Environmental Chemistry Letters (2021) 19:2967–2980
https://doi.org/10.1007/s10311-021-01214-x

REVIEW

Bacterial cellulose biotextiles for the future of sustainable fashion: a review

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Received: 8 February 2021 / Accepted: 26 February 2021 / Published online: 13 March 2021

Abstract
Fashion is one of the most polluting world industries, surpassed only by the petroleum industry. Environmental damages originate from the production, manufacture and dyeing of fabrics, calling for alternative feedstock such as bacterial cellulose. Bacterial cellulose is attracting industrial interest from the textile sector due to advanced properties of bacterial cellulose compared to plant cellulose. For instance, bacterial cellulose is produced by microorganisms in a sustainable way, is biodegradable and does not pollute the environment. Moreover, bacterial cellulose can be dyed, resulting in an attractive textile surface that meets the actual socio-environmental awareness of the industry. Here, we review properties and production methods of bacterial cellulose and applications, focusing on the textile industry. We also discuss the main features of the dyeing process using natural dyes, as well as the registration of patents related to the textile industry, in order to demonstrate the growing application potential in the fashion market. This is the first review that explores the applications of bacterial cellulose related to the textile industry.

Keywords Biotechnology · Bacterial cellulose · Natural dyes · Fashion · Industrial waste · Sustainability

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Introduction

Sustainability can be seen as a way to preserve nature without giving up economic and social growth. Such an approach is associated with less impactful production and more conscious consumption to ensure the protection of the planet's resources and the quality of life for future generations. It can and must be used by society and all industries, especially in the food and beverage, civil construction, textile and fashion sectors (Brenot et al. 2019).

However, to achieve the proposed sustainable development goals, it is necessary to use new technologies that aim to discover new raw materials, production processes, transformation, distribution and marketing. Biotechnology stands out for being a science capable of revolutionizing the production and supply of materials with the capacity for large-scale industrial applications, particularly to produce beverages, cosmetics, textiles and building materials (Rizwan et al. 2018).

Cellulose, a polymer found in plants, is widely used as a raw material to provide new biomaterials; however, the growing demand for plant-based cellulose derivatives has led to an increase in the consumption of wood as a raw material, exacerbating global environmental issues, including deforestation. Although plants are the largest source of cellulose on Earth, several types of microorganisms belonging to different genera are also capable of producing cellulose, which in this case is called bacterial cellulose or biocellulose (Gomes et al. 2013; Albuquerque et al. 2020). Biocellulose has renewable characteristics, including biodegradability and biocompatibility, which make it unique in a wide range of applications in the textile sector as a basis for sustainable clothing (Costa et al. 2017b). Biocellulose also shows applications in several other technological domains such as active packaging, filter membranes, medicines and cosmetics (Costa et al. 2017b; Albuquerque et al. 2020; Amorim et al. 2020; Qasim et al. 2021).

As for the textile industry, eco-fashion is a global concern for both producers and consumers. The development of conscious, viable processes and the search for raw materials with reduced environmental impact and competitive advantages represent a great challenge for the textile industry. Therefore, the use of natural dyes, extracted from different parts of the plant (leaves, flowers, fruit, stem and roots) to obtain special colors, gives the fashion product an esthetic, symbolic and sustainable value. Natural plant dyes are considered safe because they are non-toxic, non-carcinogenic and biodegradable (Boutrup and Ellis 2019; Sharma 2019). The combination of bacterial cellulose, used as a textile matrix, with a natural dyeing process has great prospects in this segment.

This review describes the concepts, trends and perspectives of bacterial cellulose and natural dyes for the textile industry, seeking the applicability of dyed biomaterials for the development of new textile products with fashion value, with a design concept for garments and, above all, wearability for consumers.

Textile industry and sustainability

Consumerism has been putting pressure on industries and supply chains, resulting in major negative impacts for both nature and society. The increase in pollution levels caused by industrial production is causing several researchers and experts to worry about production and consumption issues, based on a sustainable management of supply chain (Islam 2020).

Sustainable development is a dynamic process that allows to preserve and improve Earth's life support systems. In the textile industries, the search for eco-friendly solutions is justified by the discussions presented on environmental, cultural, social and economic parameters, which involve raw materials, their processing and the generation and disposal of effluents (liquids, solids and gases). To minimize the impacts caused by the textile and fashion industries, the production and processing of products must use sustainable materials in the collections in order to preserve the environment (Costa et al. 2017b; Kumar et al. 2020). Fuels and/or electricity are used, which cause the generation of steam and the elimination of many gases that affect the ozone layer. A large volume of quality water is also disposed of as a contaminated effluent with a high chemical load from these processes (Brenot et al. 2019).

The large number of textiles produced and discarded in the world is quite alarming, especially if linked to the development of fashion items, be they accessories, footwear, or clothing, which are characterized by a short life cycle. On the other hands, it is known that there is a growth in the production of synthetic filaments and threads, as well as in all the processes involved in textile processing, including finishes that seek to meet the trends of the fashion industry to dress the world society (Thiyagarajan and Hari 2014; Jain and Gupta 2016; Kaur and Chanchal 2016).

The increase in the unsustainable consumption rate attributed to the fashion industry is evident. Approximately $ 172 million worth of garments is estimated to be disposed of in landfills each year, with large quantities of them being discarded after simple wear (Wood 2019). In addition, despite the relevance of synthetic fibers as a raw material for modern life, their production, use, washing and disposal have caused environmental damage of enormous proportions. Studies have revealed that microplastics released from these synthetic textiles, as well as the incorrect disposal of fashion items and artifacts, cause irreversible damage to the ecosystem and its inhabitants (Jemec et al. 2016; Islam 2020).

