basically, these biopolymers are composed of triglycerides. They offer the advantages of low cost, nontoxicity and biodegradability. Among the VOs, soybean oil is one of the most attractive due to its low price and abundant availability. To increase their reactivity, double bonds can be replaced by more reactive functional groups such as epoxide, acrylate, hydroxyl or maleate.

Most commonly, double bonds are epoxidized and then acrylated, reacting with carboxyl groups of acrylic acids, allowing free radical polymerization. Acrylated epoxidized soybean oil (AESO) has been studied extensively in the production of composites with high renewable content. AESO was used in this work to produce a hydrophobic composite with high bio-based content (Fernandes et al. 2019a, b).

A mixture was prepared by adding different reactive monomers to AESO at room temperature. This mixture was composed of acrylated epoxidized soybean oil (50% m/m); lauryl methacrylate (40% m/m)-a fatty acid-based reactive diluent, potentially bio-based, which reduces the viscosity of the mixture; 1,6-hexanodiol diacrylate (5% m/m); and tri(propylene glycol m/m) diacrylate (5% m/m)-bifunctional monomers which can enhance the crosslinking. BC membranes (with about 3.0 cm in thickness, with a size of 12.0 × 2.5 cm and weighting 90 g) were each treated by exhaustion with 100 g of emulsified AESO mixture for 9 days at 40 °C followed by a 3 h curing step at 90 °C, to accelerate the cross-link of the emulsified AESO mixture. The composites were then dried at 40 °C in an oven (WTC series) for 5 days (Fernandes et al. 2019a, b).

The wetting properties of the BC and BC-based composites were investigated by measuring the water contact angles (WCAs). BC has a highly hydrophilic surface, bearing the lowest water droplet angle (63.1°), which increased for the BC composites to values between 79.0° and 138.0°, indicating a significant increase in hydrophobicity. Values of 95.8° and 79.0° were observed for BC/AESO and BC/AESO/PEG, respectively. AESO, despite being more hydrophobic, the WCAs over time decreased quickly in these BC composites, as compared to BC (Fernandes et al. 2019a, b).

Kim et al. (2021) and collaborators carried out a study with the aimed to develop eco-friendly bacterial cellulose (BC) bio-leather with improved durability using plant-based proteins, namely soy protein isolate (SPI) and mushroom protein (MP), which were physically entrapped inside the BC, respectively. The enhanced properties of mechanical strength and durability of BC bio-leather were measured in terms of changes in water resistance, tensile strength, flexibility, crease recovery, and dimensional stability. Before testing, BC bio-leathers were dried in a drying oven at 25 °C for 5 h.

The water resistance of BC bio-leather was measured by water contact angle (WCA) and the water absorption time. The original BC had the lowest WCA (79°). This is due to the free hydroxyl groups in BC, which exhibit hydrophilic properties. BC-glycerol also had a low WCA, which was related to the hydrophilic behavior of glycerol (81°). After physical entrapment of plant-based proteins inside BC, WCAs were increased significantly. The increased WCAs could be attributed to the formation of hydrogen bonding between BC fibers and plant-based proteins, reducing the number of free hydroxyl groups, and thus increasing the hydrophobicity of BC bio-leather (Kim et al. 2021).

It was also found that BC entrapped with both protein and glycerol had improved WCA than BC entrapped with protein only. According to authors, this could be explained by the rearrangement of hydrophobic moieties of protein molecules: Glycerol may strengthen the interactions with protein molecules by forming hydrogen bonds, resulting in the reorientation
of hydrophobic moieties of proteins on the surface of BC bio-leathers. Moreover, both BC-SPI (with glycerol) and BC-MP (with glycerol) were found to have better WCAs when glycerol was added: BC-SPI (with glycerol) = 110°; BC-SPI (without glycerol) = 90°; BC-MP (with glycerol) = 110°; BC-MP (without glycerol) = 105° (Kim et al., 2021).

Hydrophobic methods for packaging that can contribute to the Textile Industry

Patwa et al. (2019) researched a hydrophobicity method for application in bacterial cellulose. The authors’ research was also directed towards packaging and the membrane was studied for use in the dry state. This research can contribute to the textile industry, both for its use in clothing and for packaging in the fabric sector. BC films were carefully kept in vacuum oven 40°C for 12 h.

According to authors, the synthesis of lactic acid oligomer-grafted-untreated bacterial cellulose (OLLA-g-BC) by in situ condensation polymerization increased compatibilization between hydrophobic poly(lactic acid) (PLA) and hydrophilic BC, thus enhancing various properties of PLA-based bionanocomposites, indispensable for stringent food-packaging applications (Patwa et al. 2019).

