BACTERIAL CELLULOSE: PRODUCTION AND APPLICATIONS IN FOOD INDUSTRY

CELULOSE BACTERIANA: PRODUÇÃO E APLICAÇÕES NA INDÚSTRIA DE ALIMENTOS

CELULOSA BACTERIANA: PRODUCCIÓN Y APLICACIONES EN LA INDUSTRIA ALIMENTARIA

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ABSTRACT
Bacterial cellulose (BC) is a natural biopolymer of high purity, free of lignin and hemicellulose, with high crystallinity, water retention capacity, and mechanical strength. Its production depends on factors such as strain selection (especially from the genus Komagataeibacter), culture medium composition, carbon source, pH, temperature, and cultivation method, with static fermentation being the most suitable for obtaining films with greater structural organization. The use of agro-industrial residues as substrates emerges as a sustainable and economically viable alternative. In the food industry, BC is recognized as GRAS by the FDA and has applications as a fat replacer, texturizing agent, stabilizer, and source of dietary fiber. Studies demonstrate improvements in ice cream creaminess, juiciness of plant-based burgers, emulsion stability, and the quality of reduced-fat cheeses and processed meats. In addition, it stands out in the production of active films and packaging with antioxidant and antimicrobial properties, contributing to shelf-life extension. Thus, BC represents a sustainable and functional alternative for innovation in food products and packaging.

Keywords: Food Applications. Biomaterials. Microbial Consortium. Kombucha.

RESUMO
A celulose bacteriana (CB) é um biopolímero natural de alta pureza, livre de lignina e hemicelulose, com elevada cristalinidade, capacidade de retenção de água e resistência mecânica. Sua produção depende de fatores como seleção de cepas (especialmente do gênero Komagataeibacter), composição do meio de cultura, fonte de carbono, pH, temperatura e método de cultivo, sendo a fermentação estática a mais adequada para obtenção de filmes com maior organização estrutural. A utilização de resíduos agroindustriais como substrato surge como alternativa sustentável e economicamente viável.Na indústria de alimentos, a CB é considerada GRAS pelo FDA e apresenta aplicações como substituto de gordura, agente texturizante, estabilizante e fonte de fibra alimentar. Estudos demonstram melhorias na cremosidade de sorvetes, suculência de hambúrgueres vegetais, estabilidade de emulsões e qualidade de queijos e embutidos com teor reduzido de gordura. Além disso, destaca-se na produção de filmes e embalagens

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ativas com propriedades antioxidantes e antimicrobianas, contribuindo para a extensão da vida de prateleira. Assim, a CB representa uma alternativa sustentável e funcional para inovação em alimentos e embalagens.

Palavras-chave: Aplicações em Alimentos. Biomateriais. Consórcio Microbiano. Kombucha.

RESUMEN

La celulosa bacteriana (CB) es un biopolímero natural de alta pureza, libre de lignina y hemicelulosa, con elevada cristalinidad, capacidad de retención de agua y resistencia mecánica. Su producción depende de factores como la selección de cepas (especialmente del género Komagataeibacter), la composición del medio de cultivo, la fuente de carbono, el pH, la temperatura y el método de cultivo, siendo la fermentación estática la más adecuada para la obtención de películas con mayor organización estructural. El uso de residuos agroindustriales como sustrato surge como una alternativa sostenible y económicamente viable. En la industria alimentaria, la CB es considerada GRAS por la FDA y presenta aplicaciones como sustituto de grasa, agente texturizante, estabilizante y fuente de fibra alimentaria. Los estudios demuestran mejoras en la cremosidad de helados, la jugosidad de hamburguesas vegetales, la estabilidad de emulsiones y la calidad de quesos y embutidos con contenido reducido de grasa. Además, se destaca en la producción de películas y envases activos con propiedades antioxidantes y antimicrobianas, contribuyendo a la extensión de la vida útil. Así, la CB representa una alternativa sostenible y funcional para la innovación en alimentos y envases.

Palabras clave: Aplicaciones en Alimentos. Biomateriales. Consorcio Microbiano. Kombucha.

1 INTRODUCTION

Cellulose is an insoluble biopolymer and exopolysaccharide composed of repeating D-glucose units linked by β-1,4-glycosidic bonds, forming linear chains that assemble into highly ordered crystalline structures. Although it is widely recognized as the primary structural component of eukaryotic plant cell walls, cellulose is also synthesized by a broad range of organisms, including marine animals, protists, bacteria, algae, and fungi, as well as through cell-free enzymatic systems (Avcioglu et al. 2021). This widespread biosynthetic capability underscores its fundamental biological relevance and structural versatility.