Due to growing global concern, the textile industry has proven to be very engaged in the research and production of wearable artifacts produced with high quality and environmentally friendly filaments, fibers and fabrics. The discovery of different manufacturing processes and materials has made possible the development of new fabrics and, consequently, a textile revolution beneficial to the environment (Costa et al. 2017b).

Natural fibers

The term "raw material" refers to the commodity used to produce goods or materials. For example, a cotton T-shirt will be made with raw cotton that will be converted into yarn to make mesh structures and finally a standard cut, then trimmed and sewn to be sold as a retail T-shirt (Islam 2020).

A natural fiber is any fiber that exists as such in its natural state. Some examples are cotton, linen, wool and silk, which differ in arrangement, color, surface contour, chemical structure, as well as length and width. Natural fibers can be classified into three groups according to their origin, namely

Table 1 Most known natural textile fibers

Natural textile fibers	Source	Examples
Vegetable	Leaf	Sisal, Abaca
	Seed	Cotton, Coconut and Kapok
	Stalk	Hemp, Linen and Jute
Animal	Glandular secretion	Silk
	Hair bristles	Wool, Mohair and Camel
Mineral	–	Asbestos

vegetable, animal and mineral fibers (Nayak et al. 2020). The fibers, within each group, can come from different sources, some examples of which are shown in Table 1.

Fibers classified as natural are biodegradable and renewable and have a greater added value than chemical fibers due to slow processing (Costa et al. 2017b). Animal fibers are called protein fibers, while vegetable ones are called cellulosic fibers, both of which can be used as raw material to produce different types of textiles (Nayak et al. 2020). Although fabrics of natural origin are often considered ecologically sustainable, with the evolution of agriculture and animal husbandry for their production, serious damage to the soil has occurred, with often irreversible effects. But the increase in the production of synthetic fabrics has had an even more negative impact on the environment as many of them are not biodegradable and contribute to the growth of landfills (Wood 2019).

That said, searching different industrial processes and raw materials that reduce carbon emissions and waste is essential to minimize the environmental impacts. Sustainable clothing designs are structured for all stages of the life cycle, from production to disposal (Costa et al. 2017b).

Plant and bacterial cellulose

Plants are the main source of cellulose, which in this case is called vegetable cellulose. Vegetable cellulose is a sustainable, biodegradable and biocompatible polymer raw material that can be used to meet the growing demand for environmentally friendly products (Dai et al. 2019; Varghese et al. 2018; Hassan et al. 2020).

Cellulose is classified as a structural carbohydrate basically made up of carbon, hydrogen and oxygen and can be described by the general molecular formula $(C_6H_{10}O_5)n$. Its molecules are formed by long unbranched linear chains of β-D-glucose joined by β-1,4-glycosidic bonds that interact with each other through intra and intermolecular hydrogen bonds (Klemm et al. 2005; Lima et al. 2015). The polymeric structure begins its formation when two glucose molecules condense and form the repeating dimeric unit of the molecule called cellobiose. This structural conformation of cellulose results in the formation of long and rigid microfibrils (Esa et al. 2014). Moreover, the large number of hydroxyl groups present in the glucose rings facilitates the chemical modification processes, which allow obtaining cellulose derivatives with different properties (Shaghaleh et al. 2018).

From an economic point of view, vegetable cellulose was the cornerstone of the wood industry in the last century. However, as this sector contributes significantly to environmental degradation, the search for alternative sources of cellulose is essential (Amorim et al. 2020). In addition, vegetable cellulose is naturally associated with other biopolymers such as lignin, hemicellulose and pectin (Fig. 1); therefore, for its use as a textile, or in other applications, it requires a purification process (Peng et al. 2020).

An alternative way to obtain cellulose is through the use of microorganisms. Bacterial cellulose is composed of cellulose nanofibers secreted extracellularly by some bacteria (Amorim et al. 2020). Even though vegetable and bacterial celluloses have the same molecular formula, they show significant differences in their chemical, physical and mechanical properties, due to different spatial configuration and thickness of the fibers (Wang et al. 2019). Vegetable cellulose has a fibrillar structure on a micrometer scale, while the bacterial one on a nanometer scale. Such a structural difference is also reflected in its visual appearance, as vegetable cellulose is present in fibrous form, while bacterial cellulose is similar to wet/damp leather (Donini et al. 2010), as shown in Fig. 2.

Depending on the desired application, bacterial cellulose has several advantages over the vegetable one, such as a high degree of purity, excellent permeability, low density, greater crystallinity, stability, high mechanical resistance, large surface area (Gao et al. 2016; Costa et al. 2019). Table 2 shows

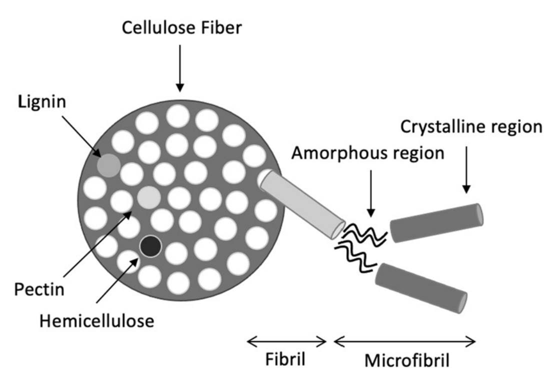

Fig. 1 Hierarchical structure of vegetable fibers. Cellulose chains are arranged in the form of microfibrils that aggregate, forming structures that in turn are held together by the amorphous matrix of lignin and hemicellulose. Microfibrils are composed of highly ordered crystalline regions and amorphous and disordered regions

