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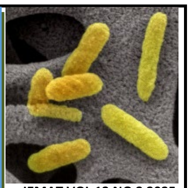

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False color SEM of *A. hydrophila*

Multifunctional Applications of Bacterial Cellulose: Bridging Food, Cosmetic and Environmental Sectors

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Abstract

In recent years, with increasing demand for sustainable, environmentally friendly materials, bacterial cellulose (BC) has attracted significant attention as a promising biomaterial. BC possesses excellent mechanical strength, good biocompatibility, extremely high water-holding capacity (more than 100 times its own weight), and can be easily modified. These unique properties make BC superior to plant cellulose in many applications. This review summarizes recent progress in BC across several important fields. In the food industry, BC has been widely used as edible films and coatings, enhancing the shelf life of fresh products. Moreover, when natural antimicrobial agents or pH indicators were incorporated, active and intelligent packaging were developed. As a food additive, BC acts as a high-quality dietary fiber that can adsorb cholesterol and bile salts in the gastrointestinal tract. BC also improves the texture of low-calorie foods and protects probiotic bacteria during storage. In the cosmetic field, BC is well-suited for facial masks because its three-dimensional structure can hold a large amount of active compounds and conform well to the skin surface. When BC was combined with propolis or other natural extracts, the antioxidant and anti-aging effects were greatly enhanced. In wastewater treatment, the abundant hydroxyl groups and large surface area enable heavy metal ions and organic dyes to be removed effectively. Besides, BC has been used as a reinforcement material in the paper and textile industries. The addition of BC greatly increases tensile strength and provides hydrophobicity while maintaining complete biodegradability. Although BC has numerous excellent properties and great potential in many fields, large-scale production still faces some challenges, mainly high costs and low yields. The use of agro-industrial waste as a substrate and the development of new bioreactors can significantly reduce production costs. Based on the above-mentioned research, it is clear that BC will play an important role in the future sustainable industry.

INTRODUCTION

In recent years, with increasing demand for sustainable, eco-friendly materials, bacterial cellulose (BC) has attracted significant attention as one of the most promising biomaterials of the 21st century. Unlike plant cellulose, BC is produced by certain bacteria, such as *Gluconacetobacter xylinus*, resulting in a three-dimensional nanofibrillar network with high crystallinity and purity [1]. BC possesses excellent mechanical properties, good biocompatibility, high water-holding capacity (up to 100 times its dry weight), and can be easily modified [1,2]. These unique features make BC a very promising material that can replace traditional petroleum-based polymers in many fields. The utility of BC has been widely explored in various consumer and industrial applications. In the food industry, BC is used as edible films and coatings that can effectively prevent oxygen and moisture penetration, thus extending the shelf life of fresh products [2,3,4]. Moreover, BC can act as a carrier for antimicrobial agents and pH indicators, thereby enabling the development of active and intelligent packaging [3,4]. As a direct food additive, BC has been reported to serve as a low-calorie dietary fiber that absorbs cholesterol in the gastrointestinal tract and improves gut health [5-7]. In the cosmetic field, the three-dimensional structure of BC is well-suited for preparing facial masks, in which active ingredients can be slowly released to the skin [8,9]. Furthermore, when BC was combined with natural compounds such as propolis, the antioxidant and anti-aging effects were significantly enhanced [10,11]. In addition, BC shows great potential in environmental remediation.

BC membranes possess high surface area and abundant hydroxyl groups; therefore, heavy metal ions like Cu^{2+}, Pb^{2+} , and Cd^{2+} can be efficiently removed from wastewater [12,13]. The adsorption capacity can be further improved by chemical modification or compositing with graphene oxide and other nanoparticles [13,14]. In the paper and textile industry, the addition of BC greatly increases tensile strength and gives hydrophobic properties to final products while maintaining biodegradability [15-17]. Previous researchers [15-17] have shown that BC-reinforced paper has much better mechanical performance than conventional paper. Besides, biomedical applications of BC have been extensively studied in the last decade. BC wound dressings can maintain a moist environment and accelerate the healing process, especially when silver nanoparticles or antimicrobial peptides are incorporated [20,21].