Among the various forms of cellulose, bacterial cellulose (BC) has gained scientific and industrial attention. BC is an eco-friendly natural polymer biosynthesized by specific microorganisms and is increasingly recognized as a promising material for advanced technological applications due to its distinctive physicochemical and mechanical properties (Nguyen et al. 2021, Gao et al. 2023). Although it shares the same fundamental chemical structure as plant-derived cellulose, BC offers significant advantages in terms of purity, as it is inherently free from lignin, hemicellulose, and other plant-associated impurities. Consequently, it requires fewer purification steps, which simplifies processing and enhances its applicability in sensitive sectors such as food production (Ullah et al. 2019).

Beyond its intrinsic purity, BC exhibits remarkable structural versatility, high water-holding capacity, mechanical robustness, and excellent biocompatibility, attributes that collectively strengthen its potential as a sustainable and value-added biomaterial (Volova et al. 2022). These properties are particularly relevant in the food industry, where BC has emerged as a multifunctional ingredient capable of improving texture, stabilizing formulations, and modulating rheological behavior. Its nanofibrillar network structure provides exceptional water retention and gel-forming ability, which are critical for the formulation of structured and semi-solid foods (Płoska et al. 2023). As a result, BC can function as a thickener, stabilizer, fat replacer, and dietary fiber source, contributing to enhanced mouthfeel and structural integrity without significantly altering flavor or caloric content. Such characteristics enable the development of low-calorie and low-cholesterol products, supporting healthier food formulations aligned with current consumer demands (Oliveira et al. 2022, Płoska et al. 2023).

In addition to its direct incorporation into food matrices, BC demonstrates considerable potential in the development of innovative preservation and packaging strategies. Due to its compatibility with other polysaccharides and functional biopolymers, BC can be blended to improve mechanical strength and barrier performance, facilitating its use in edible films, coatings, and active packaging systems. These applications contribute to enhanced product stability by reducing moisture transfer, slowing oxidative and other chemical reactions, and limiting microbial growth, thereby extending shelf life (Dhakal et al. 2025).

Moreover, BC aligns with the growing demand for clean-label, sustainable, and health-oriented food systems (Mehta et al. 2024). As a biodegradable, non-toxic, and naturally derived polymer, it supports greener production processes and reduces reliance on synthetic additives. Its high purity minimizes the need for extensive chemical treatments, while its three-dimensional network can serve as a carrier matrix for bioactive compounds, probiotics, flavors, and micronutrients, enabling the development of functional foods with controlled release properties (Ullah et al. 2019). Collectively, these attributes position of bacterial cellulose as a strategic material for innovation in the food sector.

In this context, the present work aims to analyze the potential applications of bacterial cellulose in the food industry, emphasizing its functional, technological, nutritional, and preservation-related contributions for diverse food systems.

2 METHODOLOGY

A bibliographic search was conducted in internationally recognized academic databases, including Scopus, Web of Science, and Google Scholar. Combinations of English-language keywords were employed to ensure broad and targeted coverage of the topic, such as “bacterial cellulose fat replacer”, “kombucha food additive”, “bacterial cellulose for food preservation”, and “bacterial cellulose for food packaging”. The research encompassed studies published between 2010 and 2026, with emphasis placed on recent peer-reviewed articles that reflect current technological advances and emerging trends in the field. Scientific articles, review papers, and relevant book chapters were considered eligible for inclusion. Duplicate records, studies not directly related to food applications, and publications outside the defined scope were excluded.

Following the initial search, identified records underwent a screening process based on title and abstract evaluation to assess their relevance to the objectives of this review. Subsequently, the selected studies were analyzed in full to extract data concerning functional properties, processing strategies, application categories, and technological performance of bacterial cellulose in food systems. The collected information was organized and synthesized descriptively, allowing for a structured discussion of the main findings and research gaps, thereby providing a comprehensive overview of the current state of knowledge and future perspectives for the use of bacterial cellulose in the food industry.

3 RESULTS

3.1 SYNTHESIS OF BACTERIAL CELLULOSE

Bacterial cellulose (BC) is an extracellular exopolymer that constitutes the fundamental structural framework of β-(1→4)-linked D-glucan chains with the empirical formula $(C_6H_{10}O_5)_n$ (Esa et al., 2014; Costa et al., 2017; Betlej et al., 2020). These linear glucan chains are tightly associated through extensive intra- and intermolecular hydrogen bonding, which stabilizes the polymeric structure and promotes the formation of highly ordered crystalline domains (Esa et al., 2014).