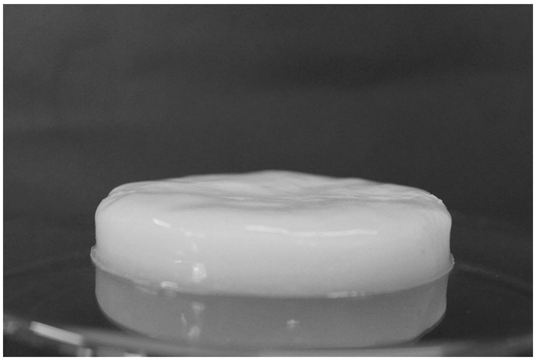

Fig. 2 Bacterial cellulose produced by a bacterium belonging to the genus *Gluconacetobacter* sp. Note that the appearance resembles a wet/damp leather

comparative data for some of the main properties of the two types of cellulose.

Bacterial cellulose production

Bacterial cellulose is produced extracellularly by many species of Gram-negative bacteria of the genera *Acetobacter*, *Aerobacter*, *Gluconacetobacter*, *Azobacter, Agrobacterium, Achromobacter*, *Sarcina*, *Rhizobium*, *Pseudomonas*, *Salmonella* and *Alcaligenes*. Among these, those belonging to the genus *Gluconacetobacter* are extensively studied for their ease of maintenance and for being able to use a wide variety of carbon sources (Rajwade et al. 2015). During biosynthesis, the bacteria, or group of microorganisms, form a film (also known as pellicle or membrane) consisting of a random nanofibrillar network of cellulose chains (Fig. 3), interspersed between water regions that occupy 90–98% of the total volume of the material (Picheth et al. 2017).

During the production process, protective envelopes are formed around the microbial cells, protecting them from ultraviolet radiation and drying processes. Alternative production methods are currently being investigated to decrease production costs, as well as increase the yield of microbial cellulose (Gromovykh et al. 2017; Wang et al. 2019).

Current methods for obtaining bacterial cellulose membranes are agitated and static cultures, the choice of which greatly influences their macroscopic appearance (Fig. 4). Static cultures allow the formation of cellulose membranes with a uniform surface similar to a white leather, while the agitated ones result in irregular masses with the appearance of spheres or pellets. The choice of the method depends on the final application of the bacterial cellulose, since the two products have different physical, morphological and mechanical characteristics. Other essential factors that must be considered in the production process are the environmental conditions of the culture, including the bacterial strain, nutrients, pH, oxygen supply, composition of the culture medium and fermentation time (Wang et al. 2019).

Bacterial cellulose can be produced in different sizes and shapes, with applications in the engineering field, paper production, textile and optical industries, acoustics, packaging, cosmetics, pharmaceutical and biomedical products (temporary artificial skin for wounds and burns, dental products, artificial blood vessels), separation of DNA, electronic paper, paint additives, coatings, reinforcement for optically transparent films, nutrition (Iguchi et al. 2000; Klemm et al.

Table 2 Comparison of properties of bacterial cellulose (BC) and vegetable cellulose (VC)

Property	BC	VC	References
Purity (%)	> 99	< 80	Klemm et al. (2005), Wang et al. (2019)
Polymerization degree	800–10,000	500–15,000	Klemm et al. (2018)
Young modulus (GPa)	15–30	39–100	Amorim et al. (2020)
Water storage capacity (%)	> 95	25–35	Wang et al. (2019)
Crystallinity degree (%)	60–90	40–78	Campano et al. (2016), Wang et al. (2019)