BC scaffolds have been used for tissue engineering of bone, cartilage, and nerve regeneration, and good biocompatibility has been observed in animal models [22,23]. Moreover, BC-based nanocomposites were developed for controlled drug-delivery systems that allow sustained release of therapeutic agents [24,25]. Although BC has numerous excellent properties and wide applications, several challenges remain for its large-scale commercialization. The production cost is relatively high due to low yield and the high cost of the culture medium [1,18]. Regulatory approval and long-term clinical studies are also needed before medical products enter the market [20,18]. However, recent studies have clearly shown that new bacterial strains and novel bioreactor designs can significantly improve productivity [19]. With continuous efforts in strain engineering, process optimization, and functionalization, it is believed that BC will play an important role in the future sustainable industry [1,19]. The overall pathway from BC production to its sustainable applications is summarized in **Fig. 1**.

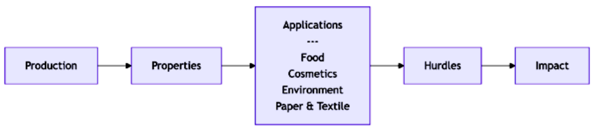

Fig. 1. The value chain of bacterial cellulose applications.

Food Industry (Packaging & Additives)

Bacterial cellulose (BC) has been considered a very promising material for food packaging and as an additive due to its renewable nature and excellent properties. BC possesses high crystallinity, good mechanical strength, and forms a nanofibrillar network that can effectively block oxygen and water vapor [2]. In addition, BC is completely biodegradable and edible. These features make BC superior to many synthetic plastics in sustainable food packaging. In recent years, many researchers have focused on BC-based edible coatings and films. For example, BC coating was applied on strawberries, and the shelf life was extended to 14 days at 4 °C compared with the control group [3]. Moreover, when antimicrobial substances such as garlic extract, fermented soymilk, or zinc oxide nanoparticles were added to BC films, the growth of pathogenic bacteria was significantly inhibited [3,26,27]. BC films containing curcumin or essential oils also delay lipid oxidation and keep food fresher longer, especially in fish and meat products [4,28,29]. Furthermore, BC can act as a carrier for colorimetric pH indicators, which change colour when food begins to spoil [4].

All these active and intelligent functions show great potential in the food industry [2,4]. Besides, BC is often combined with other biopolymers to improve overall performance. For instance, blending with alginate or carboxymethyl cellulose (CMC) increases the tensile strength and water resistance of the final films [30]. Alginate-based composite incorporated with probiotic or fruit pulp exhibits better antioxidant activity [31]. Chitosan-alginate hydrogel containing nanoencapsulated antimicrobial agents was found to control moisture release and reduce microbial contamination more effectively [29,31]. Previous studies [30-33] had clearly shown that such composites not only extend shelf life but also decrease the use of petroleum-based plastics.

In addition, BC reinforced with silver nanoparticles or prodigiosin shows a strong antibacterial effect. It was reported that a BC/silver nanocomposite can kill 99.9% of mixed bacteria within 72 hours and prolong the shelf life of packed food up to 30 days [34]. Similarly, BC-chitosan film containing prodigiosin effectively inhibits *Staphylococcus aureus* and *Pseudomonas aeruginosa* [32]. Nanoemulsion of carboxymethyl cellulose with cardamom oil was used on the tomato surface, and the growth of *E. coli* and *Listeria monocytogenes* was greatly reduced [35]. Moreover, a BC composite with a Pickering emulsion of curcumin provides UV protection and freshness indication at the same time [4]. These multifunctional materials are biodegradable and meet environmental protection requirements [36,37]. **Table 1** summarizes some typical applications of bacterial cellulose and its composites in the food packaging area.

Table 1. Applications of bacterial cellulose and composites in food packaging.