The surface wetting characteristics of the PLA/OLLA-g-BC and bionanocomposite films was studied using the sessile drop contact angle measurements. The contact angle measured for PLA was around 83.5 ± 0.8°. Due to the in situ polymerization, condensation polymerization, the grafting process occurred where the polar (OH) groups on BC backbone were replaced by hydrophobic ester groups of OLLA. As a result of which, at low loadings of OLLA-g-BC fillers, that is, 5 wt % and 10 wt %, the contact angles were 102.5 ± 1.7°, 85.4 ± 1.7°, respectively. According to authors, upon further increasing the filler concentration, agglomeration of filler particles takes place which results in improper dispersion thus affecting the surface roughness and as a result of which the wettability of the films is similar to PLA (Patwa et al. 2019).

Bandyopadhyay et al. (2019) carried out a study to evaluate a bacterial cellulose and guar gum (BC-GG) hydrogel film based on polyvinylpyrrolidone—carboxymethylcellulose (PVP-CMC) as an alternative for food packaging. The GG was incorporated into the PVP-CMC-BC film to increase its mechanical and barrier properties. The samples were cut from the films in dimension 2 cm × 2 cm and dried to constant weight at 60°C. The dry films were then immersed in 50 ml distilled water and kept in a BenchRocker™3D with low constant shaking (approx. 15 rpm) at RT 21 °C and RH 57% for 24 h. The films were taken out from water after 24 h and dried to constant weight. The results showed an improvement in the elastic capacity of the PVP-CMC-BC films with the incorporation of GG and also in the barrier and hydrophobic properties. The authors reported that all films were 80% biodegraded after 28 days in vermicompost (Bandyopadhyay et al. 2019).

Another study aimed at packaging, but which can contribute to the textile industry was carried out by Indriyati et al. (2020) and collaborators. In this research, bacterial cellulose (BC) based films incorporated with beeswax (BW) were investigated. BC suspension was taken out from the refrigerator and let the temperature of the suspension equal room temperature, whereas BW was melted at 60–65 °C in water bath. Pure BC and BC-based films were prepared by mixing BC suspension under stirring condition at 60°C until homogenized suspension was achieved. Tween 80 was used as surfactant in the mixture containing BW. The mixture was then degassed to remove bubbles using vacuum pump, casted and dried in an oven at 45 °C for 16–20 h.

Different concentrations (10–40 wt% based on dry weight of BC suspension) of BW was added to enhance hydrophobicity and elasticity of BC-based films. Carboxymethyl cellulose at 20 wt% and Tween 80 at 30 wt% based on dry weight of BC suspension are also added as the homogenizer and the surfactant, respectively. Contact angle measurements confirm significant enhancement of hydrophobicity of BC films from 53° without BW to 124° for addition of 40 wt% BW. Tensile testing revealed that elasticity of the films also increased according to percentage of elongation at break for about 38% by addition of 40 wt% BW, whereas tensile strength decreases for about a quarter (Indriyati et al. 2020).
Other hydrophobic methods found in the literature: polyaniline, electrospinning, lauryl gallate oligomers, poly(2-fluorephenol) and oxygen plasma

Shim et al. (2019a, b) explored functionalized bacterial cellulose as a green material for technical textiles, wearables, and other applications. Conductive and colored bacterial cellulose (BC) was developed by entrapment of polyaniline (PANI) onto dry BC membranes. The polyaniline was produced by in situ green polymerization of aniline by Myceliophthora thermophila laccase at pH = 4, 25 °C, in the presence of a mediator, 1-hydroxybenzotriazol (HBT), using two different reactors, a water bath (WB) and an ultrasonic bath (US). According to authors, molecules entrapment and processing conditions might alter the hydrophilicity and disturb BC behavior. BC were dried in a drying convection oven (OF-21, Jeio tech Co.) at 35 °C.

The hydrophobicity acquired by the samples is favorable depending on the final applications envisaged. The untreated and bleached BC samples present high swelling capacity over 110%. With polyaniline incorporation, a significant decrease in the swelling capacity was observed under 60%, which might be attributed to the obstruction of the BC pores by polyaniline as well as to its hydrophobic nature. The swelling capacity of samples coated in the presence of laccase is slightly lower, confirming the higher amount of polyaniline entrapped inside BC that hinder the water absorption (Shim et al. 2019a, b).

Naeem et al. (2019) have presented a simple method to prepare seamless tubular bacterial cellulose hybrid fabric, using electrospun nanofibrous membrane (BC/ENM), by wrapping regenerated cellulose (RC ENM) around a tubular polypropylene mesh template, followed by in-situ cultivation of BC. Functional and mechanical properties of as-prepared hybrid fabrics were also analyzed and discussed. The membranes were dried in a vacuum oven at 80 °C for 12 h after electrospinning.