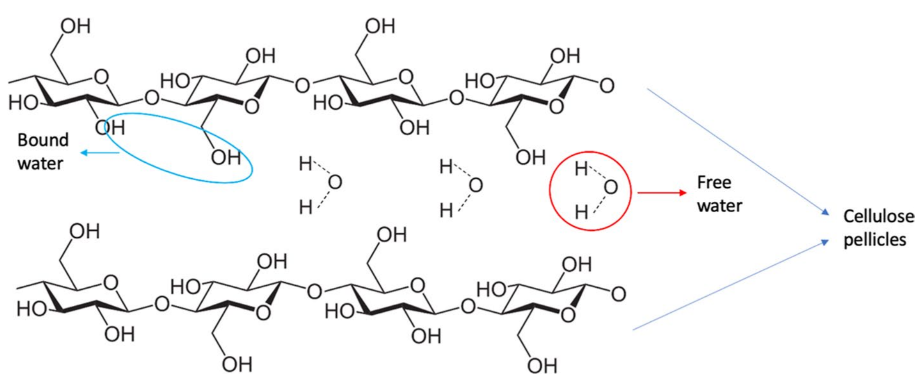

Fig. 3 Random nanofibrillary network of bacterial cellulose chains

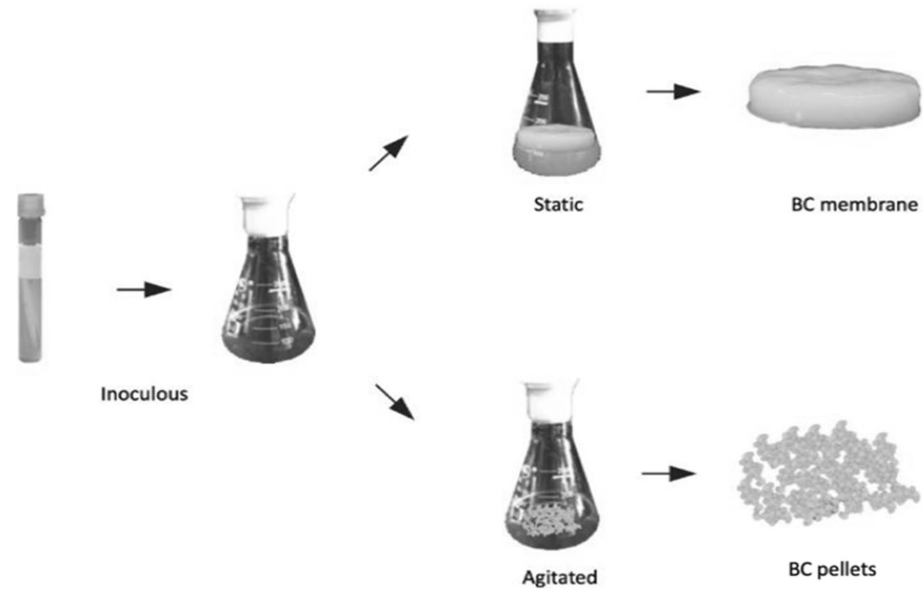

Fig. 4 Scheme of bacterial cellulose (BC) production in agitated and static cultures and their respective appearance

2001; Svensson et al. 2005; Bäckdahl et al. 2008; Wang et al. 2011; Cavka et al. 2013; Li et al. 2015; Albuquerque et al. 2020; Amorim et al. 2020; Galdino et al. 2020; Pandey 2021).

Another form of bacterial cellulose cultivation is through kombucha, a common name given to fermented drinks by a consortium of microorganisms, starting from the plant *Camellia sinensis* or others rich in caffeine. This drink is consumed all over the world for its refreshing taste and its beneficial effects on human health. Research indicates that kombucha can promote digestive functions, boost the immune system, reduce inflammatory responses and have many other health benefits for people who consume it (Amarasekara et al. 2020).

According to Villarreal-Soto et al. (2018), kombucha is microbiologically composed of bacteria and fungi, which are present in a powerful symbiosis capable of inhibiting the growth of potential contaminating bacteria, thereby making this culture medium very versatile and economical. Among the microorganisms found in the drink, there are acetic acid bacteria (*Gluconobacter* sp., *Acetobacter* sp. and *Komagataeibacter* sp.) (Roos and Vuyst 2018), lactic acid bacteria (*Lactococcus* sp. and *Lactobacillus* sp.) (Marsh et al. 2014) and yeasts (*Zygosaccharomyces bailii*, *Saccharomyces cerevisiae*, *Schizosaccharomyces pombe*, *Saccharomycodes ludwigii*, *Kloeckera apiculata*, *Torulaspora delbrueckii*, *Brettanomyces bruxellensis*) (Coton et al. 2017).

According to Sreeramulu et al. (2000), the cellulose produced during fermentation appears as a thin membrane on top of the tea, where a large part of the bacteria and yeasts are attached, which acts as a flotator for microorganisms. It is made up of glucose from sucrose used to sweeten tea, which is metabolized by bacteria for the synthesis of cellulose and gluconic acid. This membrane is also known as SCOBY, which is an acronym for the term "Symbiotic Culture of Bacteria and Yeast."

To reduce production costs several studies have also focused on the feasibility of using industrial waste as a source of nutrients to produce bacterial cellulose. Therefore, bacterial cellulose membranes have been produced in different media, based on wastes and alternative carbon and nitrogen sources, having physicochemical compositions very similar to that of the commercial Hestrin and Schramm (1954) medium. The results of these investigations, summarized in Table 3, provide a broad idea of the potential for waste to produce sustainable and economical bacterial cellulose.

The results obtained using the culture media listed in Table 3, whose composition included different industrial wastes, were very promising in terms of bacterial cellulose production, especially under static conditions, allowing to obtain dry weight yields ranging from 0.66 and 12.60 g L^{-1} in the temperature range between 25 and 35 °C and at pH between 4 and 7. From a sustainable point of view, such an exploitation of industrial by-products would not only reduce the environmental and health risks associated with their discharge, but would also allow to minimize the main disadvantage of bacterial cellulose production, namely its high manufacturing cost due to use of expensive components of the culture medium (Hussain et al. 2019).

Natural dyeing

Colors are the result of the physical modification of light by the dyes present in objects, detected by the eye and interpreted in the brain. In other words, the reflectance of light by

Table 3 Different media based on wastes and alternative carbon and nitrogen sources for bacterial cellulose production