The biosynthesis of BC begins with the assimilation of diverse carbon substrates including hexoses, glycerol, pyruvate, and dicarboxylic acids through central metabolic and gluconeogenic pathways, leading to the formation of uridine diphosphate glucose (UDP-glucose), the immediate precursor for cellulose polymerization. The elongation of β-(1→4)-glucan chains is catalyzed by membrane-bound cellulose synthase complexes. During synthesis, glucose chain protofibrils are secreted through nanoscale pores located on the bacterial cell envelope. Each bacterial cell contains approximately 50–80 pores, also referred to as terminal complexes (TCs), with diameters of around 3.5 nm, through which cellulose chains are extruded. Once outside the cell, individual glucan chains spontaneously aggregate into protofibrils, which further assemble into nanofibril ribbons (Esa et al., 2014; Costa et al., 2017).

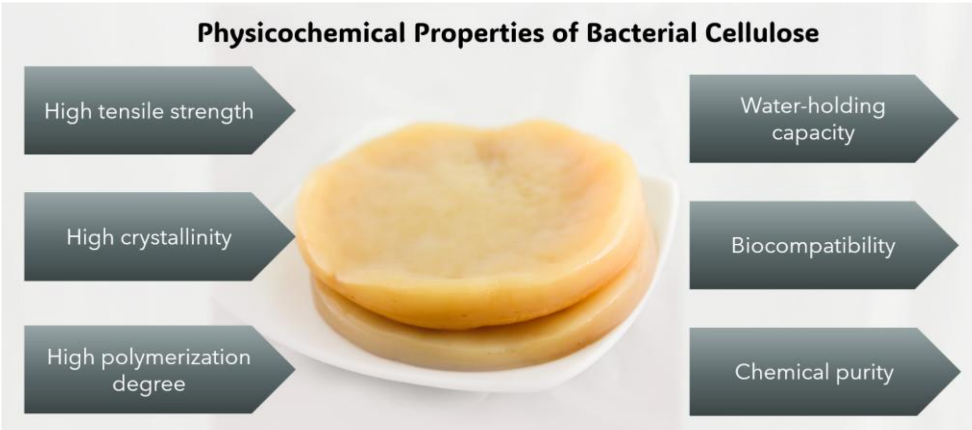
These nanofibril ribbons subsequently organize into thicker fibrillar structures, often termed macrofibrils, composed of roughly 1,000 aggregated glucan chains. The continuous deposition and entanglement of these fibrils generate a highly porous, three-dimensional (3D) interconnected network. This web-like architecture is responsible for the remarkable physicochemical characteristics of BC, including its ability to retain up to 200 times its dry mass in water, thereby conferring hydrogel-like behavior and exceptional hydration capacity.

Structurally, bacteria can produce two crystalline forms of cellulose: cellulose I and cellulose II. Cellulose I corresponds to the native, ribbon-like polymer composed of bundles of highly ordered microfibrils, whereas cellulose II is a thermodynamically more stable but relatively less ordered and more amorphous form (Villarreal-Soto et al., 2019). The spatial arrangement of these two allomorphs on the bacterial membrane differs, and the formation of cellulose II may be induced under specific physical or chemical conditions, such as increased aeration or the presence of additives like carboxymethylcellulose or calcofluor white (Laavanya et al., 2021). In static cultures, particularly those involving symbiotic consortia such as SCOBY, cellulose I predominates, which explains the superior tensile strength and structural integrity observed in BC films produced under these conditions.

Compared with plant-derived cellulose, BC microfibrils are approximately 100 times thinner, resulting in a much finer and less branched architecture (Costa et al., 2017). Moreover, unlike plant cellulose, BC is not associated with lignin or hemicelluloses, which contributes to its higher purity and crystallinity, typically ranging from 60% to 90% (Costa et al., 2017; Villarreal-Soto et al., 2019; Betlej et al., 2020). Its elevated degree of polymerization, enhanced biocompatibility, high specific surface area, and superior water absorption capacity collectively account for its improved wet mechanical strength and functional performance (Laavanya et al., 2021). Figure 1 showed the physicochemical properties of BC. These structural and compositional advantages distinguish BC as a unique form of cellulose with enhanced physicochemical properties and broad applicability across food, biomedical, and packaging sectors.