Regarding the contact angle, static water contact angle is considered as a representative parameter to evaluate the surface hydrophilicity or hydrophobicity of nanocomposite structures. The static water contact angle measurements were used to compare the wettability of BC/ENMs and ENMs. All three types of samples were subjected to a drop of deionized water. The contact angle values obtained for BC/ENM fabrics, in zero and 45 s of analysis, were 70.98° and 59.39°, respectively (Naeem et al. 2019).

Because of surface roughness and very fine fiber diameters, ENMs usually exhibit high surface hydrophobicity. ENM showed contact angle of 128.47° and appeared to be more hydrophobic. According to researchers, it might be because the comparatively crystalline electrospun fibrous membranes make the diffusion and transformation of water molecules difficult, resulting into a hydrophobic membrane surface. In case of hybrid fabrics, the BC nanofibrils largely covered the surface of hybrid fabrics, which might have resulted into improved hydrophilicity in comparison with ENMs (Naeem et al. 2019).

Song et al. (2019a, b) and collaborators, carried out a study to improve the properties of bacterial cellulose nonwoven fabrics by physical entrapment of lauryl gallate oligomers. The lauryl gallate oligomerization process was conducted by laccase-mediated oligomerization. Lauryl gallate was chemically confirmed by matrix-assisted laser desorption/ionization with time-of-flight analyses. After treatment, BC nonwoven fabrics were washed for 0, 30, 60, and 180 min., then dried for 3 h at 25 °C. After drying, the WCA of treated BC nonwoven fabrics was evaluated.

The controlled oligomerization conditions were 160 U/mL of laccase and 20 mM lauryl gallate. After bacterial cellulose was treated by the physical entrapment of lauryl gallate oligomers, X-ray photoelectron spectroscopy analysis showed that the N1 atomic composition (%) of bacterial cellulose increased from 0.78 to 4.32%. This indicates that the lauryl gallate oligomer molecules were introduced into the bacterial cellulose nanofiber structure (Song et al. 2019a, b).

Generally, untreated BC nonwoven fabric has a low water contact angle (WCA) value of 48.1 ± 1.5° with high surface energy (56.15 ± 0.4 mN/m) due to the numerous hydroxyl groups. After BC nonwoven fabric was entrapped with lauryl gallate oligomers, its surface became more hydrophobic with the increase of the WCA. This is because of the decline in the number of hydroxyl groups and moisture uptake, since lauryl gallate oligomers convert hydroxyl groups of BC nonwoven fabric to hydrophobic groups (Song et al. 2019a, b).

According to authors, the more laccase concentration was added during lauryl gallate oligomerization, the more hydrophobic surface was indicated on treated
BC nonwoven fabrics. The highest value of the WCA (118 ± 1.4°) with the longest water absorption time (over 7 min) was obtained when laccase of 160 U/mL was used. To evaluate the fastness of treated BC nonwoven fabric, treated BC nonwoven fabrics were washed in distilled water for 0, 30, 60, and 180 min. After washing for 30 min, the WCA was decreased from 118 ± 1.4° to 91.5 ± 1.5°. However, treated BC nonwoven fabric kept its WCA value over 88° after washing for 180 min (Song et al. 2019a, b).

In another study by Song et al. (2019a, b) have conducted a study to improve the hydrophobicity and durability of bacterial cellulose (BC) nonwoven by functionalization with poly(fluorophenol). Laccase was first entrapped onto BC and then used to polymerize the fluorophenol {4-[4-(trifluoromethyl)phenoxyl]phenol} in-situ. After treatment, BC nonwoven fabrics were washed for 0, 30, 60, and 180 min., then dried for 3 h at 25°C. After drying, the WCA of treated BC nonwoven fabrics was evaluated. The authors related after BC functionalization with poly(fluorophenol) (20 mM) that the water contact angle (WCA) increased from 54.5 ± 1.2° to 120 ± 1.5° while the surface energy decreased (11.58 ± 1.4 mN/m).

The findings confirmed the polymerization of fluorophenol by laccase and its entrapment onto a BC nanofiber structure. The durability of the functionalization with poly(fluorophenol) was confirmed by evaluating the washing fastness, tensile strength after washing and dimensional stability. The results indicate that the functionalized BC nonwoven had higher tensile strength (×10 times), better dimensional stability (30%) and greater hydrophobicity than the non-functionalized BC nonwoven material (Song et al., 2019a, b).

Leal et al. (2020) conducted a new strategy for the surface modification of bacterial cellulose (BC) through the combination of oxygen plasma deposition and silanization with trichloromethyl silane (TCMS). The combined use of the two techniques modifies both the surface roughness and energy and maximizes the obtained hydrophobic effect. The obtained dried membranes as “Non-treated” were processed by solvent exchange with ethanol, in order to accelerate drying. Membranes were compressed between two aluminum plates for 30 min, expelling the water entrapped in the BC network, until the thickness of the membrane was reduced by around 80%. The densified membranes were allowed to dry at 37°C for 24 h.