Wastes and alternative carbon and nitrogen sources	Microorganism	Dry weight yield (g L^{-1})	Time (days)	References
Lipid fermentation wastewater	*Gluconacetobacter xylinus* CH001	0.66	5	Huang et al. (2016)
Sugarcane molasses	*Gluconacetobacter intermedius* SNT-1	12.60	6	Tyagi and Suresh (2016)
Corn steep liquor	*Gluconacetobacter hansenii* UCP1619	9.63	10	Costa et al. (2017a)
Durian shell hydrolysate	*Gluconacetobacter xylinus* CH001	2.67	10	Luo et al. (2017)
Cashew tree residues	*Komagataeibacter rhaeticus*	6.00	7	Pacheco et al. (2017)
Mature black spear grass (*Heteropogon contortus*) hydrolysate	*Gluconacetobacter xylinus* isolated from rotten banana juice	4.88	15	Dirisu and Braide (2018)
Distillery effluent	*Gluconacetobacter oboediens* MTCC 5610	8.50	8	Jahan et al. (2018)
Cheese whey	*Komagataeibacter medellinensis* NBRC 3288	2.37	10	Molina-Ramírez et al. (2018)
Rotten banana juice	*Komagataeibacter medellinensis* NBRC 3288	4.81	10	Molina-Ramírez et al. (2018)
Rotten mango juice	*Komagataeibacter medellinensis* NBRC 3288	1.95	10	Molina-Ramírez et al. (2018)
Pullulan fermentation wastewater	*Gluconacetobacter xylinus* BC-11	1.18	10	Zhao et al. (2018)
Potato peel wastes	*Gluconacetobacter xylinus* ATCC 10,245	4.70	6	Abdelraof et al. (2019)
Tomato juice	*Acetobacter pasteurianus* MTCC 25117	7.80	7	Kumar et al. (2019)
Tobacco waste extract	*Acetobacter xylinum* ATCC 23767	5.20	16	Ye et al. (2019)
Fruit residues	*Gluconacetobacter hansenii*, (ATCC 53582	6.98	10	Amorim et al. (2019)
Corn steep liquor	*Gluconacetobacter hansenii* UCP1619	2.69	6	Galdino et al. (2020)

an object as a function of wavelength determines the color of the object. The coloring of a textile is cited as one of its most important characteristics (Becerir 2017).

The change of color of a given textile can be done using pigments and/or dyes, which differ according to their specific characteristics in contact with the textile to be colored (Boutrup and Ellis 2019). Their main differences are the solubility and the modifications they cause on the characteristics of the textile. Dyes used for dyeing are hydrophilic, penetrate inside the fibers having affinity for the textile surface and do not mask the basic coloring of the fibers. On the other hands, pigments are not soluble in water and adhere to the fiber surface with the help of an adhesion facilitator. Pigments can hide defects in the lower layers and can also change the texture and appearance of textiles, as their presence on the surface can change their luster and other characteristics (Boutrup and Ellis 2019).

The replacement of natural dyes with synthetic ones by industries occurred due to the numerous advantages of using the latter, such as an easier availability for industrial use and the attribution of specific characteristics to treated textiles, including shine, resistance to prolonged washing and a wide variety of characteristic tones that provide sensory and esthetic comfort (Kasiri and Safapour 2014; Sharma 2019). However, despite all these advantages, the use of synthetic dyes has been subject to intense monitoring due to the environmental problems generated by the processing phases, which need large volumes of water and release wastewater into water bodies, thereby affecting the reproduction of fauna and flora, as well as the health of the population depending on these water sources (Costa et al. 2017b; Dsikowitzky and Schwarzbauer 2014). In addition, the precursors used in their synthesis have many dangerous and carcinogenic effects for workers, are extremely harmful to the environment and, above all, are not biodegradable, thus making the environmental contamination even greater (Kumbhar et al. 2019; Sharma 2019).

The main chemical pollutants found in synthetic dyes are carcinogenic amines, heavy metals, pentachlorophenol, bleaching chlorine, free formaldehyde, biocides, fire retardants and softeners (Rovira and Domingo 2019). Heavy metals and their derivatives present in synthetic dyes as pigments, such as titanium oxide, chromates, iron and others, have been significantly reduced in the last two decades, because they pose serious health risks and cause environmental damage also due to their ability to pollute groundwater (Mia et al. 2019). In this context, natural dyes have been regaining space on the market, as they are biodegradable, do not cause health risks and, therefore, can be easily used without many environmental concerns (Arora et al. 2017; Alebeid et al. 2020).

Natural dyes seek sustainability and are well known for producing very unusual and soft tones compared to synthetic dyes. This industrial rethinking toward natural dyes is also attributed to the stringent environmental standards imposed by many countries and consumers (Varadarajan and Venkatachalam 2016; Sharma 2019). They have been used since the beginning of civilizations to color food, leather, as well as common textile fibers, such as wool, silk and cotton. Natural dyes have properties that provide significant advantages, but also disadvantages over synthetic dyes, as shown in Table 4.

According to İşmal and Yıldırım (2019), textile fibers, especially those of cellulosic origin, do not have much affinity for most natural dyes. Therefore, before being dyed, they need to be treated with a dye fixative called mordant. Unlike fibers of animal origin, plant fibers such as cotton do not quickly fix the mordants, resulting in less brilliant colors than these obtained from wool and silk.

In addition to fixing the color to the fibers, mordants prevent color fading over time due to exposure to light or washing. Using different stains, designers can also achieve a variety of colors and shades of the same dyes (Arora et al. 2017). A mordant is usually a metal salt that binds to the fiber if it is a protein or is left as an insoluble compound in the fiber if it is a cellulose. The quantity, quality and type of application of the mordant also influence the color at the end of the dyeing process (Boutrup and Ellis 2019). During the dyeing process, the dye already diluted in water enters the fiber, where it binds to the mordant, forming an insoluble component that makes the dyeing permanent and resistant to washing (Boutrup and Ellis 2019).

