The Journal of Green Energy and Environmental Engineering

Review Paper

Research progress on microbial preparation of bacterial cellulose based intelligent color changing materials and their properties

Sina Deger [1,*], Sanna Meena [1], Sonia Rioz [2]

[1] Department of Electrical and Electronic Engineering, Federal University of Santa Catarina, Campus Trindade, 88040-900, Florianópolis, Brazil
[2] Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, Kuala Lumpur 54100, Selangor, Malaysia
*Corresponding author: sinadeger@ufsc.br

Abstract. Bio-based aerogel is a lightweight, porous and high specific surface area nanomaterial prepared from natural biomacromolecules, which has shown great potential for application in the food field in recent years.Bio-based aerogels exhibit excellent adsorption, sustained release, and biocompatibility. This review systematically maps how bio-aerogels are made—covering feed-stock choices, sol–gel chemistry and drying routes—then weighs their physical traits and end-use functions. The applications of bio-based aerogels in food preservation mats, food freshness indication labels, nutrient delivery carriers, and fat in artificial meat substitutes were summarized. In addition, the challenges of bio-based aerogels in terms of large-scale production, food safety and consumer acceptance were discussed, and the future development of bio-based aerogels in functional food and industrial production were prospected.

Keywords: *Bio-based aerogel; sol-gel method; water absorption and water stability; freshness pads; artificial meat fat substitutes*

Received on 02 March 2024, Accepted on 28 May 2024, Published on 15 July 2024

1 Introduction

Amid rapid urbanization, petroleum plastics such as PE and PP refuse to break down, fueling “white pollution” and micro-plastic swarms that invade oceans and food chains alike. Their production and incineration processes release greenhouse gases, exacerbating climate change, while their reliance on non-renewable petroleum resources results in high energy consumption and the potential release of toxic substances, further endangering the environment and health [1-3]. Against the backdrop of sustainable development, bio-based materials are increasingly becoming an ideal alternative to petroleum-based materials due to their renewability, degradability, and environmental friendliness, attracting growing attention.

Cellulose, as a highly promising bio-based material, is one of the most widely distributed and abundant biodegradable polymers on Earth, found extensively in plants and microorganisms. Bio-based cellulose materials (such as bacterial cellulose, plant cellulose) are composed of glucose units. Their renewability and biodegradability make them one of the most promising green materials today and an ideal substitute for petroleum-based materials [4, 5]. Simultaneously, bio-based cellulose materials possess high mechanical strength, excellent biocompatibility, and multifunctionality, finding widespread applications in healthcare, food packaging, and smart materials [6]. Furthermore, their low-cost production and industrial chain development not only contribute to achieving green manufacturing and sustainable development goals but also create numerous job opportunities and promote economic growth [7].

Nanocellulose has made significant progress in recent years. It refers to cellulose nanomaterials with a diameter less than 100 nanometers, exhibiting high mechanical strength (theoretical tensile strength 1.6-6.6 GPa, modulus 56-220 GPa), dimensional stability, and impact resistance. Its density is only one-fifth that of steel, and it originates from renewable biomass resources, is completely biodegradable, has a small environmental impact, and meets the requirements of sustainable development [8, 9]. In practical applications, nanocellulose has been widely used in various fields, such as paper enhancement technology, biodegradable bottle caps, fully degradable tableware, biodegradable packaging materials, medical dressings and drug carriers, and bone tissue repair scaffolds. With technological advancements, nanocellulose also shows great potential in fields like 3D printing, smart textiles, and electronic devices [10, 11]. As a representative of bio-based materials, nanocellulose is gradually replacing traditional petroleum-based materials, promoting sustainable development, and offering new solutions to global resource and environmental problems.

2 Research Progress on Bacterial Cellulose

Cellulose—Earth's most plentiful biopolymer—can be harvested from plants, photosynthesized in the lab, or spun by algae, fungi and bacteria, guaranteeing a never-ending feed-stock.Whereas plants weave cellulose microfibrils inside Golgi stacks and lock them into walls with lignin and hemicellulose, bacteria extrude pure ribbons straight into the broth. The resulting bacterial cellulose offers an ultrafine, 3-D nano-web: low-density yet non-abrasive, effortlessly functionalized, mechanically strong, super-hydrophilic, highly water-retentive and fully bio-compatible and -degradable (Fig. 1.1) [8,12]. With fibrils only 20–100 nm thick, BC reaches crystallinities of ~95 %, arrives lignin- and hemicellulose-free, and shows chain lengths (DP 2 000–8 000) that dwarf those of plant cellulose.Since Brown first reported the synthesis of bacterial cellulose in 1886, its renewable, non-toxic, cost-effective, eco-friendly, and biodegradable characteristics have gradually drawn attention to its application potential in materials science, biomedicine, textile industry, and other fields [13, 14].

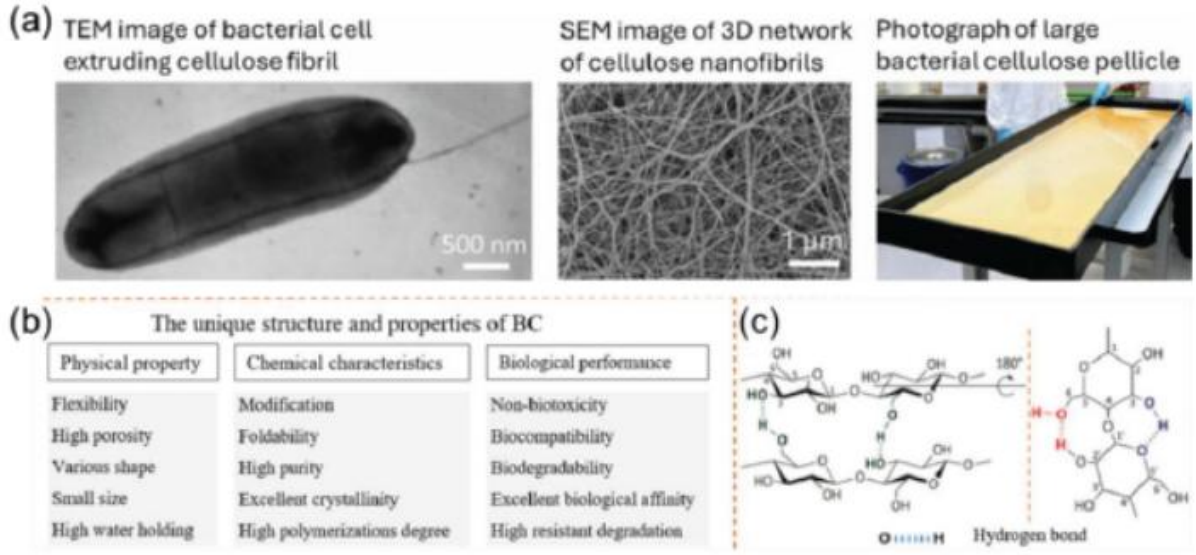

Figure 1 (a) TEM images of BC fibril extrusion, SEM images of nanofibril network and gel-like large-scale BC photos [15]; (b) Advantages of BC; (c) Chemical structure and hydrogen bonds of BC [12].

2.1 Microbial Fermentation Synthesis of Bacterial Cellulose

BC is secreted by a host of Gram-negative genera—Gluconacetobacter, Acetobacter, Agrobacterium, Achromobacter, Aerobacter, Sarcina, Azotobacter, Rhizobium, Pseudomonas and Alcaligenes—yet

Gluconacetobacter (notably G. xylinus) remains the champion industrial producer [16]. During biosynthesis (Fig. 1.2a), glucan chains exit the cell through membrane pores and line up parallel to the bacterium's long axis, nucleating a ribbon that grows outward. These chains bundle into 1.5 nm sub-fibrils that emerge from the linear pores, crystallize side-by-side and ripen as 30–80 nm nanoribbons—each ribbon an assembly of ~64 glucan oligomers [17,18] (Fig. 1.2c). Whether the broth sits still or is shaken, the same bug spins fibres with subtly different architectures—another knob that turns bacterial cellulose into a darling of materials science.

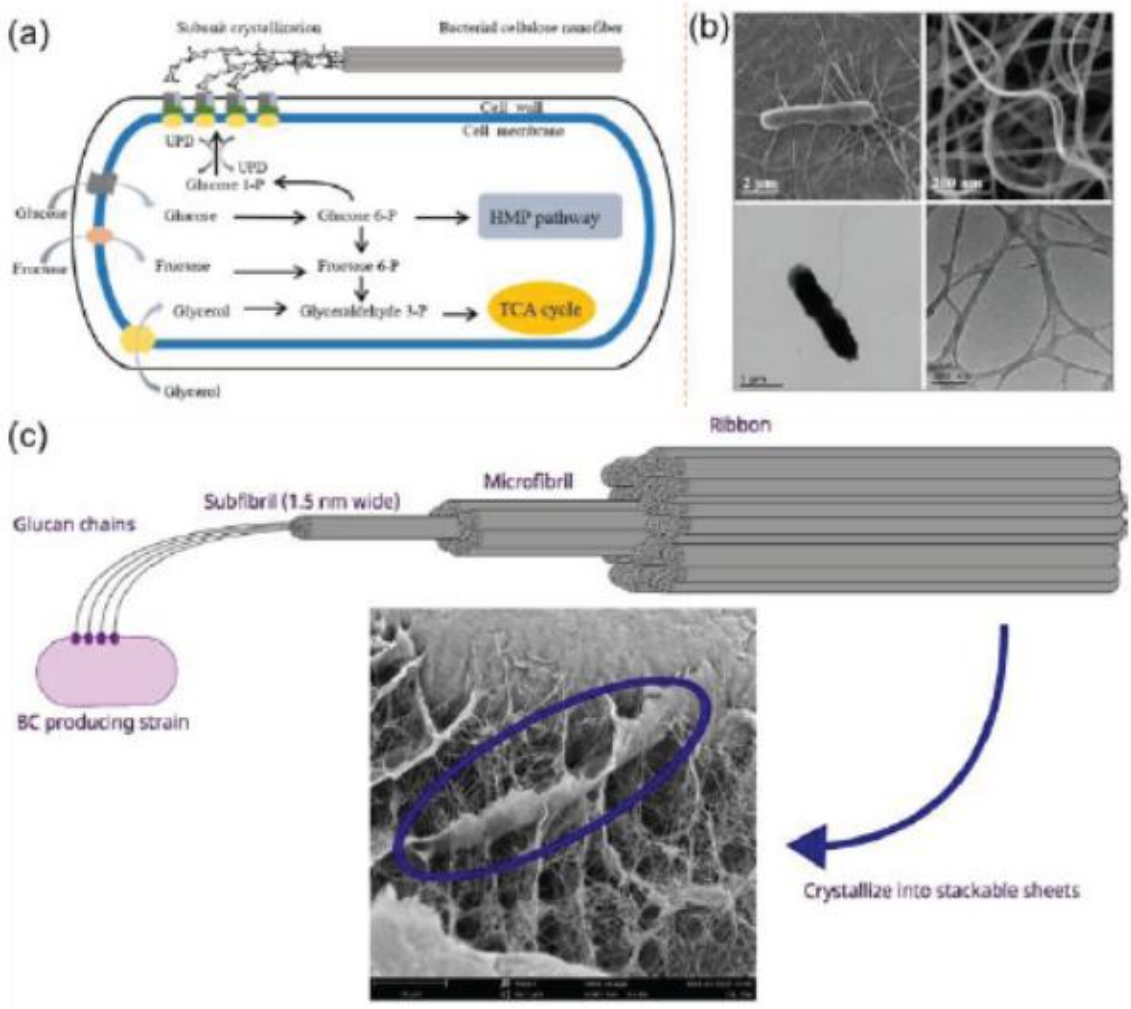

Figure 2 (a) Bacterial biosynthesis of cellulose; (b) SEM and TEM images of BC and A.x. bacteria [12]; (c) Conceptual schematic diagram of the bacterial biosynthetic cellulose structure [21].