Silanization was conducted in a reduced pressure chamber at a temperature set at 95°C. The silanizing reagent, TCMS, was placed inside the chamber together with the plasma-treated BC membranes and set to react for 60 min, at—50 kPa. Following that period, the beaker containing the remaining TCMS (in toluene) was removed from the oven and replaced with only toluene which was left for 10 min for the washing of some of unbound TCMS upon toluene condensation on BC surface. After this, the membranes in the chamber, were subject to vacuum (-50 kPa) for 5 min to further remove the toluene and obtain the dried BC membranes (Leal et al. 2020).

The contact angle formed upon deposition of the water droplet (26.68°) does not significantly change, as compared with the non-treated material (24.98°). Differently, the treatment with TCMS on its own (Sil) is able to increase the static contact angle to 119.8°, due to the presence of the hydrophobic moieties of Si-CH3, as detected by XPS and FTIR. Surface O2 plasma treatment previous to the TCMS silanization (PlasSil) further increases the contact angle to 132.6° (Leal et al. 2020).

According to authors, BC remained hydrophobic even after 6 months, in dry conditions or after being submerged in distilled water for about a month, enabling the production of a biodegradable and hydrophobic platform that can be applied to different areas of research and industry. The higher hydrophobicity is explained by the formation of a convex meniscus, due to high contact angle, leading to air entrapment in the rough surface, which contributes to a higher contact angle and lower wettability of the surface, a phenomena well documented in the literature (Leal et al. 2020).

Therefore, from the researched literature, a range of possibilities of hydrophobization of bacterial cellulose was found. As mentioned before, BC has a high hydrophilicity, so drying methods are extremely important in this process. Drying temperatures ranged from 25°C to 120°C, and drying time ranged from 1 min to 5 days. However, the most used drying method was the lowest temperatures (25°C to 40°C), with drying time above 12 h. According to Domskiene et al. (2019), the best deformation properties retain when BC material is dried at low temperature (about 25°C). BC material becomes stiffer and ruptures at
lower deformations due to rapid water evaporation at higher drying temperature.

Regarding the methods used, low-cost alternatives such as plant based products are highlighted. In the case of the Textile Industry and thinking of a large scale of production, using food waste could be considered a way to foster the Circular Economy. Because, according to Wilkes et al. (2015), with regard to waste management and circular economy, partnerships between sectors can be an excellent solution, since through interdisciplinarity one sector can provide a function for the waste generated in another. Reports of improvements in the properties of bacterial cellulose, in addition to hydrophobicity, such as elastic capacity (Bandyopadhyay et al. 2019) were also cited.

Bacterial cellulose applications for the textile industry

The textile industry, despite being an important global manufacturing sector, is directly related to negative environmental impacts resulting from the use of toxic chemicals, the consumption of huge amounts of energy and water and inadequate disposal (Luo et al. Wang, 2020; Singh et al. 2019). Therefore, to achieve a more sustainable consumption scenario, it is necessary to find solutions to reduce the negative environmental, social and economic impacts of this industry (Freudenreich and Schaltegger 2019; Ingulfsvann 2020).

One solution would be to invest in areas such as biotechnology and biofabrication that explore alternatives, such as the use of microorganisms, for the manufacture of textiles, both for clothing and in the footwear industry (Camere and Karana 2018; Saraç et al. 2019). The biofabrication of bacterial cellulose is regarded as a major bioeconomy technology, meaning its sustainability and associated footprint in the downstream processing and finishing phases should be closely monitored (Hildebrandt et al. 2021).

Therefore, several tests have been carried out on bacterial cellulose (BC), to explore its exclusive properties, such as high purity, absence of lignin and hemicellulose, high crystallinity, high polymerization, good flexibility, tensile strength and nanofibril network structure (Chan et al. 2018; Fernandes et al. 2019a, b). BC resources grown from bacteria have been developed mainly as fine materials to replace animal leather (Camere and Karana 2018; Chan et al. 2018; Fernandes et al. 2019a, b), as can be seen in Fig. 5.

Nowadays the fashion industry faces increasing pressures to reduce the environmental impacts associated to the production of leather-based fashion products, particularly considering issues regarding public acceptance due to animal welfare standards and due to the toxicity of tanning chemicals (Hildebrandt et al. 2021). The tannery industry faces several challenges associated with high environmental impact, scarcity of raw materials and increasing consumer demand for environmentally friendly products. Worldwide, for bovine skin, 370 billion liters of water are consumed annually, generating 6.5 million tons of solid waste (Fernandes et al., 2019a, b).