However, in contrast to the huge amount of dyes found in the environment, today only a minimal amount is applied to the coloring of textiles. Much of the data on natural dyes used by man was lost when synthetic dyes were introduced to the market and industry interest turned to them (İşmal and Yıldırım 2019). Continued research efforts are being expected in relation to agro-industrial waste biomordants, which are cheaper and environmentally benign, but require development of research and methods. In addition, functional finishing effects such as antimicrobial and insect repellent effects are worth investigating (İşmal and Yıldırım 2019). Since much of the natural dyeing waste is made up of biomass, it can be reused in composting, for biogas production and even in animal feed, supporting the 3R principle, reduce, reuse and recycle (Elsahida et al. 2019). That said, using natural dyes can be beneficial to the environment.

According to Elsahida et al. (2019), sustainability in naturally dyed textiles consists of four aspects: environmental, social, economic and creativity to bring all aspects together. Several companies are able to increase production and quality of their processes, not only aiming at the economy, but considering the social and environmental aspects of production. Finally, by overhauling the dyeing processes and its mordants, it is inevitable to provide a successful and sustainable dyeing process in the near future. Furthermore, it can be expected that new ecological technologies, such as ultrasound, enzymes, dyeing of biotextiles, among other industrial applications, can lead to the reduction or even elimination of the use of non-ecological metal mordants (Arora et al. 2017).

According to Shim and Kim (2018), bacterial cellulose can be dyed not only after its production (ex situ), but also while being produced, by adding dye during cultivation (in situ). With both dyeing methods, cellulose fibril networks showed smooth surfaces and retained their inherent nanostructures during dye penetration, although the in situ method allowed for a smoother surface and a more even color than the ex situ one. Based on that, studies applying various colors to bacterial cellulose as a fabric can be performed, and various colors can be obtained using vegetable dyes, as can be seen in test samples shown in Fig. 5.

Perspectives of bacterial cellulose in fashion

The natural biodegradable microbial polymer can stimulate the development of new textile and sustainable materials and manufacturing practices in the future (Chan et al. 2017). Suzanne Lee, a British fashion designer, pioneered the use of bacterial cellulose by developing a sustainable fashion research project called BioCouture. Experimenting with kombucha, she produced a bacterial cellulose textile directly in a rectangular vessel and created a microbial cellulose jacket and gloves using conventional garment construction techniques such as cutting to shape clothing panels and sewing (Wood, 2019; Lee, 2021). After that, numerous researches and experiments out on bacterial cellulose were carried, which resulted in naturally or synthetically dyed or

Table 4 Advantages and disadvantages of natural dyes over synthetic dyes

Advantages	They are renewable, biodegradable, non-toxic and non-allergenic They can be easily extracted from plants, fruits, leaves and barks Fabrics show greater absorption of UV rays, resulting in reduced incidence in those wearing dyed fabrics Industries that use natural dyes may have the potential to generate carbon credits Generated production wastes can be used as biological fertilizers They can be used in a wide range of colors, thus increasing the range of possibilities for the same dyeing extract
Disadvantages	Mordants are needed in most dyeing They are unstable to sunlight, heat and extreme pH They are less available and therefore more expensive They are less stable in terms of the number of washes They are less striking and have lighter color tones

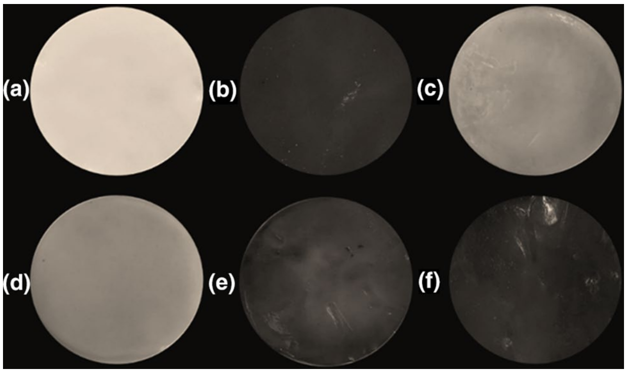

Fig. 5 Bacterial cellulose dyeing tests in situ by an alternative rich in color culture medium: **a** without dyeing process, **b** *Clitoria ternatea L. flowers* extract, **c** *Brassica oleracea var. capitata F. rubra* extract, **d** Propolis extract, **e** *Vitis labrusca* extract, **f** *Hibiscus rosa-sinensis* flowers extract

undyed bacterial cellulose artifacts such as those illustrated in Fig. 6 as examples.

An initiative called 'Malai' produces vegan alternatives to leather, based on bacterial cellulose produced from a culture medium composed of coconut water and industrial residues, which are used to develop fashion accessories in different colors and shades (Arora, 2020). Manufacturers claim that the material is durable and biodegradable and can have a long life, as long as care is taken for its preservation.

According to Amorim et al. (2020), the number of scientific publications regarding the application of bacterial cellulose has grown significantly in recent years, as has the registration of patents in this sector. Table 5 lists the main aspects relating to properties, production methods and dyeing of bacterial cellulose in the context of the textile and fashion industry that have emerged from scientific works from the last 6 years.

Based on these work applications, it can be stated that production by static culture is proposed by all researchers for the production of bacterial cellulose in the form of a sheet. The major problems reported by the researchers are a reduction in flexibility, the structural disintegration of bacterial cellulose during the drying process and the consequent loss of breathability. Tensile test results proved that bacterial cellulose film is sensitive to drying temperature, being harmful to the material as a fashion business. Lower drying temperatures help to preserve the porous structure, strength and deformation properties of the polymer. The ideal properties for its use as a textile were obtained at low temperatures (about 25 °C). Table 6 lists some perspectives for bacterial cellulose applications in the textile industry found in some patents registered in recent years.