Because the polymer is extruded outside the cell wall, every broth variable—pH, temperature, shake rate, carbon/nitrogen ratio—writes directly on yield, ribbon width and crystallinity [19]. A simple tweak—raising the C/N ratio or sparging extra oxygen—can double the harvest while tightening crystal packing and boosting the final modulus. More air and gentle agitation keep oxygen evenly distributed, yet too much shear snaps the delicate ribbons, so aeration must be balanced against mixer speed. In recent years, researchers have also used genetic engineering techniques to modify bacterial strains to further enhance the synthesis efficiency and functional properties of bacterial cellulose. The optimal temperature is typically 30°C, and the pH should be around 6; deviations from these conditions will reduce yield [20].

Currently, methods used for bacterial cellulose (BC) preparation include static and dynamic cultures. Researchers have further investigated agitated/shaken cultures and bioreactor dynamic cultures. The bacterial cellulose obtained by these methods exhibits significant differences in macroscopic morphology, microstructure, and properties [22]. Static culture methods form a gelatinous cellulose film at the nutrient solution surface,

while agitated/shaken cultures produce spirals, spheres, granules, or irregular masses (Fig. 1.4c). Traditional bioreactor designs may limit microbial growth and productivity due to insufficient oxygen transfer rates [23]. Agitated culture leads to reduced cellulose crystallinity and the formation of irregular granular structures; high agitation speeds may damage the cellulose structure, especially in stirred-tank bioreactors. Static culture produces a uniform three-dimensional structure. The choice of method depends on the final application of the bacterial cellulose and the requirements for its physical, morphological, and mechanical properties [24].

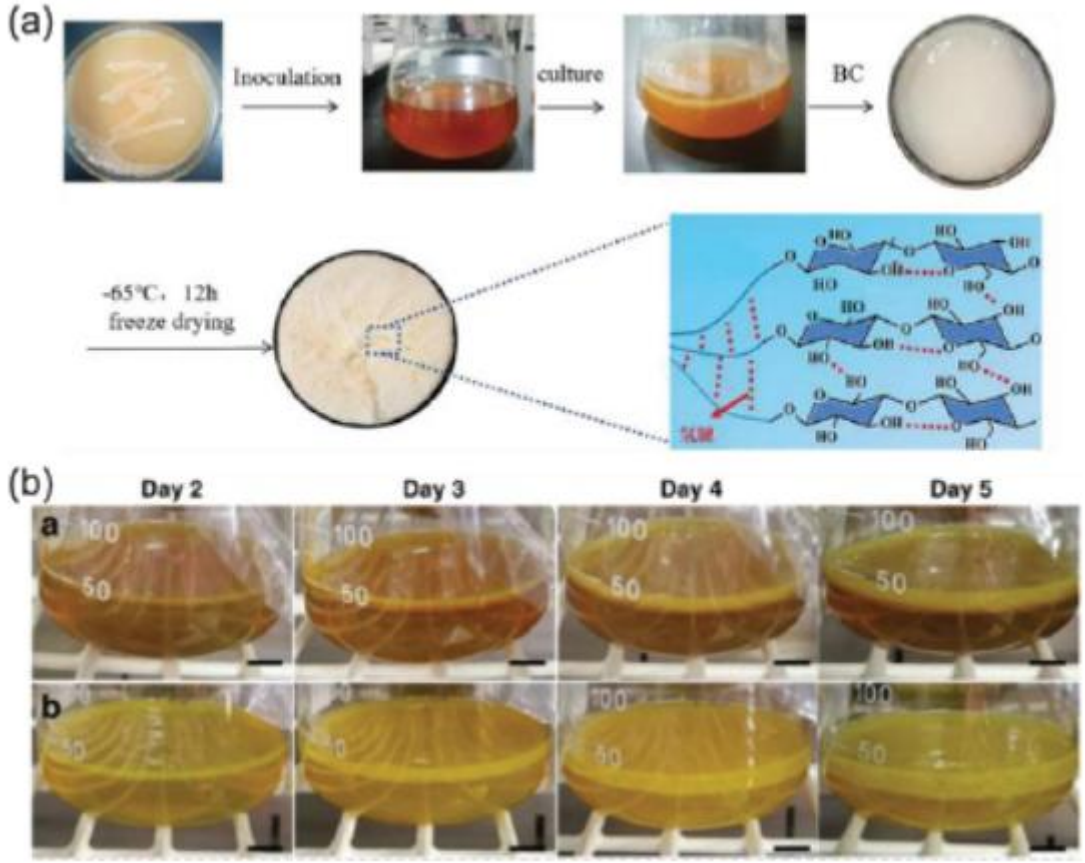

Figure 3 (a) Growth mechanism of bacterial cellulose membrane static culture; (b) BC thickness images during the growth process [25].

(1) Static Culture: This is a method for producing bacterial cellulose (BC) where bacteria grow in a stationary liquid medium without agitation. This method can form a film (gel) at the air-liquid interface (Fig. 1.3a) and is suitable for large-scale BC production, although oxygen transfer and yield are limited. Its advantage is the formation of a uniform cellulose film with high crystallinity, suitable for specific applications like biomaterials. To overcome the limitations of static culture, unconventional static culture systems (such as surface aeration or static continuous culture) have been developed, successfully increasing BC yield by 25%. As a traditional production method for bacterial cellulose (BC), fresh nutrient solution is injected into a container and cultured at 28-30°C and a fixed pH value (4 < pH < 7) for 1-14 days, which has been widely used [26]. Fresh BC emerges as a pale-yellow hydrogel sheet; after a hot-water/NaOH rinse it bleaches snow-white (Fig. 1.3a) while retaining a dense, high-modulus, tear-resistant network that locks in water yet springs back to shape. The pellicle grows downward from the air–liquid interface, thickening with every hour of static incubation (Fig. 1.3b); yield scales almost linearly with surface area and stays shear-free—hence static trays remain the bench-top default.

(2) Dynamic Culture: The dynamic culture of bacterial cellulose (BC) achieves large-scale production through agitation methods like stirring or shaking, offering higher production efficiency and controllability. Compared with static trays, stirred or air-lift systems give tighter command of oxygen, nutrient flux and shear, lifting output while tailoring ribbon architecture—an edge that makes them the front-runner for commercial-scale fermenters

[27]. Shake speed, run time and any additive (CMC, alginate, surfactant) decide whether the same microbe delivers BC as nanofibre slurry, micro-pellets, glossy spheres or chunky granules (Fig. 1.4c). With the right additives—CMC, alginate, surfactants—the pellicle fragments into fibres, beads or pellets (Fig. 1.4d,e); no longer tied to the air-liquid interface, cells keep spinning cellulose wherever oxygen and sugar remain plentiful. Pushing productivity in stirred tanks means cranking up both aeration and volumetric mixing; the final count, size and shape of BC pieces hinge on impeller design, oxygen flux, rpm, run length, continuous shear and whatever additives lace the broth. Inoculum density also steers bead diameter and harvest (Fig. 1.4a), yet shaken systems carry a hidden cost: chronic shear can select cellulose-negative mutants that outrun the producers and erode yield [29].

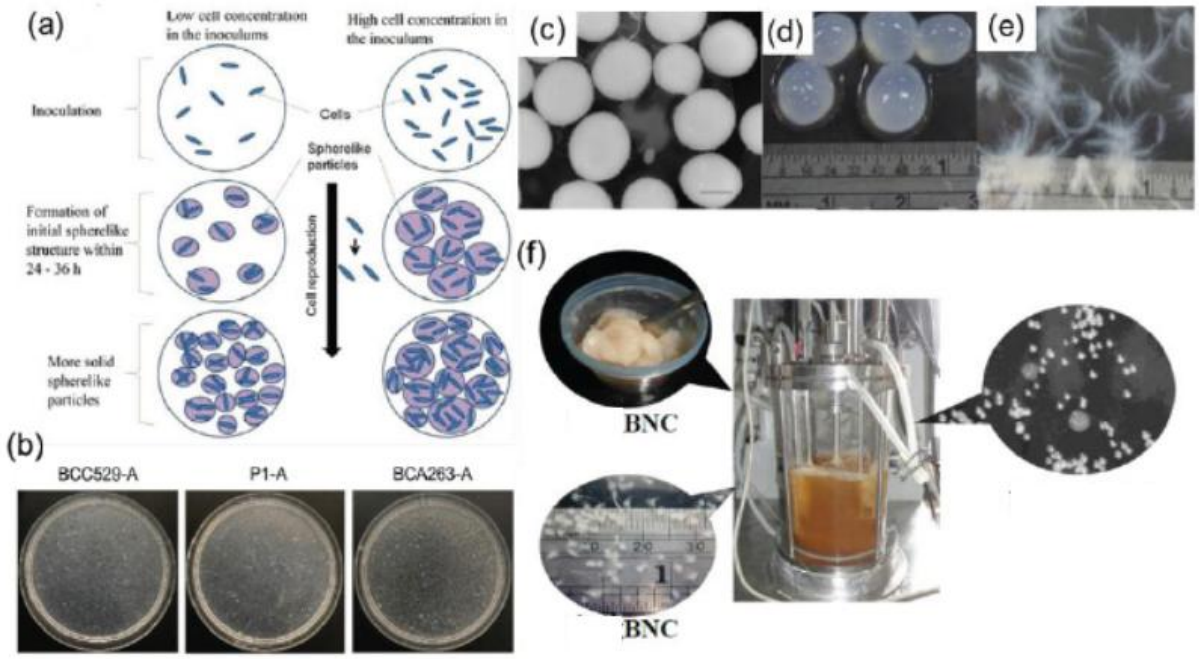

Figure 4 (a) Schematic diagram of growth at different strain concentrations; (b) Photograph of dynamic culture; (c) Preparation of spherical BC under agitation; (d)(e) Preparation of heteromorphic BC by stirring in different additives [30]; (f) BC strain mutation induced by agitation [29].

To shave cents off every gram, labs now feed the bugs on farm scraps and industrial side-streams—molasses, whey, corn-steep liquor—turning waste streams into ribbon factories. For example, using bagasse, corn stover, and waste molasses as raw materials can not only lower production costs but also achieve resource recycling, facilitating large-scale application production [31]. Furthermore, researchers have developed continuous fermentation and immobilized cell technology to improve production efficiency and reduce energy consumption [32]. These low-cost and sustainable production technologies provide new possibilities for the industrial application of bacterial cellulose, while also aligning with green manufacturing and sustainable development goals.

2.2 Structural Characteristics of Bacterial Cellulose

2.2.1 Chemical Structure and Morphology

BC assembly is choreographed by the cellulose-synthase complex: first glucose polymerisation, then chain extrusion, crystallisation and ribbon bundling into the cellulose-I lattice built from β-1,4-linked D-glucopyranose. With DP 2 000–8 000 it dwarfs plant cellulose; at mesoscale it weaves a nanofibrillar sponge able to hoard water yet stay air-permeable. Even after drying it reswells to >1 000 % water regain. Electron zoom reveals 3–4 nm elementary fibrils that merge into 40–60 nm ribbons, yielding a silky, mesoporous lattice whose surface

nanopores and huge specific area drive its famed water-holding power. BC has high crystallinity (usually above 95%), primarily cellulose I crystal structure. The crystallinity index is influenced by various factors, ranging from 60% to 81%. Inside every crystal domain, dense hydrogen bonds and van-der-Waals contacts lock the chains, gifting the mesh surprising tensile strength and spring. Simultaneously, hydrogen bonds bind water molecules within the BC structure [33, 34]. BC consists of 98% water, of which about 10% is free water, and the remaining water molecules are bound to hydroxyl groups of cellulose molecules via hydrogen bonds.