Material	Key Function	Benefit / Outcome	Ref
BC-based Coatings/Films	Barrier against gases/moisture	Extends shelf life; preserves quality.	[2,3]
	Carrier for antimicrobial/antioxidant agents	Inhibits microbes, delays spoilage.	[28,4]
	Platform for smart packaging	Monitors food freshness.	[4]
BC & Biopolymer Composites	Alginate with CMC	Improves strength, water resistance, & antimicrobial properties.	[31]
	Alginate with bioactives	Enhances barrier & antioxidant properties.	[32]
	Chitosan-Alginate Hydrogels	Controls moisture release.	[32]

As a direct food additive, BC has been widely studied for its functional and nutritional properties. BC is a high-quality dietary fiber that can adsorb cholesterol (11.910 mg/g) and sodium cholate (16.149 mg/g) in the digestive tract, which helps reduce blood lipid levels [5]. In an animal model of hyperlipidemia, BC supplementation significantly improved lipid metabolism [5]. Furthermore, BC improves the texture of ice cream and reduces calories by 21% while preventing large ice crystal formation [6]. BC also acts as a protective carrier for probiotics. For example, *Saccharomyces boulardii* encapsulated in a BC pellicle shows a higher survival rate in simulated gastric fluid [7]. When combined with nisin, the antimicrobial activity of BC was further enhanced [38]. In traditional Asian foods such as nata de coco, BC has been consumed for many years without safety issues [39,40]. Based on the above-mentioned studies, it is obvious that BC has great potential as a healthy food additive in the future [41].

Cosmetics and skincare

Bacterial cellulose (BC) has attracted increasing attention in the cosmetic industry due to its unique three-dimensional network structure and good biocompatibility [42,43]. BC contains no hemicellulose, lignin, or pectin, which are usually present in plant cellulose, so it can easily combine with various active ingredients, such as antioxidants, vitamins, and plant extracts [8]. BC possesses a very high water-holding capacity (up to several hundred times its dry weight) and a nanofibrillar morphology. These properties make BC very suitable as a carrier for cosmetic compounds. In recent years, BC has been widely used in facial masks. The wet BC pellicle fits perfectly to the skin surface and can slowly release active substances into the skin layer [9,44]. Moreover, BC gives good mechanical strength and stability to cream, gel, and emulsion products [43,45].

Many commercial BC facial masks are already available in the market, especially in Asia countries [8]. Furthermore, BC is completely biodegradable and can be produced from a renewable source, which meets the demand for green and sustainable cosmetics [22]. Besides, functionalization of BC with natural additives has been extensively studied. Propolis is one of the most popular choices. Propolis is a natural resin collected by honeybees and contains large amounts of phenolic compounds, flavonoids, and terpenoids [10]. These components exhibit strong antioxidant activity and can effectively scavenge free radicals that contribute to skin aging [46]. Previous research [10,11,46,47] has clearly shown that propolis exhibits excellent anti-inflammatory and antimicrobial effects, which are very helpful for acne treatment and for skin protection against UV damage.

When propolis was incorporated into the BC matrix, the resulting composite exhibited significantly better antioxidant and anti-aging performance than pure BC [10,11]. In some studies, propolis-loaded BC mask significantly increases skin hydration and elasticity after several weeks of use [48]. In addition, nanoemulsion and encapsulation techniques were used to improve the solubility and stability of propolis in a cosmetic formulation [11]. BC also acts as an ideal carrier for other natural substances, such as aloe vera, green tea extract, and essential oils [49,50]. Based on the above-mentioned studies, it is obvious that BC plays an important role in the development of natural, high-performance cosmetic products. With continuous improvements in production technology and functionalization methods, BC-based skincare materials will have great potential in the future market [1,8,51].