An examination of these patents and academic research demonstrates the variety of promising applications for bacterial cellulose in the textile industry. It is also evident that the versatility of the biopolymer, combined with the use of biodegradable, non-polluting agents such as vegetable dyes, has great chances to provide new sustainable and environmentally friendly bioproducts capable of meeting the needs of the current world market (Costa et al. 2019).

Society is increasingly aware of the damage caused by the fashion business and the importance of quality sustainable products, planned according to their production, dyeing, function and life cycle based on ecologically sound methods. The fashion market expects colors and changes combined with quality, sustainability and functionality (İşmal and Yıldırım 2019).

A greater understanding in terms of sources of supply, applications and properties, of biomaterials, be they dyes or biofibers, is essential to expand the boundaries of research applicable to the textile sector. Studies using biotechnology are not new, but their use is rapidly transforming society with an infinite number of beneficial possibilities. In addition, the current scope of science allows for a completely new way of rethinking the materials that will emerge as new products around us (Carvalho and Santos 2015).

Conclusion

A growing awareness of actual environmental problems, such as climate change, scarcity of resources, exploitation of labor and pollution of water resources, has raised the expectations of consumers about brands and their products. In this sense, the use of biotechnology and natural materials such as bacterial cellulose in industrial processes

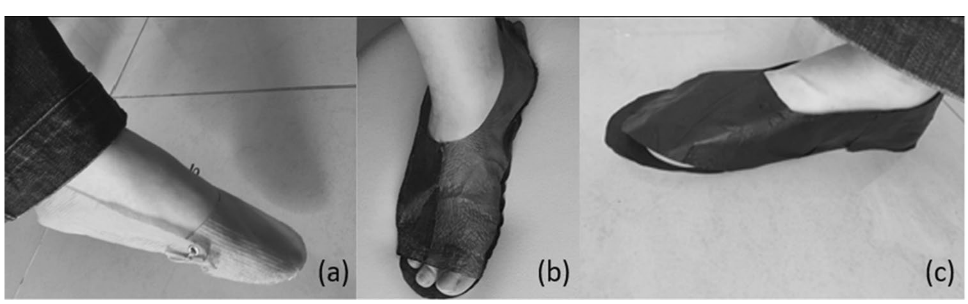

Fig. 6 Examples of bacterial cellulose artifacts: **a** without dyeing, **b** natural dyeing based on *Hibiscus rosa-sinensis* flowers, **c** dyeing with the synthetic dye ARAQCEL RL 500

Table 5 Properties, production methods and dyeing of bacterial cellulose in the context of the textile and fashion industry that have emerged from scientific works from the last 6 years

Article	Description	References
A study of the receptivity to bacterial cellulose pellicle for fashion	This study investigated the bacterial cellulose formation process in different concentrations of green tea broth and at different incubation times. The results suggested that the pellicle grown for 6 days on 15 g L^{-1} broth was the best in terms of comfort and appearance for fashion creation. The authors continued went on to design and create various 3D bio-fashions	Ng and Wang (2015)
The role of technology toward a new bacterial cellulose-based material for fashion design	This study evaluated the potential application of textile finishing processes in the bacterial cellulose development with suitable properties to be used as a material for fashion design. The results of bacterial cellulose showed the achievement of a hydrophobic material. According to these results, it is expected that the hydrophobic cellulose may find interesting applications as textile material in clothing, flooring and other interior design materials	Araújo and Gouveia (2015)
Production and characterization of bacterial cellulose fabrics by nitrogen sources of tea and carbon sources of sugar	This study aimed to develop eco-friendly fashion fabrics based on bacterial cellulose. The bacterial cellulose fabric had 0.213 ± 0.01 mm of thickness, smooth surface (155.56 nm of roughness) and $74.26 \pm 5.24\%$ of crystallinity when green tea and sucrose were used as nitrogen and carbon sources in the medium. The bacterial cellulose fabric had a tensile strength value twice that of leather and a similar appearance and thickness. Therefore, further cultivation conditions have to be investigated to improve its durability in sewing, wearing and washing	Yim et al. (2017)
Development of tailor-shaped bacterial cellulose textile cultivation techniques for zero-waste design	The purpose of the study was to produce a bacterial cellulose membrane with the ability to be cultivated in any desirable garment panel shape, with no cutting and with less textile waste. Two different types of tailor-shaped cultivation techniques (contacting surface-blocking cultivation and panel-shaped cultivation) were successfully developed to be used for the development of new sustainable textile materials	Chan et al. (2017)
Effects of cultivation, washing and bleaching conditions on bacterial cellulose fabric production	This study compared different cultivation, washing and bleaching conditions to produce a white bacterial cellulose fabric to be proposed as a new type of fabric in the textile industry. The white microbial cellulose fabric was bleached using 5% H_2O_2 solution. The fabric was obtained with a white index of $73.15 \pm 1.09\%$ without a natural yellowish-brown color. The fabric is expected to have various applications after further treatments (e.g., dyeing and finishing)	Han et al. (2018)
Coloration of bacterial cellulose using in situ and ex situ methods	This study aimed at different dyeing methods. The production yield of bacterial cellulose cultured by the in situ method on glucose as the carbon source and using a reactive dyestuff was the highest (about 86%) The ex situ dyeability of cellulose was improved by setting the dyeing conditions to pH 3 and 135 °C. The in situ method was more effective than the ex situ one, allowing for a smoother surface and a more even color. These results are useful for future studies on the application of various colors to bacterial cellulose as a fabric	Shim and Kim (2018)