2.2.2 Mechanical Properties

The high strength and modulus of bacterial cellulose stem from its unique nanofibrous network structure. Bacterial cellulose is composed of slender fibers with diameters of only 3-10 nm. These fibers form a dense network structure in three-dimensional space, endowing the material extremely high tensile strength and elastic modulus [35]. That supramolecular glue lets a single BC sheet hit 200–300 MPa tensile strength and a 15–18 GPa modulus—numbers that rival lightweight plastics yet come from nothing more than intertwined, highly crystalline nanofibrils. By coaxing nanofibrils into perfect axial alignment, researchers have spun BC micro-filaments that register 826 MPa tensile strength and 65.7 GPa stiffness—delivering a specific strength (598 $MPa \cdot g^{-1} \cdot cm^3$) that leaves modern lightweight steel (227 $MPa \cdot g^{-1} \cdot cm^3$) behind [36,37]. Bacterial cellulose possesses good flexibility and deformability. Despite its high mechanical strength, bacterial cellulose can absorb energy through elastic deformation of the fiber network when subjected to force, exhibiting a high elongation at break (typically 2-10%). This characteristic gives bacterial cellulose significant advantages in applications such as flexible electronic devices, wearable devices, and wound dressings.

2.2.3 Biocompatibility

Bacterial cellulose (BC) is an important material in the biomedical field due to its very low cytotoxicity, high cytocompatibility, and excellent tissue compatibility. BC has no significant negative impact on the survival rate of various cell lines (such as fibroblasts, osteoblasts, and skin cells). Research by Saska and Backdahl, H. et al. has shown that bacterial cellulose scaffolds can achieve cell viability exceeding 95% in cell culture [38, 39]. High purity and low impurity content further reduce cytotoxicity. Czaja et al. showed that BC's nanofibrillar topography mirrors the extracellular matrix, giving cells a ready-made niche that speeds attachment, division and lineage commitment [38,39]. Implanted BC quietly fuses with host tissue—no capsule, no rejection—while its wet, air-permeable mesh keeps chronic wounds moist and pathogen-free, accelerating re-epithelialization [40]. Tailorable strength plus clean enzymatic breakdown lets surgeons fine-tune BC implants from skin-like softness to cartilage-grade stiffness, opening doors across the biomedical spectrum.

2.2.4 Biodegradability

Bacterial cellulose is a microbe-made, linear β-1,4-glucan that breaks down naturally—no micro-plastic legacy, just water and CO_2. Unlike man-made plastics, BC quietly dissolves into water and CO_2 under the action of ambient microbes or enzymes, earning it a clean-green label. Its biodegradation process is mainly achieved through the action of enzymes, such as cellulase, which specifically hydrolyzes its β-1,4-glycosidic bonds, breaking it down into low molecular weight sugars [41, 42]. Since the degradation products are non-toxic and can be recycled in nature, bacterial cellulose exhibits good biocompatibility and safety in biomedical applications [41, 42]. Excellent biodegradability makes it an ideal material for sustainable development, widely used in degradable packaging, disposable medical supplies, and environmentally friendly composite materials. In biomedicine, bacterial cellulose, as an absorbable wound dressing or tissue engineering scaffold, can degrade naturally after fulfilling its function, reducing the need for secondary surgery. Meanwhile, its degradation process does not cause environmental pollution, conforming to the principles of green chemistry and the circular economy [43].

3 Functionalization Methods for Bacterial Cellulose

Thanks to its nanofibrillar lattice, high crystallinity and steel-like stiffness-to-weight ratio, BC is now being drafted for implants, scaffolds, flexible circuits, next-gen textiles and beyond. However, the single surface functional

groups of native BC limit its functional applications. To expand the application range of BC, researchers have developed various functionalization methods, mainly including in-situ methods and ex-situ methods [44].

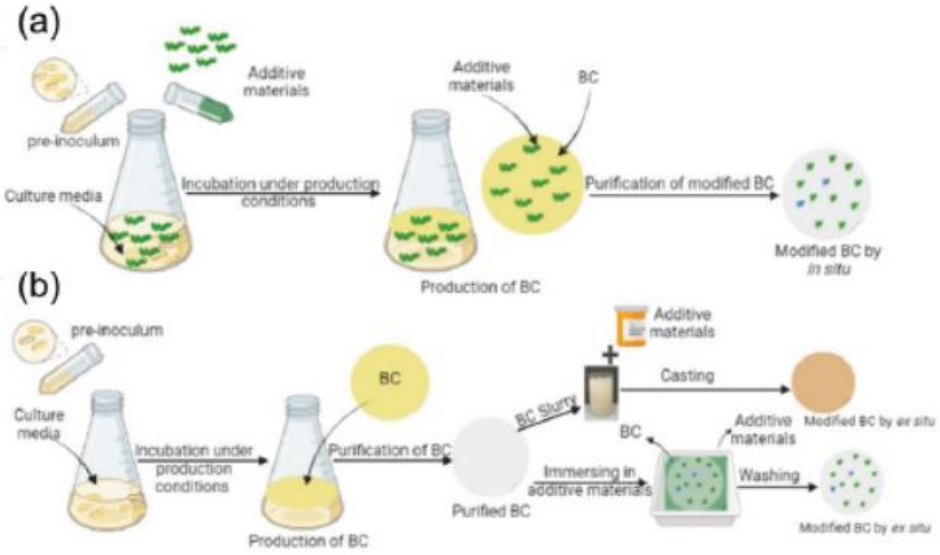

Figure 5 BC functionalization methods (a) in-situ method; (b) ex-situ method [43].

3.1 In-Situ Modification

In-situ tweaks happen while the bug is still spinning: feed it additives, tweak pH or lace the broth with nano-fillers and the growing ribbons entangle foreign guests, yielding BC composites straight from the fermenter [45]. In this process, microbial strains are mainly responsible for integrating additives into the BC fiber structure, thereby ensuring the functional modification of BC. Studies have shown that additives can interfere with the structural conformation of BC fibers or interact with the fibers, forming self-assembled biocomposites, while simultaneously altering the physicochemical, mechanical, and morphological properties of BC composites to a certain extent.

BC composites prepared by in-situ fermentation modification via microbial methods have advantages such as no cytotoxicity, simple preparation without post-processing, etc. Typical one-pot upgrades drop nanoparticles, secondary polymers or bio-actives into the culture; the nascent ribbons weave through the additives, locking them into a uniform 3-D lattice that keeps BC's native architecture yet adds new functions. Liyaskina's team simply spiked a static Komagataeibacter b-11267 culture with 2 % alginate at 28 °C; the growing ribbons laced through the polysaccharide, yielding a BC/alginate nanocomposite that kills microbes and needs no post-processing for wound use [46].

Abdelraof et al. synthesized BC/NBG nanocomposites by adding nano bioactive glass (NBG) [47], increasing BC yield and enhancing its application potential in the biomedical field. Other methods include biosynthetic modification through genetic or metabolic engineering to modify bacteria so that they directly introduce functional groups or modifier molecules during BC synthesis; gas-assisted synthesis using gases (e.g., CO2) to induce reactions between BC and inorganic salts during fermentation to form composites, etc. [48, 49]. By adjusting the type and concentration of additives, the structural properties of BC fibers, such as fibril size, surface area, and crystallinity, can be further optimized to meet the needs of different application scenarios.

3.2 Ex-Situ Modification

Ex-situ routes wait until fermentation ends: the purified mat is harvested, rinsed and then grafted, dipped, pressed or coated with secondary phases. Because the scaffold is already formed, every extra step—chemical grafting, enzyme trimming, plasma or hot-pressing—can be tuned to the nanometre, giving tighter command

over pore size, surface chemistry and mechanical response [44,50]. For example, introducing different functional groups or changing the molecular structure of cellulose through chemical methods can enhance the solubility, antimicrobial properties, or drug release properties of cellulose. Bio-enzymatic methods utilize specific enzymes to degrade, modify, or engineer cellulose. Physical treatments such as ultrasonication, plasma treatment, and high-pressure treatment can alter the morphology, crystallinity, and mechanical properties of cellulose [51, 52].

In-situ cocktails must stay biocompatible, so ex-situ tricks such as impregnation or dissolution–regeneration open a wider toolbox. Soaking the never-dried hydrogel in nanoparticle or monomer baths lets solutes ride the water channels and anchor homogeneously throughout the nanofibrillar web. Li flooded BC with acrylamide and triggered polymerisation in place, netting a BC/PAM super-adsorbent [53]; Sulaeva dipped it in alginate, converting the sheet into a longer-lasting, extra-moist wound dressing [54]. Alternatively, strong shear or cellulose solvents can first dissolve the nanofibre mat; additives are stirred into the clear dope and BC is then regenerated around them, locking guests into a newly coagulated lattice. Older “viscose” routes relied on hot CS_2 and heavy-metal baths that vent toxic fumes; newer green analogues switch cellulose solubility on-and-off with benign CO_2-triggered solvents, eliminating the legacy hazard while still letting BC dissolve and re-emerge around chosen dopants [55,56]. Later came Lyocell, where hot NMMO/water cocktails safely dissolve cellulose; today ionic liquids and deep-eutectic solvents extend the menu, letting BC be liquefied, doped and re-set around almost any functional guest, greatly widening its design space [57,58].

Ex-situ modification of bacterial cellulose (BC) can precisely modifying its structure and properties through chemical, physical, or biological means, enhancing solubility, antibacterial properties, drug release performance, etc., allowing for a wider selection of functional materials and broadening the application scope. However, this method has complex processes, higher costs, may involve toxic chemicals posing potential risks to human health, and improper treatment of generated waste liquids and solid waste may pollute environmental media such as soil and water bodies. Overall, the ex-situ method provides broad prospects for the functionalization of BC but requires further process optimization and cost control.

3.3 Applications of Bacterial Cellulose Materials

Riding the green-chemistry wave, biodegradable BC nano-fleece is now being scaled for edible films, tissue scaffolds, wound patches and even conductive fabrics that fold or stretch without tearing. The biological preparation of bacterial cellulose and its functionalized materials have gradually become a research hotspot. BC, as a biodegradable novel nanomaterial, shows broad application potential in textiles, medicine, food, cosmetics and other fields (Figure 1.6) [59].

Figure 6 Applications of BC in the medical industry, cosmetics industry, textile industry, and food industry [21].

3.3.1 Applications in the Textile Field

Thanks to leather-like strength, drape and guilt-free disposal, BC is moving from lab curiosity to runway-ready "vegan leather" and compostable cloth that can be sewn, embossed or dyed like hides and fabrics—without the hides. British fashion designer Suzan Lee first applied bacterial cellulose to the apparel field by developing a sustainable fashion project named BioCouture (Fig. 1.7a). She used kombucha (tea fungus) fermented in rectangular containers to produce bacterial cellulose textiles and employed traditional garment-making techniques (such as cutting and sewing) to create microbial cellulose jackets and gloves[60]. BC is regarded as an ideal alternative to traditional leather and textiles due to its high tensile strength, flexibility, and biodegradability. This innovation demonstrated the application potential of bacterial cellulose in the apparel field, marking its early exploration as an eco-friendly leather alternative. However, its practical application still faces challenges in key performance indicators such as wettability, abrasion resistance, elasticity, breathability, dyeability, and wearing comfort. Early research used BC as a leather alternative, but simply dried BC fabrics had issues like fragile texture, poor breathability, and insufficient hydrophobicity. In recent years, by combining with mushroom protein, adding glycerol, and using materials such as soybean oil (AESO), polyethylene glycol (PEG), polydimethylsiloxane (PDMS), and fluoropolymers[61,62], researchers have significantly improved the waterproofness, tensile strength, and abrasion resistance of BC, expanding its application prospects in high-end textiles.