Leather is a natural fabric material obtained from skins of animals, the treatment process of leather is highly complicated, especially the tanning process, because toxic chemicals such as metal salts and hexavalent chromium are used, and the decomposition of protein wastes causes serious odor. Furthermore, the supply of the leather is currently decreasing due to the animal protection movements (Kim et al., 2021). An alternative solution facilitated by the bio-textiles industry is the introduction of vegan and bio-based leather substitutes for the production of shoes, handbags, clothing and upholstery i.e. on the basis of natural fibres, bio-based polymers, microbial cellulose and fungal mycelium composite products (Hildebrandt et al. 2021).

The idea of BC as a potential leather substitute rests on the industrial production of cellulose fibres by members of the genera Komagataeibacter (also known as Acetobacter xylinum) (García and Prieto, 2018; Rathinamoothy and Kiruba, 2020). This bacteria ingested as part of kombucha tea and other fermentations, enjoys Generally Regarded As Safe (GRAS) status. These can be generated at desired thicknesses and when dried produce a resilient leather-like material with properties that resemble the type of animal leathers used in the footwear industry (García and Prieto, 2018). According to Hildebrandt et al. (2021) the choice of the feedstock for bacterial conversion is very important as it affects the environmental footprint of the entire production process, as well as the properties of the final products, e.g., flame retardancy and hydrophobic properties.
Some bacteria naturally produce cellulose (BC). If produced biotechnologically in large quantities, it might afford an alternative to plant cellulose. BC is already used commercially in high-end acoustic products, in medical wound dressings, and to make many other goods. At the laboratory scale, it has even been used to create artificial blood vessels and biodegradable tissue scaffolds, and has shown promise in organic light-emitting diode displays, flexible electrodes, sensors and other devices (García and Prieto 2018). The application of bacterial cellulose in the fashion industry has been the focus of several studies, as shown in Table 1.

It is possible to observe through Table 1 that the authors cite the main advantages of bacterial cellulose as its biodegradability properties, the possibility of being a substitute for animal leather, the reduction in the use of water and toxic products, among others. As well as, its disadvantages are due to its high hydrophilicity, heterogeneous production, among others. As well as the articles cited in Table 1, this review article highlights the numerous benefits of using BC, so it is necessary that tests be done to improve its properties for the commercial use of fashion products.

Researchers such as Chan et al. (2018) and collaborators developed an innovative technique for the production of bacterial cellulose textiles called “bespoke cultivation”, taking advantage of the fact that bacterial cellulose can be cultivated and grown in any format. This type of cultivation is suitable for producing basic fashion items, such as simple shirts, t-shirts and trousers, as these items do not require complicated shapes and their timeless styles are not restricted to trends (Chan et al. 2018).

According to Domskiene et al. (2019), investigating the unique features of BC film, researchers provided innovative ideas to grow seamless garments as direct 3D formation of BC sheets. Thus, scientists, working in the textile field, recently got interested in BC material, however, only a few studies are investigating this material as a new type of textile fabric for the fashion industry.

The functionalization and modification of BC have been achieved through chemical or mechanical alteration of the polymer, and by making adjustments to the conditions of cultivation. By controlling the growth of the producing bacteria, the BC generated could be tailored to have properties desired by the footwear industry (sheets of BC measuring $40 \times 40$ cm—a size compatible with footwear manufacturing requirements). If the solubility limitations of BC can be overcome, a BC-based printable fluid might be produced and used to 3D print shoes (García and Prieto 2018).

Ng and Wang (2015) performed tests related to the comfort and appearance of tissues obtained from bacterial cellulose. A total of 150 individuals participated in the test and the factors considered were comfort associated with touch, comfort associated with flexibility and comfort related to breathability. The result regarding the patterns analyzed was positive and it was possible to produce some prototypes of pieces of continuous 3D fashion.

According to Chan et al. (2018), the use of bacterial cellulose in the textile industry adheres to the concept of low to zero waste, but these materials are limited to