Water Purification and Environmental Remediation

Bacterial cellulose (BC) has been considered a very promising material for wastewater treatment due to its unique structure and surface chemistry [12,52,53]. The BC membrane possesses a high surface area, abundant hydroxyl groups, and a porous three-dimensional network. These features enable effective adsorption of heavy metal ions via electrostatic interactions and an ion-exchange mechanism [12,52]. Moreover, the adsorption capacity can be further improved by chemical modification. Many studies have clearly shown that grafting amine, carboxyl, or carbonyl groups onto the BC surface provides more active binding sites for metal ions [13,54]. For example, BC modified with polydopamine and carboxylated cellulose nanocrystal exhibits much higher removal efficiency for Pb^{2+} and organic dyes [14]. In addition, when graphene oxide was incorporated into the BC matrix, the composite showed strong adsorption ability toward Cu^{2+}, Cd^{2+}, and Pb^{2+} because of the negative charge on the graphene oxide surface [55]. Furthermore, magnetic Fe_3O_4 nanoparticles were added to make the adsorbent easy to separate by magnet after use [56]. The BC membrane also keeps good reusability after several cycles [12,57]. Besides heavy metal, BC-based materials were used for the removal of organic pollutants and bacteria.

The high porosity and mechanical strength make BC suitable for filtration applications [14,58]. An electrospun BC nanofiber membrane exhibits excellent antifouling properties and long-term stability [59,60]. These membranes can achieve high water flux and rejection rates in microfiltration, ultrafiltration, and nanofiltration processes [61,62]. Moreover, surface functionalization allows targeted removal of viruses, microplastics, and natural organic matter [63]. **Table 2** summarizes the main factors that contribute to the high removal efficiency of BC membranes for heavy metal ions.

Table 2. Removal efficiency of BC membranes for heavy metal ions.

Factor	Mechanism / Method	Key Outcome	Ref
Intrinsic property	High surface area, porosity, –OH groups	Effective cation exchange	[12,54]
Chemical modification	Grafting amine, carboxyl groups	Increase binding sites	[13,56]
Composite formation	GO, polydopamine, Fe_3O_4 nanoparticles	Higher capacity, magnetic separation	[14,57,58]
Structural design	3D network, porous structure	Better contact with pollutant	[13]
Reusability	Stable after multiple cycles	Practical application	[12,59]

Based on the above-mentioned studies (**Table 2**), it is clear that BC and its composites have great potential for water purification. With the ongoing development of modification techniques and large-scale production methods, BC-based adsorbents and filters will play an increasingly important role in environmental remediation in the future [14,58,60].

Industrial Reinforcement (Paper and Textile)

Bacterial cellulose (BC) has been widely used as a reinforcement material in the paper and textile industries because of its nanofibrillar structure and excellent mechanical properties. BC is produced by bacteria such as *Gluconacetobacter sucrofermentans* and possesses high crystallinity, a high degree of polymerization, and good compatibility with plant cellulose fibers [15]. When BC was applied to the paper surface, a thin, compact layer was formed that retained mechanical strength even after an accelerated aging test [15]. Moreover, BC coating reduces air permeance and imparts hydrophobicity to paper [15,64]. Previous research [65-69] has clearly shown that BC is well-suited for the conservation of ancient books and documents.

In paper reinforcement, BC shows many advantages. For example, amino-silanized BC improves interfacial bonding with aged paper, increases tensile strength, and stabilizes pH, which play an important role in long-term preservation [65]. BC was also mixed with eucalyptus pulp or sugarcane bagasse pulp; the obtained composite paper exhibits much higher tensile index and tear resistance than the control sample [66,67]. Furthermore, BC can form strong hydrogen bonds with cellulose fibers in paper, so no additional adhesive is needed during consolidation [68]. When nanometer-sized magnesium oxide was added to the BC suspension, the anti-aging performance of the paper relic was further enhanced because an alkaline environment was maintained [69]. Based on the above-mentioned studies, it is clear that BC has great potential for paper conservation and high-performance paper production [15,65-69]. Besides, BC has been explored as a reinforcement agent in the textile field. BC nanofibers exhibit mechanical properties similar to or even better than those of Lyocell fiber, and they are completely biodegradable and non-toxic [70,71]. In addition, BC can be produced from organic waste, such as fruit juice or agricultural by-products, which align well with the circular economy concept [17].