Corporate Innovation and Commercialization Progress: Currently, several companies are actively advancing the commercialization of BC textiles[59]. Nanollose Company uses Lyocell fiber technology to convert waste into BC fibers, yarns, and fabrics. Its developed Nullarbor fabric mitigates the disadvantages of non-woven BC textiles (Fig. 1.7b[63]). Modern Synthesis Company focuses on developing BC non-wovens and received $4.1 million in seed funding in 2022 to develop a microbial weaving platform (Fig. 1.7c). Polybion Company built the world's largest BC biomanufacturing facility, producing Celium™ leather, and collaborated with the Ganni brand to launch leather jackets (Fig. 1.7d), marking the successful application of BC in the high-end fashion field. BC, possessing excellent properties and sustainability, is gradually overcoming technical bottlenecks and demonstrating great potential in the textile field.

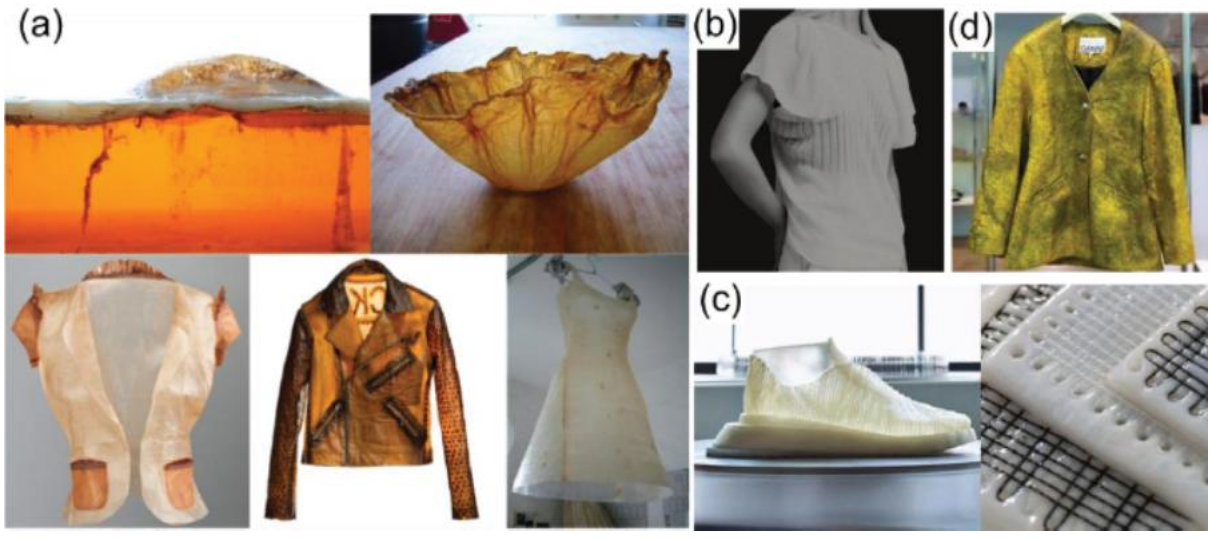

Figure 7 (a) BC clothing products from the BioCouture line[60]; (b) Nullarbor knit fabrics; (c) microbial weaving products from Modern Synthesis; and (d) Celium leather BC jackets made under the Ganni brand.

3.3.2 Applications in the Food Field

BC has been authorized by the U.S. Food and Drug Administration (FDA) as a safe supplement and is widely used in various foods. It is often used in low-calorie meal replacement foods, healthy snacks, and functional foods to help consumers reduce calorie intake while increasing dietary fiber intake[64]. Among them, "Cellulon" is a

commercially available dietary fiber that is allergen-free and consumable; nata de coco and kombucha are both made using BC as raw material; The same nanofibres that make nata de coco chewy turn BC into a clean-label additive: a pinch of the hydrogel locks moisture into bakery, dairy or meat products, keeping them soft, succulent and fresh longer [65,66]. For example, in dairy products such as jelly, yogurt, and ice cream, bacterial cellulose can act as a thickener and stabilizer[67], improving the smoothness and stability of the products.

Strong, transparent and backyard-compostable, BC films already wrap cheeses and cured meats, trimming petro-plastic quotas while extending shelf life. BC combined with lysozyme has antibacterial properties and can be used for packaging fruits, vegetables, and meats, extending shelf life and reducing plastic use[18,68]. Furthermore, BC is also used to develop functional foods, such as serving as a probiotic carrier to regulate intestinal flora and enhance health. The applications of BC in the food field are extensive, ranging from improving food texture to developing healthy foods and eco-friendly packaging, demonstrating significant multifunctionality.

3.3.3 Applications in the Medical Field

Tough, airy, germ-resistant yet cell-friendly, BC is a ready-made scaffold for dressings, drug patches or even blood-vessel grafts that breathe, swell and degrade on cue. Surgeons already press it into service as burn masks, artificial skin, slow-release antibiotic pads and even tubular grafts that stand in for small-diameter blood vessels or cartilage rings, speeding repair while starving infection [69–71].

Today's biggest market for BC is the clinic: its nanofibre mat arrives inherently able to hoard and meter out water (high WHC/WRR), keeping wounds moist but not soggy without added petrolatum layers [72]. Doctors have patched deep second-degree burns with nothing but a BC membrane; skin regenerated completely, sparing patients both graft surgery and heavy scarring [73]. Taking the next step, researchers now seed BC scaffolds with stem cells to grow living skin, while BC conduits implanted in animals rapidly endothelialize and provoke only minimal immune chatter—proof that the cellulose highway can guide blood-vessel regrowth as well. To keep a lumen open, labs let the pellicle form around silicone or PTFE rods suspended at the broth surface; the rod templates the inner diameter while the air-liquid interface supplies fresh oxygen, yielding seamless BC tubes ready for vascular graft trials. Freeze-drying BC around removable mandrels produces shape-memory conduits that snap back to their moulded diameter after compression, letting surgeons stock "off-the-shelf" small-diameter grafts that double as drug-eluting patches for local delivery and tissue repair [74,75].

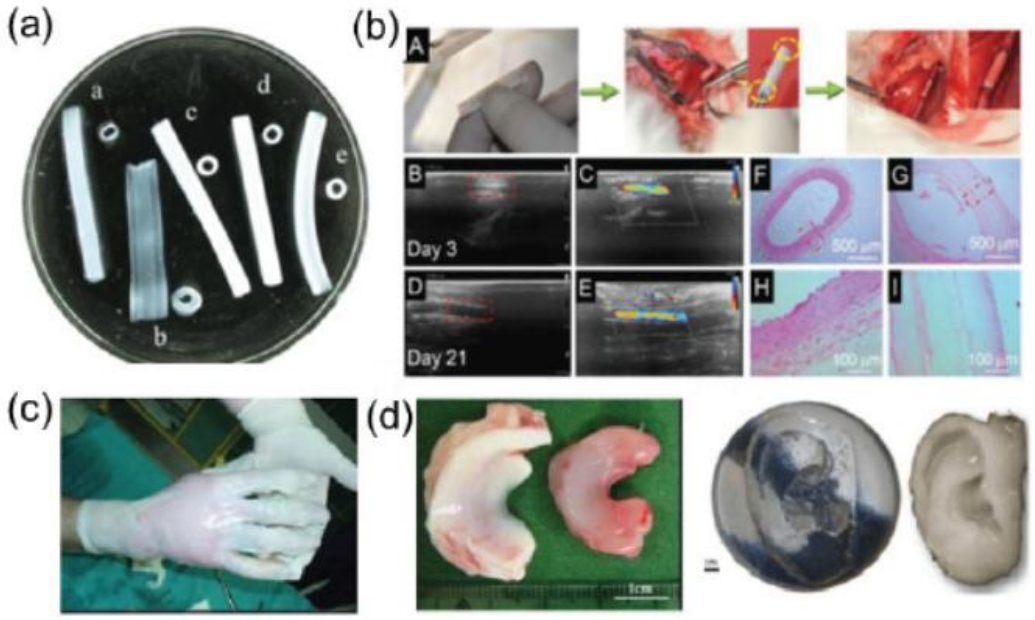

Figure 8 Applications of BC in the biomedical field[12]. (a) artificial blood vessels; (b) Evaluation of BC tubes in rabbits; (c) Wound dressing; (d)

3.3.4 Applications in the Cosmetics Field

Bacterial cellulose (BC) nanofiber structures can form a three-dimensional network that effectively locks in moisture and maintains skin hydration for extended periods, offering multiple application advantages in the cosmetics industry [76]. Its high water absorption and retention capabilities make it an ideal moisturizing material, suitable for developing hydrating masks and skincare product bases, providing exceptional moisturizing effects and a pleasant tactile experience. BC masks, with their high conformability, breathability, and biocompatibility, can closely adhere to facial contours, making them suitable for sensitive skin. Furthermore, the nanofibrous structure of BC offers gentle physical exfoliation and can be combined with other natural ingredients to develop highly effective exfoliating products. Its high specific surface area and biocompatibility allow it to function as a drug carrier for delivering functional ingredients such as whitening, anti-wrinkle, anti-inflammatory, and reparative agents. With growing consumer demand for eco-friendly products, BC, as a biodegradable natural material, aligns with the sustainable development trends in the cosmetics industry. Its production process is relatively green, and the final product is environmentally friendly.

4 Intelligent Discoloration Materials and Their Applications in Smart Textiles

Colour-switch “smart” films flip hue or clarity the moment light, heat, voltage, strain or pH drifts, acting as built-in sensors that report their surroundings without batteries or chips. This functionality gives them wide application potential in fields like smart wearables, sensing, displays, and anti-counterfeiting. Common types include photochromic, thermochromic, electrochromic, and mechanochromic materials. The core of these materials lies in their molecular structure undergoing reversible changes (such as isomerization, conformational changes, or energy level transitions) upon stimulation, thereby altering the light absorption or reflection characteristics of the material. Compared to traditional functional materials, smart discoloration materials are highly favored in the field of new materials due to their rapid response, excellent reversibility, and controllability.

Recent work has broadened the palette—new chromophore families, tougher fatigue life and multi-trigger systems—so a single coating can now log both temperature spikes and pH swings without fading after thousands of cycles. Photochromics, for example, have migrated from early silver halide crystals to today’s fast-switching spiropyran polymers that flip colour in milliseconds under LED light. thermochromic materials have achieved precise color control by adjusting the composition and microstructure of microcapsules. Furthermore, by combining smart discoloration materials with flexible substrates (such as textiles, films), researchers have developed various flexible smart devices, greatly promoting the application of these materials in wearable technology, soft robotics, and other emerging fields. The development of smart discoloration materials not only enishes the material science system but also provides new solutions for many industries, indicating broad application prospects.