Table 5 (continued)

Article	Description	References
Kombucha bacterial cellulose for sustainable fashion	This article is based on the evaluation of kombucha material properties and the investigation of bacterial cellulose as a type of material for the fashion industry. Based on the experimental results, some recommendations for kombucha cellulose film production are provided such as an optimal drying temperature of 25 °C. Advantages and disadvantages of the material are discussed in the paper, in order to show how to adapt the new type of material to the fashion business	Domskiene et al. (2019)
Development of novel bacterial cellulose composites for the textile and shoe industry	This research had the objective of producing a malleable, breathable and water impermeable nanocomposite. Bacterial cellulose was impregnated with hydrophobic polymers used in textile finishing (polydimethylsiloxane and perfluorocarbon) by an exhaustion process. Targeted bacterial cellulose was obtained, with promising properties for application in the textile and shoe industries	Fernandes et al. (2019a)
Bacterial cellulose and emulsified AESO biocomposites as an ecological alternative to leather	This research investigated the development of bio-based composites comprising bacterial cellulose and acrylated epoxidized soybean oil (AESO) as an alternative to leather. The composite was successfully prepared with emulsified AESO resin, polyethylene glycol, polydimethylsiloxane and perfluorocarbon-based polymers to enhance the flexibility and hydrophobicity of the bacterial cellulose, showing overall satisfactory performance as a potential alternative to leather	Fernandes et al. (2019b)
Hydrogel bacterial cellulose: a path to improved materials for new eco-friendly textiles	This research investigated the synthesis and modification of kombucha bacterial cellulose in order to produce textiles with specific physicochemical and mechanical properties. The procedure of manufacturing cellulose in the form of a stable hydrogel bacterial cellulose (HGBC) ensures the desired properties for the application of such a material in the textile industry. Finally, the synthesized fabrics were used as wristbands and parts of T-shirts and tested on volunteers to determine a skin-to-skin contact behavior of the prepared fabrics. The reported results confirmed that the HGBC fabric may be used as a new textile	Kamiński et al. (2020)

Table 6 Patents related to dyeing and bacterial cellulose production

Patent	Description	References
EP2331699	The invention relates to a method for producing bacterial cellulose in a flat form. The purpose of the invention is a universally usable method that is suitable for large-scale and efficient bacterial production of homogeneous and planar materials, of any defined length and thickness, thus allowing application in different industrial segments such as that of textiles	Dana et al. (2011)
CN103481720A	The patent provides a method of producing a decorative paint using bacterial cellulose. The method includes the following steps: (a) partial drying of the bacterial cellulose membranes, (b) immersion in dyeing solutions with the desired colors, (c) dyeing, (d) drying and (f) molding according to the desired base pattern. Due to the relatively dense mesh structure of the material, the colors do not fade after dyeing and can be stored for a long time	Chunyan (2014)
US2017314193A1	The invention provides a process for obtaining garments, with emphasis on producing fabrics with a multi-tonal appearance. The process includes a step of incorporating a layer of the bacterial biopolymer, which, after dyeing, is removed from the fabric to achieve the desired staining effect	Eryilmaz et al. (2017)
TW201716659A	A method for dyeing the microbial polymer is described in this patent. The bacterial cellulose is dyed using an ultrasonic vibration step to disperse the dye in the dyeing solution. After dispersion, the microbial cellulose is dipped in the solution with the dye, where ultrasonic vibration is used to help fix the color. Finally, cellulose is washed with running water to remove unattached dyes	Li et al. (2017)
KR102039415B1	The invention relates to a method for making a colored biocellulose for a mask pack. The manufacturing method is based on the production of a colored bacterial cellulose fabric, using natural materials with no side effects on the human body, which are able to prevent the discoloration and color loss by cosmetics	Park (2019)

can have a positive impact on both companies and consumers. The current trend of using biomaterials in fashion and clothing products is growing and offers perspectives on sustainable design aiming at social well-being and innovation. Fashion designers should look at biotechnology as a tool to use as part of the creative process. Bacterial cellulose and natural dyeing, despite the difficulties shown in their use, are useful implements in the design of textile items, in order to better serve the garment industry in terms of innovative and quality clothing.

Authors' contributions All authors contributed to this work. Leonie Asfora Sarubbo and Andrea Fernanda de Santana Costa conceived the project. Claudio José Galdino da Silva Junior, Alexandre D'Lamare Maia de Medeiros, Julia Didier Pedrosa de Amorim, Helenise Almeida do Nascimento and Andrea Fernanda de Santana Costa wrote the paper. Leonie Asfora Sarubbo and Attilio Converti analyzed the data, revised the manuscript, performed manuscript editing and final improvement.

Funding This study received funding from the Brazilian fostering agencies Fundação de Amparo à Ciência do Estado de Pernambuco (FACEPE [State of Pernambuco Science Assistance Foundation]), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES [Coordination for the Advancement of Higher Education Personnel]—Finance Code 001), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq [National Council for Scientific and Technological Development]) and the Research and Development Program of the Agência Nacional de Energia Elétrica (ANEEL [National Electrical Energy Agency]).

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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