Life cycle assessment studies have shown that the environmental impact of BC is much lower than that of traditional cotton or synthetic fibers [72,73]. However, large-scale production of BC still faces some challenges, especially the low yield and high cost of culture medium [16,19]. Many researchers are working on strain improvement and new bioreactor design to solve these problems. Overall, BC has numerous excellent properties that make it a very promising reinforcement material for both the paper and textile industries. With continuous optimization of the production process, BC will play a more important role in sustainable manufacturing in the future [16,17,71]. The main applications of BC in paper and textile reinforcement are summarized in **Table 3**.

Table 3. Main applications of bacterial cellulose in paper and textile reinforcement.

Application	Key modification/ composite	Main benefit	Reference
Paper surface coating	Pure BC or amino-silanized BC	Increase strength, reduc aging	[15,66]
Paper pulp reinforcement	BC with eucalyptus or bagasse pulp	Higher tensile and tear index	[67,68]
Paper relic conservation	BC with MgO nanoparticles	Deacidification, UV resistance	[69,70]
Textile fiber replacement	Pure BC nanofiber	Biodegradable, high-strength	[73,74]
Waste-based production	BC from fruit waste	Circular economy, low impact	[17,71,72

Challenges and Future Prospects of Bacterial Cellulose

Although bacterial cellulose (BC) possesses numerous excellent properties and wide application potential, its large-scale commercialization still faces several important challenges. The main obstacle is the high production cost, because traditional culture media are expensive and the yield of BC is relatively low in static cultivation [18,74]. Many studies have clearly shown that using agro-industrial waste, such as fruit peel, wastewater from wine distilleries, or biodiesel production, as a carbon source can significantly reduce costs and also align with the circular economy concept [16,75]. Moreover, these waste-based media provide BC with mechanical performance similar to or even better than that of the standard HS medium [75]. In addition, the production process needs to be optimized for industrial-level production.

Evolution of Bacterial Nanocellulose Applications Across Food, Cosmetic, and Textile Industries (2016-2024)