4.1 Photochromic Materials

Photochromic materials refer to substances that can reversibly change their color upon exposure to light of a specific wavelength (typically ultraviolet or visible light). This phenomenon is widespread in nature, such as the photochromism of squid skin. Based on their material composition, photochromic materials can be primarily classified into the following types:

(1) Inorganic Photochromic Materials: Typical examples include metal oxides (e.g., titanium dioxide TiO_2, zinc oxide ZnO), metal halides (e.g., silver chloride AgCl), and rare earth complexes. Their photochromic mechanism often involves photo-induced redox reactions or charge transfer processes. For example, AgCl decomposes into silver atoms and chlorine atoms under light, causing the material to darken. Inorganic photochromic materials generally have good thermal and chemical stability, but their color change range is relatively limited, and the reversibility is often poor.

(2) Organic Photochromic Materials: These are the most widely studied and applied class, primarily including spiropyran compounds, spirooxazine compounds, azobenzene compounds, and diarylethene compounds. Their photochromic mechanism usually involves reversible isomerization reactions induced by light, such as ring-opening/closure isomerization of spiropyran or cis-trans isomerization of azobenzene. Organic photochromic

materials offer advantages such as a wide variety, rich colors, good reversibility, and ease of molecular structure modification. Spiropyran-type molecules, for example, switch from colorless to bright blue under a quick UV flash and relax back to clear once visible light or gentle warmth returns. Azobenzene compounds undergo reversible transitions between trans (long-axis, stable) and cis (short-axis, meta-stable) configurations under light of different wavelengths, accompanied by changes in molecular polarity and volume, which can be utilized for constructing light-responsive smart material systems.

Photochromic materials have a wide range of applications. In the textile field, they are used to produce color-changing clothing, achieving pattern or color changes under different light conditions, which is popular in fashion design and military camouflage [77, 80]. In the field of sensing, photochromic materials can serve as sensitive elements for sensors to detect parameters such as light intensity and UV index [87, 91]. That reversible ink lets users print, erase and reprint security codes or data spots on the same label, giving banknotes, passports and rewritable DVDs a covert, light-controlled keypad. Additionally, photochromic materials show potential in areas like smart windows and light-controlled drug release.

4.2 Thermochromic Materials

Thermochromic materials are substances that can reversibly change their color with variations in ambient temperature. Based on their discoloration mechanism, they can be mainly classified into the following types:

(1) Liquid Crystal Thermochromic Materials: Composed of chiral nematic liquid crystals, their color change arises from the temperature-dependent adjustment of the helical pitch of the liquid crystal molecules, which affects the selective reflection of specific wavelengths of light. They can display vivid colors but have a relatively narrow temperature range and are sensitive to contamination.

(2) Inorganic Thermochromic Materials: Typically composed of metal oxides, such as compounds of mercury, silver, copper, etc. Their color change often involves reversible chemical reactions (like decomposition/combination) or crystal phase transitions induced by temperature changes. For example, mercury(II) iodide (HgI_2) changes color from red to yellow upon heating. These materials generally have good temperature resistance but may have toxicity concerns and limited color variation.

(3) Organic Thermochromic Materials: The most common type, usually a ternary system composed of electron-donating color formers (such as crystal violet lactone), electron-accepting color developers (such as bisphenol A), and solvents (long-chain alcohols, fatty acid esters, etc.). The principle involves the reversible association/dissociation reaction between the color former and the color developer controlled by the melting and solidification of the solvent. Above the melting point of the solvent, the color former and developer separate, causing the material to fade or change color; below the melting point, they recombine, restoring the color. This type of material offers advantages such as rich colors, low cost, and easy processing, and is widely used in temperature indication, smart textiles, etc.

Thermochromic materials also have extensive applications. In the textile field, they are used to produce temperature-sensitive clothing that changes color with body temperature or ambient temperature, having applications in fashion and temperature indication [78, 92]. In the field of sensing, they can be used to manufacture temperature sensors or temperature indicator patches for real-time monitoring of temperature changes in objects or environments [96, 97]. In the aerospace field, thermochromic coatings can be applied to the surface of aircraft to monitor surface temperature distribution by observing color changes. They are also used in areas such as food freshness indicators and battery overheating warnings.

4.3 Current Issues and Challenges in Stimuli-Responsive Materials for Textiles

Although stimuli-responsive discoloration materials have demonstrated immense application potential in the field of smart textiles, several challenges remain to be addressed for their large-scale commercial application:

(1) Limited Durability and Stability: The discoloration performance of many stimuli-responsive materials may decay after multiple cycles of use. For example, photochromic materials can suffer from photo-fatigue, and

thermochromic materials may experience reduced sensitivity due to the migration or leakage of functional components. Enhancing the cyclic stability and lifespan of these materials is a pressing issue.

(2) Poor Compatibility with Textile Substrates: Effectively and uniformly fixing functional materials onto textile fibers while maintaining the fabric's original comfort, breathability, flexibility, and durability is challenging. Common finishing methods (like coating) may affect the handle or cause functional layer sheding.

(3) Limitations in Response Precision and Controllability: Precisely controlling the response threshold (e.g., specific wavelength of light, precise temperature point) and the discoloration effect (e.g., color, speed) remains difficult. The development of multi-stimuli responsive, multi-color, and highly sensitive intelligent systems needs further exploration.

(4) High Cost and Complex Processes: The synthesis of some high-performance functional materials and the application processes (like microencapsulation technology) are complex and costly, limiting their large-scale promotion in the textile industry.

(5) Environmental Friendliness and Biocompatibility: The potential environmental impact and biological safety of some synthetic functional materials (such as certain organic compounds, heavy metal ions) need thorough assessment. Developing green, non-toxic, and biodegradable intelligent discoloration material systems is an important direction for future development.

Addressing the aforementioned challenges, the functionalization of bacterial cellulose (BC) presents a promising research direction. BC's pristine nanofibre web—pure, cytocompatible and compostable—acts as an ideal scaffold to host and stabilise these colour-switch guests. By utilizing in-situ microbial fermentation modification technology, functional nanomaterials (like photochromic or thermochromic microcapsules) can be introduced during the BC biosynthesis process. This allows for the uniform distribution of functional components within the three-dimensional nanofiber network, enabling the green and efficient preparation of intelligent discoloration materials with excellent performance. This approach helps to avoid the compatibility issues and environmental pollution associated with traditional finishing processes, facilitating the development of a new generation of eco-friendly smart textiles

In recent years, functional and intelligent textiles with capabilities such as stimulus response, energy storage, and thermal management have developed rapidly [81-83]. Photochromic textiles, due to their ability to sense and respond to light stimuli, have garnered significant attention in fields like anti-counterfeiting, information encryption, fashion design, and ultraviolet (UV) radiation detection (Figure 9, Figure 10). However, the preparation of photochromic smart textiles using traditional printing and dyeing methods suffers from drawbacks such as complex processes and significant environmental pollution. Consequently, designing eco-friendly photochromic smart textiles through green production methods remains a considerable challenge [84, 85]. Researchers have focused on developing wearable and stable photochromic composite materials. For instance, anti-UV photochromic textiles can achieve color switching and absorption triggered by UV radiation, thereby resisting UV exposure and protecting the skin during wear. Photochromic elastomer composites are sensitive to UV light and possess self-healing capabilities; however, the substrates and reagents used in their manufacturing exhibit poor biodegradability, potentially posing threats to skin and the environment [86, 87]. Owing to their inherent rigidity and the weak interfacial bonding between photochromic particles and polymer substrates, photochromic textiles struggle to balance photochromic performance with mechanical stability.

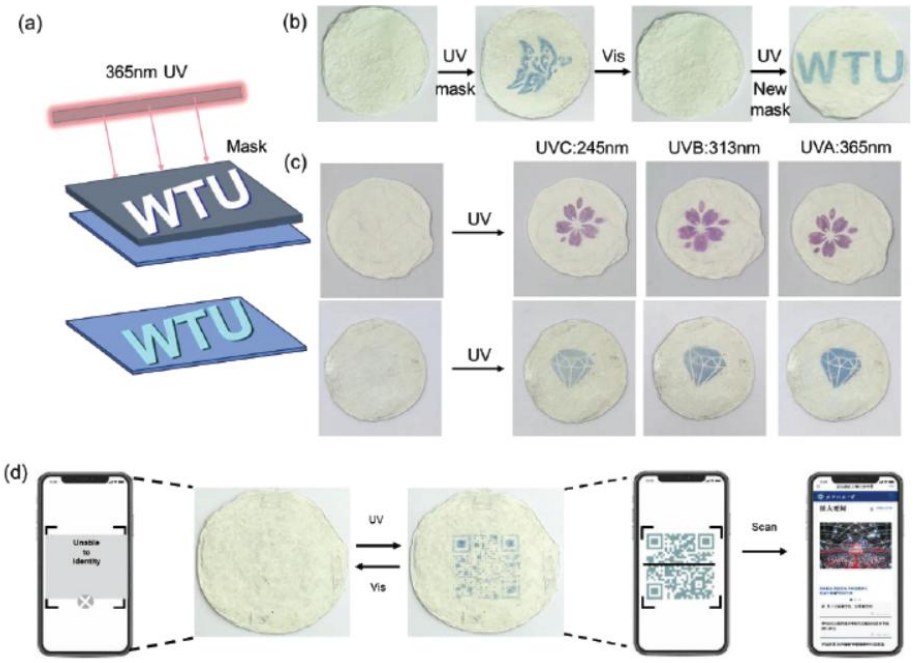

Figure 9 The application of photopatterning of PBC. (a) Schematic of the writing and erasing process; (b) Application of PBCs for photopatterning, e.g., images and letters; (c) The photopatterning photograph of PBCs after exposure to UV radiation at different wavelengths (UVA, UVB, and UVC); (d) QR code pattern information is encrypted and stored of PBC.

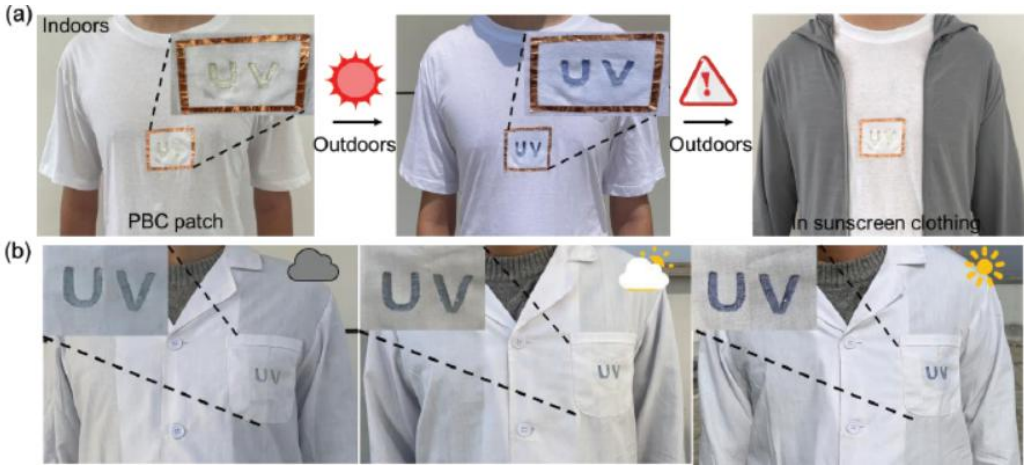

Figure 10 Application of PBCs in textiles. (a) Daily sunlight UV monitoring for wearable smart textiles; (b) Color change of PBC logo under different solar intensity such as overcast, cloudy and sunny.