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**Fig. 5** Bacterial cellulose (BC): a possibility for replacing animal leather. Project carried out at the University of Southern Santa Catarina (UNISUL)
| Author / Year          | Title                                                                 | Advantages in the textile industry                                                                 | Disadvantages in the textile industry                                                                 |
|-----------------------|-----------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|
| García and Prieto (2018) | Bacterial cellulose as a potential bioleather substitute for the footwear industry | BC production should be much more bio-economically sustainable;                                      | The inherent wettability and liquid-absorbing capacity of BC are crucial drawback in shoe manufacture; |
|                       |                                                                       | The use of plant-derived water-soluble dyes should render BC-based footwear hypoallergenic;          | The inherent incompatibility between hydrophilic cellulose and generally hydrophobic polymer matrices, as well as thermal stability issues, needs to be addressed; |
|                       |                                                                       | BC can be to undergo rapid and eco-friendly biodegradation, with no leaching of toxic compounds to groundwater; |                                                                                                       |
|                       |                                                                       | BC as a leather substitute could result in a reduced demand for animal hides, fewer greenhouse gas emissions and diminished tanning-associated toxicity; |                                                                                                       |
|                       |                                                                       | Economic production of BC using food and industrial wastes as sources of nutrients.                 |                                                                                                       |
| Camere and Karana (2018) | Fabricating materials from living organisms: An emerging design practice | The production of bacterial cellulose can be handled by using almost no additional energy and by using sustainable resources; |                                                                                                       |
|                       |                                                                       | Large potential in replacing animal- or plant-based material production systems.                     |                                                                                                       |
| Chan et al. (2018) | Development of Tailor-Shaped Bacterial Cellulose Textile Cultivation Techniques for Zero-Waste Design | Bacterial cellulose is a sustainable biomaterial;                                                   | Mass produce specific cultivation containers in future bulk production;                                |
|                       |                                                                       | This organic material is able to be cultivated in any desirable garment panel shape, with no cutting and less textile waste; | Dispose of unused blockers and containers at the end of their life cycles;                            |
|                       |                                                                       | Self-synthesizing property;                                                                         | Would be necessary to pay attention to the ongoing genetic and biochemical research works focused on bacterial cellulose production at the molecular/biological level in order to incorporate innovative applications into fashion and textile industries. |
| Domskiene et al. (2019) | Kombucha bacterial cellulose for sustainable fashion                   | BC is eco-friendly, safe to the human body, and renewable raw material;                             |                                                                                                       |
|                       |                                                                       | Can be grown to the extent necessary;                                                               | The high hydrophilicity of bacterial cellulose;                                                      |
|                       |                                                                       | Can be use food waste;                                                                               | Mechanical behaviour of BC film (when material is wet and when it is dried) shows that ability to apply direct 3D formation technique is limited and needs further studies; |
|                       |                                                                       | Worn BC clothes can easily biodegrade.                                                               | It is difficult to get material with even structure and constant mechanical parameters even for small experimental sample; |
| Fernandes et al. (2019a, b) | Bacterial Cellulose and Emulsified AESO Biocomposites as an Ecological Alternative to Leather | Reduction of the animal hide dependency by the development of composites from bacterial cellulose. | BC film loses its elasticity over time and products produced from elastic and strong BC material are unlikely to be durable. |
| Author / Year       | Title                                                                 | Advantages in the textile industry                                                                                           | Disadvantages in the textile industry                                                                                     |
|---------------------|-----------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| Fernandes et al.    | Development of novel bacterial cellulose composites for the textile    | BC is free of lignin, hemicellulose and pectin, therefore, no extra processing is required for purification;              | The loss of flexibility upon drying is a disadvantage for several applications such as in the textile and shoe industry; |
|                     | and shoe industry                                                      | BC features a unique porous interconnected structure, organized three-dimensional network of interconnected nanofibres, properties which are very advantageous for the production of composite materials; | Due to the collapse of the 3D nanofibrillar BC network, a significant reduction in gas permeability also occurs, heavily reducing the material’s breathability; |
|                     |                                                                       | BC exhibits high crystallinity, which results in a high Young’s modulus;                                                    | The hydrophilic nature of BC hinders the combination with hydrophobic polymer matrices;                                   |