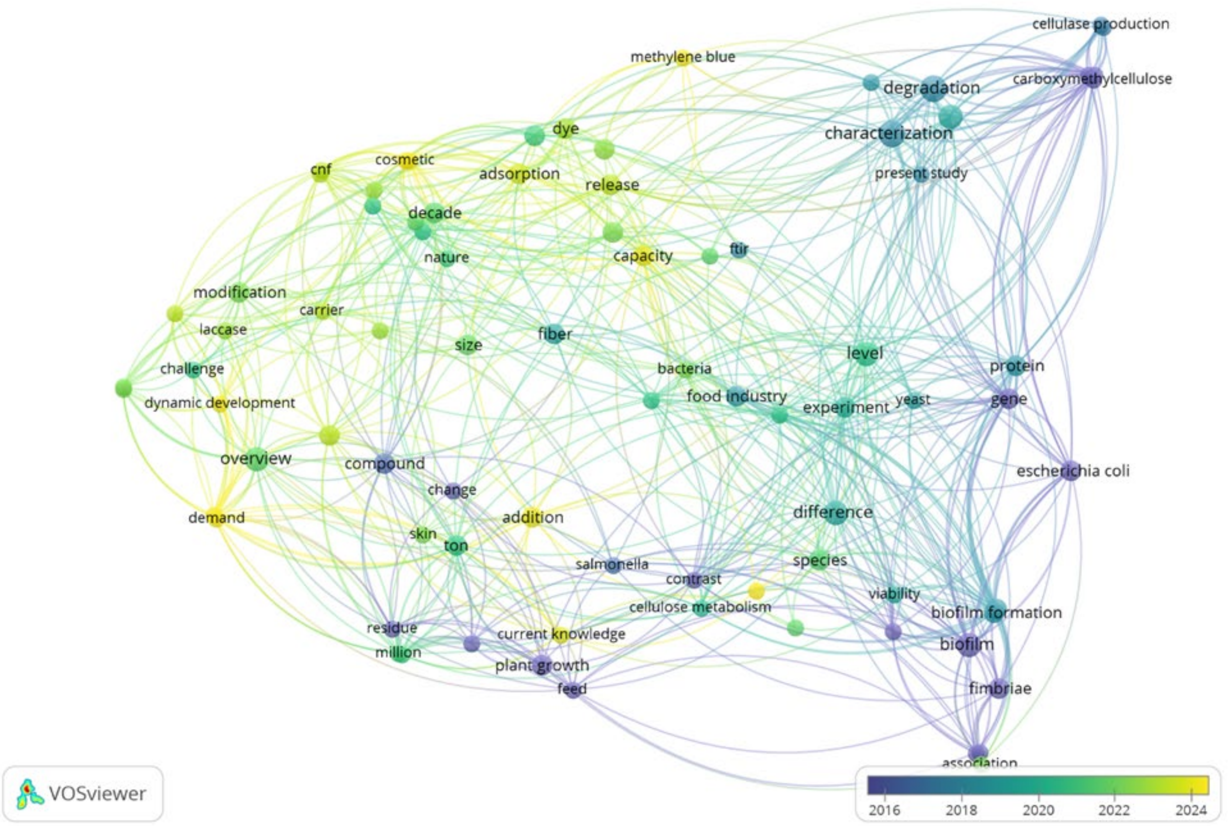

Fig. 2. Overlay visualization of bibliometric keywords from 2016-2024. Yellow and green colour indicate recent research topics, while blue nodes represent earlier studies

Static culture produces BC in the form of pellicle, which is difficult for continuous operation, while agitated culture often decreases crystallinity and water-holding capacity [74]. Recently, many new bioreactor designs, including air-lift reactors, rotary disc reactors, and membrane reactors, have been developed to improve productivity while maintaining BC quality [19]. Strain engineering through genetic modification also plays an important role in increasing BC yield and modifying its properties directly [1,76]. Previous studies [19,76] have reported that mutated *Gluconacetobacter* strains can produce 2-3 times more BC than wild type. Besides technical problems, regulatory approval is another major challenge, especially for biomedical applications. BC wound dressings and implant materials must pass strict clinical trials and receive approval from the FDA or a similar organization before entering the market [20,24]. Although many animal studies have shown good biocompatibility and no toxicity, long-term clinical data remain limited [20]. Furthermore, standardization of BC quality, including purity, molecular weight, and nanofiber diameter, is necessary for reproducible medical products [74].

In spite of these difficulties, the future of BC looks very promising. With the development of low-cost, medium- to high-efficiency bioreactors and functionalized modifications, production costs are expected to decrease dramatically in the next few years [1,19]. In the biomedical field, BC-based nanocomposites for drug delivery, especially for cancer photodynamic therapy, have achieved high tumor inhibition rates in animal models [24,25]. BC scaffolds combined with stem cells or growth factors also show great potential for tissue engineering of bone, cartilage, and nerve [76]. Moreover, the sustainability of BC makes it an ideal substitute for petroleum-based plastics in food packaging, textiles, and environmental remediation [2,16]. Based on the above-mentioned progress, it is obvious that BC will become one of the most important biomaterials in the future. Continuous collaboration among microbiologists, materials scientists, and industry is needed to overcome remaining barriers and realize the full commercialization of BC products [1,20,74].

In recent years, research on bacterial nanocellulose (BNC) has increased dramatically because of its unique properties and wide application potential. **Fig.** 2 shows the keyword overlay map generated by VOSviewer software for publications between 2016 and 2024. It can be observed that in the early period (blue-green nodes), most studies focus on basic characterization, biosynthesis, microbial strain and material modification [77-81]. Terms like "characterization", "degradation", "fiber", "crystallinity" and "mechanical property" appear with high frequency. These fundamental researches have clearly shown that BNC possesses high purity, excellent water-holding capacity, and a nanofibrillar structure that differs from plant cellulose [77,78].