Driven by the market for green and wearable smart textiles, the modification of natural materials such as cellulose has received considerable attention. Microbially spun BC offers a green thread—cheap, non-toxic and backyard-compostable—ready to replace petro-fabrics without leaving micro-fibres behind. Particularly, its flexibility, mechanical durability, high porosity, biocompatibility, unique three-dimensional (3D) porous nano-network, and abundant hydroxyl groups are conducive to the infiltration and modification with functional materials, making it an ideal substrate for the green manufacturing of photochromic smart textiles. Preliminary research on preparing photochromic bacterial cellulose (PBC) was conducted by Hu et al. and Santos et al. approximately a decade ago [89, 90]. Despite extensive exploration into photochromic textiles, several key challenges remain in modification based on fermentation products. Firstly, achieving the target performance of PBC with high loading fastness and stable color fastness is challenging. Secondly, traditional physical modifications can compromise the mechanical properties of BC, while chemical modification methods often

suffer from low grafting efficiency, involve large amounts of toxic chemicals and complex procedures, exhibit poor biosafety, and unstable photochromic performance, hindering the large-scale production of PBC as an eco-friendly material. Thirdly, monochromatic switching in BC films has been achieved using conventional modification methods within a tunable color system. However, a tunable color-switching system has not yet been reported for photochromic smart textiles. Therefore, designing wearable BC-based photochromic textiles with high performance and broad applicability using green production methods remains a formidable challenge.

The aforementioned challenges highlight the existing gap between laboratory research and the practical, large-scale application of high-performance photochromic BC textiles. The inability to seamlessly integrate robust photochromic function with the inherent favorable textile properties of BC (flexibility, comfort, durability) through existing methods necessitates a novel approach. This research aims to address these limitations by exploring an in-situmicrobial fermentation modification strategy. The primary objective is to develop a green and efficient method for fabricating PBC that simultaneously achieves uniform distribution of photochromic agents, strong interfacial bonding within the BC matrix, and excellent overall performance, including mechanical properties, color fastness, and fatigue resistance. This approach seeks to bypass the drawbacks of traditional pre- or post-treatment modifications and pave the way for the development of truly wearable and sustainable photochromic textiles.

The exceptional properties of BC position it as a cornerstone for next-generation smart textiles. The tangled nanonet delivers leather-like strength while shuttling moisture away from skin; its medical-grade purity banishes the dyes and allergens that usually irritate wearers, letting BC garments sit directly on the body all day. Furthermore, the ability to tailor its porosity and morphology during biosynthesis offers a unique opportunity to control the loading and distribution of functional materials like photochromic microcapsules. This research will leverage these inherent advantages of BC to create a novel photochromic material system.

Researchers are exploring innovative technologies and novel building insulation materials to enhance residential comfort, improve energy efficiency, and mitigate adverse environmental impacts (Figure 11) such as the greenhouse effect [96, 97]. Aerogels have attracted significant attention due to their large specific surface area, low density, and high porosity. Their porous three-dimensional network structure endows them with exceptional thermal insulation properties, making them ideal energy-saving building materials. However, existing aerogels face limitations in terms of green sustainability, mechanical strength, and flame retardancy. For instance, petroleum-based polymer-derived aerogels are often characterized by high cost, complex manufacturing processes, poor biodegradability, and a tendency to decompose at high temperatures, releasing toxic gases that threaten human health [98, 99].

Enter biomass aerogels—plant-spun foams that match mineral wool's R-value, bounce back after compression and end life as compost, offering a renewable fix to insulation's petro-addiction. This is particularly relevant in the fields of building insulation and fire safety [100, 101]. Bacterial cellulose (BC), as a biomass material, possesses excellent biocompatibility and biodegradability. Its nanoscale porous network structure provides outstanding thermal insulation performance. Nonetheless, the inherent flammability and relatively suboptimal mechanical properties of pure BC limit its application in high-temperature environments. Researchers have attempted to construct aerogel frameworks with high flame retardancy and enhanced mechanical strength by incorporating flame retardants and fiber reinforcement materials. Currently, the preparation of BC-based aerogels primarily relies on sol-gel processing, impregnation techniques, and hybrid strategies. However, physical modification methods often suffer from low efficiency and weak interfacial bonding, potentially leading to irreversible mechanical damage [102-104]. Chemical methods, on the other hand, are typically complex, costly, and involve hazardous chemical reagents, posing risks to both the environment and human health [105]. Consequently, developing efficient, multifunctional, environmentally friendly, and straightforward processes for fabricating renewable BC-based flame-retardant aerogels remains a significant challenge.

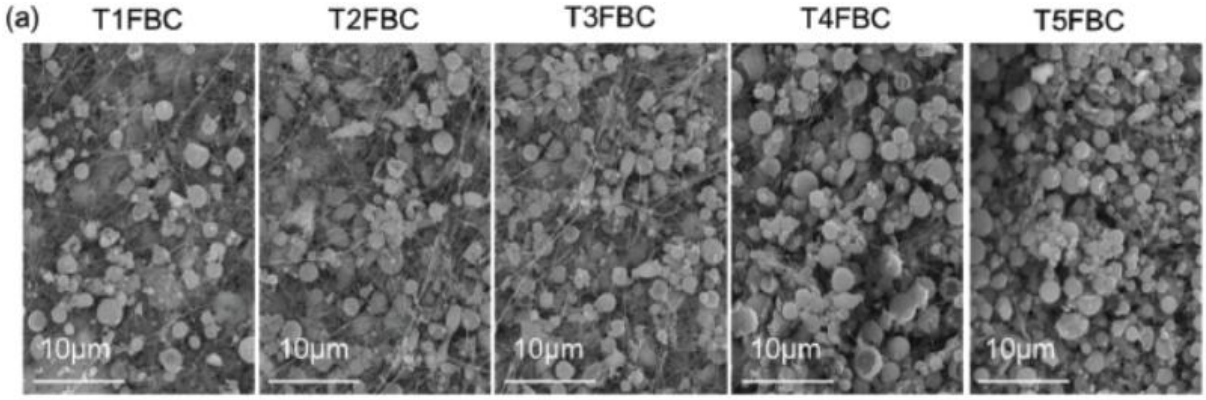

Figure 11(a) SEM images of surface morphology of TFBC composite aerogel loaded with thermochromic particles of different content;

While heat-resistant and fire-retardant aerogels can withstand high temperatures and inhibit flame spread, they generally lack a visual indicator for temperature changes, making it difficult to provide early warning of high-temperature hazards. The ability to identify and address potential risks during the initial stages of a fire could significantly reduce fire-related dangers. Integrating intelligent high-temperature detection capabilities with the inherent thermal insulation and flame-retardant properties of aerogels could unlock new possibilities for smart fire safety systems. However, most existing sensing systems rely on monitoring changes in electrical resistance or current at elevated temperatures, facing challenges related to the high-temperature resistance of sensor power sources [106, 107]. Currently, few fire alarm materials provide intuitive visual warnings through thermochromic compounds. Therefore, there is a pressing need to develop a simple, eco-friendly biomass-based thermal protection aerogel (Figure 12) . Such a material would intelligently detect abnormal fire conditions without requiring an external power source and provide thermal protection, which is crucial for ensuring personal safety and reducing property damage.

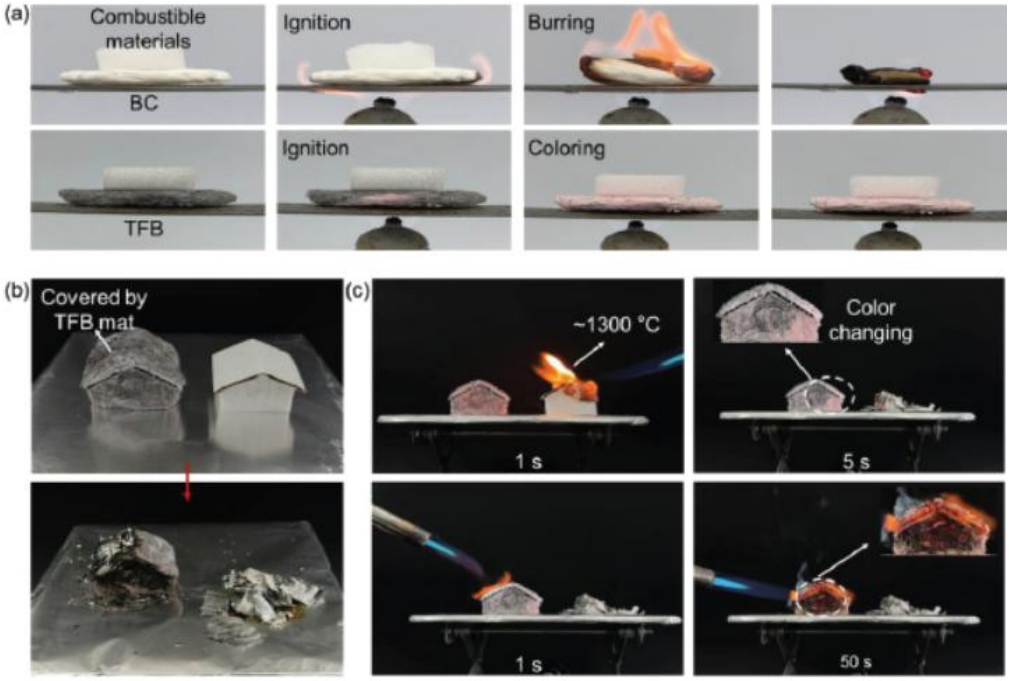

Figure 12 Building thermal protection materials for TFBC. (a) Comparison of flame retardancy and thermal insulation properties of BC and FBC in flammable flexible foams (~ 600℃). (b) Simulate the fire resistance and structural integrity of TFBC aerogel mat flame retardant building protection materials. (d) thermochromism and thermal protection process of TFBC aerogel used as building protection material

at high temperature (~1300℃).

The integration of stimulus-responsive functionality, particularly visual thermal warning, into high-performance insulating materials represents a frontier in smart building and safety material design. Traditional approaches often treat insulation and fire warning as separate system components. The development of a single material system that combines passive fire resistance with active, self-powered visual alarm capabilities would mark a significant advancement. Such a multifunctional aerogel could provide a dual-layered safety mechanism: firstly, acting as a physical barrier against heat and flames, and secondly, serving as an immediate visual sentinel that alerts occupants to temperature anomalies indicative of a potential fire, potentially before traditional smoke or heat detectors are triggered. This proactive warning system is especially valuable in scenarios where early evacuation is critical.

5 Conclusions

Bacterial cellulose (BC) presents a unique and compelling foundation for addressing these challenges. Its natural nanofibrillar structure forms an ideal scaffold for creating highly porous, mechanically robust aerogels. The abundance of surface hydroxyl groups on BC nanofibers facilitates strong interfacial interactions with various functional additives, such as flame retardants (e.g., silica nanoparticles) and thermochromic pigments, through hydrogen bonding and other physicochemical interactions. The bio-synthetic nature of BC production offers a potentially greener and more sustainable route to aerogel fabrication compared to synthetic polymer precursors. By leveraging in-situmodification strategies during BC biosynthesis or through post-synthetic design, it is possible to engineer the microstructure and composition of BC aerogels to achieve the desired synergy of properties—excellent insulation, enhanced flame retardancy, and intelligent thermoresponsive color-changing behavior—thereby creating a truly multifunctional smart material for advanced thermal management and fire safety applications.

References

[1] Geyer R, Jambeck J R, Law K L. Production, use, and fate of all plastics ever made [J]. Science Advances, 2017, 3(7): e1700782.

[2] Jambeck J R, Geyer R, Wilcox C, et al. Plastic waste inputs from land into the ocean[J]. Science, 2015, 347(6223): 768-71.

[3] Leistenschneider D, Wolinski A, Cheng J, et al. A critical review on the evaluation of toxicity and ecological risk assessment of plastics in the marine environment[J]. Science of The Total Environment, 2023, 896: 164955.