|                     |                                                                       | It also has a high degree of polymerization and high moldability in situ (during fermentation) and ex situ (after fermentation).| The bulk distribution of the particles within the BC is also heterogeneous, a feature further aggravated by the hydrophilic nature of certain polymer matrices. |
| Song et al.         | Improvement of bacterial cellulose nonwoven fabrics by physical        | Bacterial cellulose (BC) is a renewable bio-nanomaterial, with unique characteristics, that include high purity, high degree of polymerization and high crystallinity; | Hydrophilicity;                                                                                                           |
|                     | entrapment of lauryl gallate oligomers                                | Excellent biodegradability, biocompatibility, and moldability.                                                              | When BC nonwoven fabric is exposed to moist or wet conditions, it loses its original shape and it is difficult to recover its shape and strength. |
| Naeem et al.        | A preliminary study on the preparation of seamless tubular bacterial   | Bacterial cellulose (BC) is an outstanding nanofibrinous extracellular biodegradable polymer produced by nature;              | BC alone lacks the durability required for daily usage in sustainable applications for textiles;                          |
|                     | cellulose-electrospun nanofibers-based nanocomposite fabrics           | Possess high modulus and strength estimated to be 114 GPa and in excess of 1500 MPa, respectively;                          | High hydrophilicity for use in the textile industry.                                                                      |
|                     |                                                                       | It causes no harm to humans and the environment and does not contain any impurities that require intensive processes to be purified and isolated, such as lignin and hemicellulose; |                                                                                                                          |
|                     |                                                                       | Its unique physical characteristics and cultivation properties have demonstrated a great potential to achieve zero-waste design. |                                                                                                                          |
| Song and Kim        | Bacterial cellulose as promising biomaterial and its application      | BC is chemically pure (free of lignin and hemicellulose) and it does not require any extra processing to remove contaminants | BC has several drawbacks such as lack of antibacterial, antioxidant, and conducting properties;                         |
|                     |                                                                       | Biodegradability and chemical-modifying capacity;                                                                      | The high water holding capacity corresponded to its OH-rich structure causes a low interfacial compatibility, resulting in inadequate mechanical performance; |
|                     |                                                                       | The process of BC production requires simple, mild, semicontinuous static, and low-cost medium cultures and represents interesting alternatives for many developing industries. | The high moisture uptake results in the poor rehydration with loss of dimensional stability and fiber strength when BC is exposed in water. |
| Author / Year | Title | Advantages in the textile industry | Disadvantages in the textile industry |
|---------------|-------|------------------------------------|--------------------------------------|
| Kamiński et al. (2021) | Hydrogel bacterial cellulose: a path to improved materials for new eco-friendly textiles | Environmentally-friendly technology allowing for obtaining textiles based on bacterial cellulose; Bacterial cellulose can be produced from completely renewable and reusable sources and according to the principles of waste-free technologies; HydroGel Bacterial Cellulose fabric may be a viable alternative for the currently used synthetic materials; BC is a very convenient material when it comes to modifications in view of its applicability since it can be manufactured/grown in different shapes, processed to achieve enhanced properties and functionalized to gain new applications. | BC produced by Kombucha has the disadvantage is the brown colour of the product which is a result of melanoidins from the Maillard reaction, and an unpleasant smell of the material due to the presence of difficult to remove fermentation products, mainly carboxylic acids; The alkaline purification method with NaOH is commonly used in BC, however, it requires the use of significant amounts of water and neutralizers to obtain materials with neutral pH. |
| Hildebrandt et al. (2021) | The circularity of potential bio-textile production routes: Comparing life cycle impacts of bio-based materials used within the manufacturing of selected leather substitutes | Bacterial cellulose (BC) is a bio-renewable nanomaterial with a high purity, high degree of polymerization and high crystallinity. | Microbial cellulose sheet finishing requires additive materials for hydrophobic finishing, fire safety, and softening agents. The production cost and lower yield are the major issues in the bulk production of bacterial cellulose and hence. The high water-holding capacity of BC has several drawbacks. Its hydrophilicity causes poor rehydration and durability of BC bio-leather, and when exposed to moist or wet conditions, BC loses its shape and strength. |
| Rathinamoorthy and Kiruba (2020) | Bacterial cellulose-A potential material for sustainable eco-friendly fashion products | - Bacterial cellulose is one such biomaterial, sustainable, and environmental friendly and has a lot of potential in the fashion industry. | - Animal protection, avoiding the use of leather; BC is an eco-friendly cellulose material, making it environmentally friendly and biodegradable, thus helping reduce textile waste; Altering the fermentation conditions can result in BC with excellent moldability and biocompatibility; Unlike animal leather, additional processes such as tanning and graining are not necessary for BC bio-leather. |
| Kim et al. (2021) | Comparative study on the physical entrapment of soy and mushroom proteins on the durability of bacterial cellulose bio-leather | | |
| Laavanya et al. (2021) | Current challenges, applications and future perspectives of SCOBY cellulose of Kombucha fermentation | - High crystallinity, biocompatibility, non-toxicity and high porosity; - Purification of bacterial cellulose does not require harsh chemical treatment like vegetable cellulose; The growth of BC in various shapes and sizes gives rise to the idea of production of wastefree garments by the textile industry. | Unpleasant smell; One limitation that should be overcome is the regaining of moisture by the cellulose mat. |
patterns for specific types of clothing and are difficult to apply to the conventional manufacture of items of daily use. Zero waste patterns require a longer design process and more technical support for the execution of designs due to the special pattern allocation. Because it is not cost effective and is time consuming, zero waste design has not been widely used in the fashion industry.