Moreover, the cluster related to the fermentation process is also very strong. Keywords such as "bacteria", "*Gluconacetobacter*", "yeast", "viability", and "fermentation" indicate that many studies have focused on improving production efficiency and reducing costs [79,80]. In addition, modification methods, including "adsorption", "surface modification", "composite", and "controlled release", play an important role in expanding BNC functionality [81-83]. With time, research direction gradually shifts to application fields. Yellow nodes clearly show the emerging topics after 2020. In the food industry, BNC has been widely investigated as an edible film, active packaging, and a food additive because of its good barrier properties, biodegradability, and safety [84-87]. Keywords such as "packaging", "antimicrobial", "shelf life", and "edible coating" appear frequently. Previous studies [84,85] have reported that BNC-based film can effectively extend the shelf life of fresh fruit and meat products. Furthermore, cosmetic application of BNC has become another hot topic in recent years. Terms such as "skin", "mask", "carrier", "cosmetic", and "transdermal delivery" form an obvious cluster [88,89,90]. The BNC facial mask is already commercialized in many countries because it can hold a large amount of the active compound and fits well with the skin surface. BNC also acts as a carrier for antioxidant and anti-aging substances [89]. Besides, the textile and environmental fields also attract much attention. Keywords "dye", "methylene blue", "adsorption", "wastewater", and "textile" indicate that BNC was used for the removal of organic pollutants and as reinforcement material in fabric [91-93].

BNC composite shows high adsorption capacity for heavy metal ion and dye molecules. In the textile industry, BNC nanofibers provide good mechanical strength and antibacterial properties to the final product [92]. Based on the above-mentioned bibliometric analysis, it is clear that research on BNC has evolved from fundamental property studies to practical applications in the food, cosmetic, and textile industries. This trend reflects the growing demand for sustainable and multifunctional biomaterials. With the continued development of low-cost production and functionalization technologies, BNC will play an increasingly important role in the future industry [77,94].

CONCLUSION

Bacterial cellulose (BC) has been recognized as one of the most promising biomaterials in recent years because of its unique nanofibrillar structure and excellent properties. BC possesses high mechanical strength, good biocompatibility, high water-holding capacity, and complete biodegradability, which make it superior to many traditional materials. In this review, we discussed various applications of BC in different fields. In the food industry, BC has been widely used as an edible coating, an active packaging material, and a food additive. BC film can effectively block oxygen and moisture, extend shelf life, and carry antimicrobial agents. As a dietary fiber, BC helps reduce cholesterol levels and improve gut health. Moreover, cosmetic products containing BC, especially facial masks, show very good performance in skin hydration and active ingredient delivery. In environmental remediation, BC and its composites exhibit high adsorption capacity for heavy metal ions and organic dye from wastewater. Furthermore, BC acts as a reinforcing agent in the paper and textile industry; the obtained materials possess much better mechanical properties and retain biodegradable character at the same time. Although BC has numerous excellent properties and great potential across many fields, there are still challenges to its large-scale commercialization. The production cost is relatively high due to the high cost of the medium and the low yield in traditional static culture. Besides, regulatory approval, especially for biomedical products, requires long-term clinical trials and strict evaluation. Previous research has clearly shown that using agro-industrial waste as a substrate and developing a new bioreactor can significantly decrease costs. Strain modification and composite preparation also play an important role in improving BC performance. Based on the above-mentioned studies, it is clear that BC will become a very important sustainable material in the future. With continuous efforts from researchers and industry, the remaining problems will be solved step by step. BC-based products are expected to replace petroleum-based plastics in food packaging, cosmetic, and textile applications, and to also contribute to environmental protection and human health. In summary, bacterial cellulose represents a successful example of bio-based innovation that combines high performance with ecological responsibility.

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CONFLICTS OF INTEREST

The author declares that there are no conflicts of interest related to this publication.

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