[4] Ramamoorthy S K, Skrifvars M, Persson A. A Review of Natural Fibers Used in Biocomposites: Plant, Animal and Regenerated Cellulose Fibers[J]. Polymer Reviews, 2015, 55(1): 107-62.

[5] Rochman C M, Browne M A, Halpern B S, et al. Classify plastic waste as hazardous[J]. Nature, 2013, 494(7436): 169-71.

[6] Cheng H, Lijie L, Wang B, et al. Multifaceted applications of cellulosic porous materials in environment, energy, and health[J]. Progress in Polymer Science, 2020, 106: 101253.

[7] El Bourakadi K, Semlali F-Z, Hammi M, et al. A review on natural cellulose fiber applications: Empowering industry with sustainable solutions[J]. International Journal of Biological Macromolecules, 2024, 281: 135773.

[8] Klemm D, Heublein B, Fink H-P, et al. Cellulose: Fascinating Biopolymer and Sustainable Raw Material[J]. Angewandte Chemie International Edition, 2005, 44(22): 3358-93.

[9] Deng J, Song Q, Liu S, et al. Advanced applications of cellulose-based composites in fighting bone diseases [J]. Composites Part B: Engineering, 2022, 245: 110221.

[10] Shi Y, Jiao H, Sun J, et al. Functionalization of nanocellulose applied with biological molecules for biomedical application: A review[J]. Carbohydrate Polymers, 2022, 285: 119208.

[11] Wu N, Yang Y F, Wang C X, et al. Ultrathin Cellulose Nanofiber Assisted Ambient-Pressure-Dried, Ultralight, Mechanically Robust, Multifunctional MXene Aerogels[J]. Advanced Materials, 2023, 35(1): 2207969.

[12] Ghamari M, Sun D, Dai Y, et al. Valorization of diverse waste-derived nanocellulose for multifaceted applications: A review[J]. International Journal of Biological Macromolecules, 2024, 280: 136130.

[13] Acharya S, Liyanage S, Parajuli P, et al. Utilization of Cellulose to Its Full Potential: A Review on Cellulose D issolution, Regeneration, and Applications[J]. Polymers, 2021, 13(24): 4344.
[14] Mathers J C. Dietary fibre and health: the story so far[J]. Proceedings of the Nutrition Society, 2023, 82(2): 120-9.
[15] This section includes literature on the fundamental aspects of bacterial cellulose, including its biosynthesi s, structure, properties, and broad applications.
[16] Chen C T, Ding W X, Zhang H, et al. Bacterial cellulose-based biomaterials: From fabrication to application [J]. Carbohydrate Polymers, 2022, 278: 118995.
[17] Rosson L, Tan B, Best W, et al. Applications of regenerated bacterial cellulose: a review[J]. Cellulose, 2024, 31(17): 10165-90.
[18] Mishra S, Singh P K, Pattnaik R, et al. Biochemistry, Synthesis, and Applications of Bacterial Cellulose: A Re view[J]. Frontiers in Bioengineering and Biotechnology, 2022, 10: 780409.
[19] Si Y, Lin Q, Zhou F, et al. The interaction between nanocellulose and microorganisms for new degradable packaging: A review[J]. Carbohydrate Polymers, 2022, 295: 119899.
[20] Lin S P, Calvar I L, Catchmark J M, et al. Biosynthesis, production and applications of bacterial cellulose[J]. Cellulose, 2013, 20(5): 2191-219.
[21] Girard V D, Chausse J, Vermette P. Bacterial cellulose: A comprehensive review[J]. Journal of Applied Poly mer Science, 2024, 141(15): e55163.
[22] Wang J, Tavakoli J, Tang Y H. Bacterial cellulose production, properties and applications with different cult ure methods- A review[J]. Carbohydrate Polymers, 2019, 219: 63-76.
[23] Krystynowicz A, Czaja W, Wiktorowska-Jezierska A, et al. Factors affecting the yield and properties of bact erial cellulose[J]. Journal of Industrial Microbiology and Biotechnology, 2002, 29(4): 189-95.
[24] Takayama G, Kondo T. Quantitative evaluation of fiber network structure-property relationships in bacter ial cellulose hydrogels[J]. Carbohydrate Polymers, 2023, 321: 121311.
[25] Babi M, Williams A, Reid M, et al. Unraveling the Supramolecular Structure and Nanoscale Dislocations of Bacterial Cellulose Ribbons Using Correlative Super-Resolution Light and Electron Microscopy[J]. Biomacr omolecules, 2023, 24(1): 258-68.
[26] Yao J, Chen S, Chen Y, et al. Macrofibers with High Mechanical Performance Based on Aligned Bacterial Ce llulose Nanofibers[J]. ACS Applied Materials & Interfaces, 2017, 9(24): 20330-9.
[27] Chibrikov V, Pieczywek P M, Cybulska J, et al. Coarse-grained molecular dynamics model to evaluate the mechanical properties of bacterial cellulose-hemicellulose composites[J]. Carbohydrate Polymers, 2024, 3 30: 121827.
[28] Liu Y, Ran Q, Guo J, et al. In-situ CBM3-modified bacterial cellulose film with improved mechanical proper ties[J]. International Journal of Biological Macromolecules, 2023, 243: 125193.
[29] Backdahl H, Helenius G, Bodin A, et al. Mechanical properties of bacterial cellulose and interactions with s mooth muscle cells[J]. Biomaterials, 2006, 27(9): 2141-9.
[30] Czaja W K, Young D J, Kawecki M, et al. The Future Prospects of Microbial Cellulose in Biomedical Applicat ions[J]. Biomacromolecules, 2007, 8(1): 1-12.
[31] Fontana J D, De Souza A M, Fontana C K, et al. Acetobacter cellulose pellicle as a temporary skin substitut e[J]. Applied Biochemistry and Biotechnology, 1990, 24(1): 253-64.
[32] Picheth G F, Pirich C L, Sierakowski M R, et al. Bacterial cellulose in biomedical applications: A review[J]. In ternational Journal of Biological Macromolecules, 2017, 104: 97-106.
[33] Meftahi A, Samyn P, Geravand S A, et al. Nanocelluloses as skin biocompatible materials for skincare, cos metics, and healthcare: Formulations, regulations, and emerging applications[J]. Carbohydrate Polymers, 2022, 278: 118956.
[34] Choi S M, Rao K M, Zo S M, et al. Bacterial Cellulose and Its Applications[J]. Polymers, 2022, 14(6): 1080.
[35] Hasanin M S. Cellulose-Based Biomaterials: Chemistry and Biomedical Applications[J]. Starch-Starke, 202 2, 74(7-8): 2200060.
[36] Rajwade J M, Paknikar K M, Kumbhar J V. Applications of bacterial cellulose and its composites in biomedi cine[J]. Applied microbiology and biotechnology, 2015, 99(6): 2491-511.
[37] Fu L N, Zhang J, Yang G. Present status and applications of bacterial cellulose-based materials for skin tiss ue repair[J]. Carbohydrate Polymers, 2013, 92(2): 1432-42.
[38] Pang M J, Huang Y H, Meng F S, et al. Application of bacterial cellulose in skin and bone tissue engineering [J]. European Polymer Journal, 2020, 122: 109365.

[39] He W, Wu J, Xu J, et al. Bacterial Cellulose: Functional Modification and Wound Healing Applications[J]. A dvances in Wound Care, 2021, 10(11): 623-40.
[40] Cazon P, Vazquez M. Improving bacterial cellulose films by ex-situ and in-situ modifications: A review[J]. F ood Hydrocolloids, 2021, 113: 106514.
[41] Amin Ojagh S M, Vahabzadeh F, Fallah N, et al. Highly functionalized all-cellulose nanocomposites via bact eria-enabled in-situ modifications[J]. Chemical Engineering Journal, 2024, 498: 155409.
[42] Chen G Q, Chen L, Wang W, et al. Manufacture of a novel anisotropic bacterial nanocellulose hydrogel me mbrane by using a rotary drum bioreactor[J]. Carbohydrate Polymers, 2019, 211: 281-8.
[43] Liu K, Catchmark J M. Enhanced mechanical properties of bacterial cellulose nanocomposites produced by co-culturing Gluconacetobacter hansenii and Escherichia coli under static conditions[J]. Carbohydrate Pol ymers, 2019, 219: 12-20.
[44] Sharma C, Bhardwaj N K, Pathak P. Rotary disc bioreactor-based approach for bacterial nanocellulose pro duction using Gluconacetobacter xylinus NCIM 2526 strain[J]. Cellulose, 2022, 29(13): 7177-91.
[45] Gao M, Li J, Bao Z, et al. A natural in situ fabrication method of functional bacterial cellulose using a micro organism[J]. Nature Communications, 2019, 10(1): 437.
[46] Hsieh J T, Wang M J, Lai J T, et al. A novel static cultivation of bacterial cellulose production by intermitten t feeding strategy[J]. Journal of the Taiwan Institute of Chemical Engineers, 2016, 63: 46-51.
[47] Lin S-P, Liu C-T, Hsu K-D, et al. Production of bacterial cellulose with various additives in a PCS rotating dis k bioreactor and its material property analysis[J]. Cellulose, 2016, 23(1): 367-77.
[48] Chandrasekaran P T, Bari N K, Sinha S. Enhanced bacterial cellulose production from Gluconacetobacter x ylinus using super optimal broth[J]. Cellulose, 2017, 24(10): 4367-81.
[49] Singhania R R, Patel A K, Tsai M-L, et al. Genetic modification for enhancing bacterial cellulose production and its applications[J]. Bioengineered, 2021, 12(1): 6793-807.
[50] Wichai S, Chuysinuan P, Chaiarwut S, et al. Development of bacterial cellulose/alginate/chitosan composit es incorporating copper(II) sulfate as an antibacterial wound dressing[J]. Journal of Drug Delivery Science and Technology, 2019, 51: 662-71.
[51] Abdelraof M, Hasanin M S, Farag M M, et al. Green synthesis of bacterial cellulose/bioactive glass nanoco mposites: Effect of glass nanoparticles on cellulose yield, biocompatibility and antimicrobial activity[J]. Int ernational Journal of Biological Macromolecules, 2019, 138: 975-85.
[52] Sun B, Lin J, Wang T, et al. Gas assisted in situ biomimetic mineralization of bacterial cellulose/calcium car bonate bio composites by bacterial[J]. International Journal of Biological Macromolecules, 2021, 182: 169 0-6.
[53] Stanislawska A, Szkodo M, Staroszczyk H, et al. Effect of the ex situ physical and in situ chemical modificat ion of bacterial nanocellulose on mechanical properties in the context of its potential applications in hear t valve design[J]. International Journal of Biological Macromolecules, 2024, 269: 131951.
[54] Sommer A, Dederko-Kantowicz P, Staroszczyk H, et al. Enzymatic and Chemical Cross-Linking of Bacterial Cellulose/Fish Collagen Composites-A Comparative Study[J]. International Journal of Molecular Sciences, 2021, 22(7): 3346.
[55] Torres F G, Arroyo J J, Troncoso O P. Bacterial cellulose nanocomposites: An all-nano type of material[J]. Materials science & engineering. C, Materials for biological applications, 2019, 98: 1277-93.
[56] Li X L, Yuan L B, Liu R, et al. Engineering Textile Electrode and Bacterial Cellulose Nanofiber Reinforced Hy drogel Electrolyte to Enable High-Performance Flexible All-Solid-State Supercapacitors[J]. Advanced Energ y Materials, 2021, 11(12): 2003010.
[57] Sulaeva I, Hettegger H, Bergen A, et al. Fabrication of bacterial cellulose-based wound dressings with impr oved performance by impregnation with alginate[J]. Materials Science and Engineering: C, 2020, 110: 110 619.
[58] Wang F, Jin Z, Zheng S, et al. High-fidelity bioelectronic muscular actuator based on porous carboxylate ba cterial cellulose membrane[J]. Sensors and Actuators B: Chemical, 2017, 250: 402-11.
[59] Feng L, Cao X, Wang Z L, et al. A transparent and degradable bacterial cellulose-based film for triboelectri c nanogenerator: Efficient biomechanical energy harvesting and human health monitoring[J]. Nano Energ y, 2024, 120: 109068.
[60] Liu G, Zou F, He W, et al. The controlled degradation of bacterial cellulose in simulated physiological envir onment by immobilization and release of cellulase[J]. Carbohydrate Polymers, 2023, 314: 120906.
[61] Phatchaya wat P P, Khamkeaw A, Yodmuang S, et al. 3D bacterial cellulose-chitosan-alginate-gelatin hydr ogel scaffold for cartilage tissue engineering[J]. Biochemical Engineering Journal, 2022, 184: 108476.