Another relevant factor for the textile industry is the biodegradable nature of BC (Cazo´n et al. 2020; García and Prieto 2019) which could be successfully applied to obtain ecologically-friendly products (Cazo´n et al. 2020; Freudenreich and Schaltegger 2019). It should also be noted that for the manufacture of bacterial cellulose, only small amounts of water and energy are needed (Fernandes et al. 2019a, b; Yim et al., 2017). Therefore, it can be considered an eco-friendly biomaterial and a mitigator of negative impacts within the textile chain.

Despite the various benefits of using bacterial cellulose, there are still many technical and practical problems associated with the manufacture of clothing that need to be resolved, such as mechanical durability, comfort, material contamination, organic acids (responsible for the characteristic unpleasant smell), and attack by microorganisms (Kamiński et al. 2020). This review addresses one such property of BC, its wettability, as can be seen in Fig. 6.

It was observed that despite its natural characteristic of being hydrophilic, which is advantageous for many applications, for instance, in the area of health, a more hydrophobic biomaterial would be of great interest for the textile industry. According to Araújo et al. (2015) and Fernandes et al. (2019a, b), the hydrophilic nature of BC prevents the combination with hydrophobic polymeric matrices, presenting a challenge for the development of textiles (Araújo et al. 2015; Fernandes et al 2019a, b).

In the textile industry, a hydrophobic cellulose material would have a wide range of applications, for instance, for clothing and impervious stain-resistant textiles, among others. Cellulose fabrics with hydrophobic fiber surfaces are suitable for producing water repellent items, as they resist water but have some porosity, which allows the transport of moisture for user comfort. Studies to reduce the hydrophilicity of the modified cellulose surface have involved different technologies with broken effects and diameters (Araújo et al. 2015).

Although bacterial cellulose is biodegradable, renewable and biocompatible, its inherent properties, such as low strength, stiffness, high fragility and a hydrophilic nature, make it a poor biomaterial for application in commercial products (Dhar et al., 2019). However, currently, one of the main ecological problems, with regard to the textile industry and the use of clothing, is the issue of the disposal of textile waste. Since most of this waste is not biodegradable, being synthetic and derived from oil, further studies on bacterial cellulose would be of great interest (Kamiński et al. 2020).

Research seeking to improve or modify the BC properties, to address, for example, the issue of hydrophobicity, could lead to more alternative
biodegradable materials being inserted in the textile market. This issue merits increased investment, as the textile sector needs to identify new sustainable materials and, therefore, offering hydrophobicity must be aligned with proposal to increase sustainability in this sector. It should be noted, however, that other relevant properties, such as durability and biodegradability, must remain unchanged (Kamiński et al. 2020).

The Textile Industry, as well as other sectors that are related to serious environmental problems, need a quick change to contribute to the pillars of sustainability, likewise, in relation to achievement of the Sustainable Development Goals (SDGs). Therefore, investments in solutions such as new and more ecological materials are important, and bacterial cellulose is a good example.

However, when it comes to the textile market, some properties are necessary for BC to be commercialized with quality. Hydrophobia is an essential property for this area, according to research reported in this review article. Thus, it is important to look for effective changes in BC properties, without eliminating its main characteristic, which is that it is an eco-friendly biomaterial. Finally, future research on improvements in the general properties of bacterial cellulose is extremely important, as it is an eco-friendly, innovative material with great potential as a substitute for products from petroleum or animal origin.

**Trends, future perspectives and conclusions**

Studies on bacterial cellulose as a sustainable alternative for use as a fabric have been promising. Reduced water consumption, decreased use of insecticides and pesticides, and reduced waste, are among the advantages of using this biomaterial in the textile industry. The possibility of using bacterial cellulose as a substitute for animal leather was mentioned by several researchers.

Several properties of bacterial cellulose, such as mechanical strength, high crystallinity and three-dimensional structure, favor the use of this material in the textile industry, but its hydrophilicity poses a challenge for its application as a textile fiber. Based on the studies considered in this review, methods to make BC hydrophobic could be used to reduce the water absorption capacity such as: a) Acrylated epoxidized soybean oil (AESO) and Polyethylene glycol (PEG); b) Beeswax; c) Electrospinning; d) EVO Wet Fest; e) Glycerol and Plant-based proteins; f) Lauryl gallate; g) Oxygen plasma and trichloromethyl silane; h) Persofatal MS (polymethylsiloxane) and Baygard EFN (perfluorocarbon); i) Poly (fluorophenol); j) Polyani-line (PANi); k) Polyvinylpyrrolidone—carboxymethylcellulose; and l) Poly (lactic acid) (PLA).

The continuation of studies and tests is indispensable; so that biodegradable materials can be inserted in the textile market and that they can be commercialized. The main issues that could be addressed in future studies are obtaining hydrophobic biomaterials, which are durable, comfortable and which remain with their ecofriendly characteristics. Therefore, bacterial cellulose treatment processes must find environmentally friendly means.

**Acknowledgments** The authors are grateful to the Brazilian governmental agency CAPES (Higher Education Personnel Improvement Coordination) for a scholarship awarded and to the University of Southern Santa Catarina (UNISUL) for offering one of the authors the opportunity to pursue a master’s degree in Environmental Sciences.

**Funding** No funding was received to assist with the preparation of this manuscript.

**Data availability** There is no data or material to be made available for this manuscript.

**Code availability** There is no code to be made available for this manuscript.

**Declaration**

**Conflicts of interest** The authors have no conflicts of interest to declare that are relevant to the content of this article.

**Human Participants and/or Animals** The authors declare that the present review article has no involvement with human and/or animal participants.

**Informed consent** Does not apply to this manuscript.

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