[62] Phan H N, Vu N K, Bui H M. Fabrication and characterization of patterned leather-like biomaterial derived from Brazilein/Glycerol-finished Bacterial Cellulose by using 3-in-1 textile finishing process[J]. Cellulose, 2023, 30(8): 5217-37.
[63] Phan H N, Phan D T M, Vo N T T, et al. Fabrication of plasticized interpenetrating polymer network (IPN) leatherette derived from bacterial cellulose and silicon dioxide using a novel 2-in-1 thickening process[J]. Cellulose, 2024, 31(15): 9281-302.
[64] Kim J H, Park S, Kim H, et al. Alginate/bacterial cellulose nanocomposite beads prepared using Gluconacetobacter xylinus and their application in lipase immobilization[J]. Carbohydrate Polymers, 2017, 157: 137-45.
[65] Qin J M, Qin Z Y, Yin X Q, et al. Synthesis and Characterization of Alkylated Bacterial Cellulose in an Ionic Liquid[J]. Bioresources, 2015, 10(2): 2185-94.
[66] Hu W L, Liu S P, Chen S Y, et al. Preparation and properties of photochromic bacterial cellulose nanofibrous membranes[J]. Cellulose, 2011, 18(3): 655-61.
[67] Santos M V, Barud H S, Alencar M A S, et al. Self-Supported Smart Bacterial Nanocellulose-Phosphotungstic Acid Nanocomposites for Photochromic Applications[J]. Frontiers in Materials, 2021, 8: 668835.
[68] Lakatos A. Novel Thermal Insulation Materials for Buildings[J]. Energies, 2022, 15(18): 6713.
[69] Li Y Y, Sun Y M, Qiu J L, et al. Moisture absorption characteristics and thermal insulation performance of thermal insulation materials for cold region tunnels[J]. Construction and Building Materials, 2020, 237: 117765.
[70] Yu H J, Tong Z W, Zhang B J, et al. Thermal radiation shielded, high strength, fire resistant fiber/nanorod/aerogel composites fabricated by in-situ growth of TiO2/nanorods for thermal insulation[J]. Chemical Engineering Journal, 2021, 418: 129342.
[71] Yu Z L, Qin B, Ma Z Y, et al. Superelastic Hard Carbon Nanofiber Aerogels[J]. Advanced Materials, 2019, 31(23): 1900651.
[72] Chen S W, Hu Y H, Gao D F, et al. Superelastic bio-based polyimide aerogel with excellent oil/water separation performance and effective visible light photocatalytic activity[J]. Journal of Cleaner Production, 2023, 428: 139521.
[73] Nita L E, Ghilan A, Rusu A G, et al. New Trends in Bio-Based Aerogels[J]. Pharmaceutics, 2020, 12(5): 449.
[74] Huang Y, Zhou P, Zhang X X. Green synthesis of Ag-doped cellulose aerogel for highly sensitive, flame retardant strain sensors[J]. Cellulose, 2022, 29(16): 8719-31.
[75] Wang Z X, Yuyu E, Li J, et al. Sustainable bacterial cellulose-based composite aerogels with excellent flame retardant and heat insulation[J]. Cellulose, 2023, 30(15): 9563-74.
[76] Yuan B, Zhang J M, Mi Q Y, et al. Transparent Cellulose-Silica Composite Aerogels with Excellent Flame Retardancy via an in Situ Sol-Gel Process[J]. ACS Sustainable Chemistry & Engineering, 2017, 5(11): 11117-23.
[77] Pereira A L S, Feitosa J P A, Morais J P S, et al. Bacterial cellulose aerogels: Influence of oxidation and silanization on mechanical and absorption properties[J]. Carbohydrate Polymers, 2020, 250: 116927.
[78] Zhou S Y, Apostolopoulou-Kalkavoura V, da Costa M V T, et al. Elastic Aerogels of Cellulose Nanofibers@Metal-Organic Frameworks for Thermal Insulation and Fire Retardancy[J]. Nano-Micro Letters, 2020, 12(1): 9.
[79] Kim N K, Dutta S, Bhattacharyya D. A review of flammability of natural fibre reinforced polymeric composites[J]. Composites Science and Technology, 2018, 162: 64-78.
[80] Abdelhameed M M, Attia Y A, Abdelrahman M S, Khattab T A. Photochromic and fluorescent ink using photoluminescent strontium aluminate pigment and screen printing towards anticounterfeiting documents. Luminescence, 2021, 36: 865-874.
[81] Zhang Z H, Chen Z Y, Wang Y, Zhao Y J. Bioinspired conductive cellulose liquid-crystal hydrogels as multifunctional electrical skins[J]. Proceedings of the National Academy of Sciences of the United States of America, 2022, 117(31): 18310-18316.
[82] Sandt J D, Moudio M, Clark J K, Hardin J, Argenti C, Cart M, Lewis J A, Kolle M. Stretchable Optomechanical Fiber Sensors for Pressure Determination in Compressive Medical Textiles[J]. Advanced Healthcare Materials, 2018, 7: 1800293.
[83] Lin, C J, Prasetyo Y T, Siswanto N D, Jiang B C. Optimization of color design for military camouflage in CIELAB color space[J]. Color Research And Application, 2019, 44: 367-380.
[84] Li L P, Wang K, Jia W, et al. Continuous preparation of dual-responsive sensing fibers for smart textiles[J]. Journal of Colloid and Interface Science, 2021, 597: 215-22.

[85] Li Y Y, Wang Y Q, Lu J, et al. Synergistically photothermal Au Nanoprisms@MXene enable adaptive solar m odulation of HA-PNIPAM hydrogels for smart window[J]. Chemical Engineering Journal, 2023, 457: 14129 9.
[86] Zheng M R, Liu M Y, Cheng Y, et al. Stimuli-responsive fiber/fabric actuators for intelligent soft robots: Fro m current progress to future opportunities[J]. Nano Energy, 2024, 129: 110050.
[87] Morsimbiul S, Kumbasar E P A, Cay A. Photochromic Microcapsules for Textile Materials by Spray Drying-P art 3: Application of Photochromic Microcapsules on Cotton Fabrics[J]. AATCC Journal of Research, 2022, 9(2): 63-73.
[88] Yang Y, Li M, Fu S H. Screen-printed photochromic textiles with high fastness prepared by self-adhesive p olymer latex particles[J]. Progress in Organic Coatings, 2021, 158: 106348.
[89] Viková M, Periyasamy A P, Vik M, et al. Effect of drawing ratio on difference in optical density and mecha nical properties of mass colored photochromic polypropylene filaments[J]. Journal Of The Textile Institut e, 2017, 108(8): 1365-70.
[90] Yimyai T, Crespy D, Pena-Francesch A. Self-Healing Photochromic Elastomer Composites for Wearable UV -Sensors[J]. Advanced Functional Materials, 2023, 33(20): 2213717.
[91] Raeesi M, Alinejad Z, Hamrang V, et al. Solid-state photochromism of spironaphthoxazine loaded microca psules with photo-patterning and thermo-regulating features[J]. Journal of Colloid and Interface Science, 2020, 578: 379-89.
[92] Qiang P R, Zhang S, Gao J, et al. Preparation and Photochromic Properties of Copolymers Containing Spiro oxazine Compounds[J]. Acta Polymerica Sinica, 2015, (10): 1165-74.
[93] Shi Y Y, Wu L, Gao J, et al. Synthesis and photochromic properties of polymers containing spirooxazine gro ups[J]. Journal of Macromolecular Science, Part A: Pure and Applied Chemistry, 2017, 54(11): 853-9.
[94] Hong S, Peng Z W, Wu M Y, et al. Human-Hair-Derived Natural Particles as Multifunctional Sunscreen for E ffective UV Protection[J]. ACS Nano, 2023, 17(15): 14943-53.
[95] Zhang G Y, Liu C, Yang L J, et al. A flame-retardant and conductive fabric-based triboelectric nanogenerato r: Application in fire alarm and emergency evacuation[J]. Journal of Colloid and Interface Science, 2024, 6 58: 219-29.
[96] Lei Y, Chan Q N, Xu L L, et al. Smart retardant materials for fire alarm systems: integrating flame retardanc y and early detection technologies[J]. Advanced Composites and Hybrid Materials, 2025, 8(1): 112.
[97] Jin X J, Li L L, Zhao S F, et al. Assessment of Occlusal Force and Local Gas Release Using Degradable Bacteri al Cellulose/Ti3C2Tx MXene Bioaerogel for Oral Healthcare[J]. ACS Nano, 2021, 15(11): 18385-18393.
[98] Wei W, Zhang Y, Chen H, et al. Molecular dynamics simulations guided the preparation of nano-silica/poly imide/cellulose composite insulating paper[J]. Materials & Design, 2023, 233: 112176.
[99] Choi J, Hyun J. Hydrochromic film for dynamic information storage using cellulose nanofibers and silica na noparticles[J]. Carbohydrate Polymers, 2024, 327: 121663.
[100] References related to the application of BC and cellulose derivatives in food, cosmetics, and specific chem ical processes like the viscose process.
[101] Rachtanapun P, Jantrawut P, Klunklin W, et al. Carboxymethyl Bacterial Cellulose from Nata de Coco: Effe cts of NaOH[J]. Polymers, 2021, 13(3): 348.
[102] Casaburi A, Montoya Rojo U, Cerrutti P, et al. Carboxymethyl cellulose with tailored degree of substitutio n obtained from bacterial cellulose[J]. Food Hydrocolloids, 2018, 75: 147-56.
[103] Wang X T, Guo J, Ren H Y, et al. Research progress of nanocellulose-based food packaging[J]. Trends in Fo od Science & Technology, 2024, 143: 104289.
[104] Gondhalekar S C, Pawar P J, Dhumal S S, et al. Mechanism of xanthation reaction in viscose process[J]. Cel lulose, 2019, 26(3): 1595-604.
[105] Sharma A, Nagarkar S, Thakre S, et al. Structure-property relations in regenerated cellulose fibers: compa rison of fibers manufactured using viscose and lyocell processes[J]. Cellulose, 2019, 26(6): 3655-69
[106] PARALE G V, KIM T, CHOI H, et al. Mechanically strengthened aerogels through multiscale, multicompositi onal, and multidimensional approaches: a review(Adv. Mater. 18/2024)[J]. Advanced Materials, 2024, 36 (18): 2470138.
[107] WANG S, WANG F, MA S, et al. Research progress on polysaccharide-based aerogel food packaging[J]. Foo d Science, 2023, 44(19):340-349.