Figure 1

Physicochemical properties of bacterial cellulose



Over the past decade, the biosynthesis of bacterial cellulose (BC) has been extensively investigated using diverse microbial genera, including *Achromobacter*, *Agrobacterium*, *Acetobacter*, *Gluconacetobacter*, *Rhizobium*, *Sarcina*, and *Pseudomonas*, as well as through cell-free synthesis systems employing controlled enzymatic pathways (Nguyen et al. 2021). Despite its well-documented physicochemical advantages and growing commercial interest, large-scale BC production remains limited due to high production costs, the complexity of conventional culture media, and the requirement for specific additives (Petrosian 2022).

Moreover, achieving high productivity demands strict optimization of fermentation parameters, such as temperature, cultivation time, medium volume, and surface area available for oxygen transfer (Emiljanowicz & Malinowska-Pańczyk 2020). From an economic perspective, high yields are essential, as the use of costly media and specialized equipment becomes impractical when productivity is low.

Consequently, alternative strategies have been explored to reduce production costs while maintaining or enhancing BC yields. Among these, the use of kombucha has emerged as a promising approach. Kombucha is a fermented beverage produced by a symbiotic culture of bacteria and yeasts (SCOBY), comprising primarily acetic acid bacteria particularly *Komagataeibacter xylinus* alongside various yeast genera, such as *Zygosaccharomyces*, *Schizosaccharomyces*, and *Saccharomyces*.

During fermentation, this microbial consortium metabolizes sugars and tea substrates (commonly black tea), leading to the formation of a floating cellulose biofilm at the air–liquid interface. This biofilm, often referred to as “tea fungus,” “pellicle,” or kombucha-derived bacterial cellulose (KBC), consists of highly pure BC synthesized by acetic acid bacteria embedded within a dynamic microbial ecosystem (Nguyen et al., 2021; Ramírez Tapias et al., 2022).

The application of SCOBY for BC production offers several advantages, including reported yields of up to 9.5 mg/mL, reduced contamination risks, and comparatively low production costs. These attributes, combined with the structural integrity and intrinsic purity of the resulting cellulose membranes, position kombucha fermentation as a cost-effective and scalable platform for BC biosynthesis (Petrosian 2022).

3.2 FACTORS INFLUENCING BACTERIAL CELLULOSE PRODUCTION

Bacterial cellulose (BC) production is strongly influenced by interconnected biological, nutritional, and operational parameters that collectively determine both yield and material quality. According to Catarino et al. (2025), the efficiency and sustainability of BC biosynthesis depend primarily on three core components of the fermentation process: microorganism selection and maintenance, culture medium optimization, and cultivation method control. The selection of highly productive and genetically stable strains—particularly species within the *Komagataeibacter* genus—constitutes the foundation of efficient BC production. Strains capable of tolerating environmental stresses such as low pH, high ethanol concentration, or osmotic pressure tend to maintain metabolic stability and sustain higher cellulose yields. Proper inoculum preparation, strain preservation, and prevention of cellulose-negative mutants are also critical upstream factors that directly affect process consistency and industrial scalability (Catarino et al. 2025).

Equally important is the optimization of culture media and substrate composition. Carbon source type and concentration significantly influence cellulose biosynthesis, as they regulate central carbon metabolism and UDP-glucose availability. Sucrose is often preferred over glucose because glucose oxidation can lead to gluconic acid accumulation, which lowers pH and inhibits cellulose formation. Goh et al. (2012) demonstrated that sucrose at 90 g/L produced the highest BC yield (66.7%), whereas increasing sucrose concentrations beyond 110 g/L resulted in gradual yield reduction, likely due to osmotic stress and metabolic imbalance. Recent open-access studies further confirm the relevance of alternative and low-cost substrates—such as fruit processing residues, molasses, crude glycerol, and agro-industrial by-products—as sustainable carbon sources capable of reducing production costs while maintaining or even enhancing BC productivity (Jittaut et al. 2023, Catarino et al. 2025, Salari et al. 2019). Nitrogen source balance, mineral supplementation, and the carbon-to-nitrogen ratio also directly affect metabolic flux and polymerization efficiency. It was confirmed that medium supplementation with nitrogen and phosphorus sources would increase BC production (Gomes et al. 2013).

In kombucha-derived bacterial cellulose (KBC), substrate composition extends beyond sugar concentration to include the type of tea infusion used. Polyphenols, caffeine, and other bioactive compounds present in tea may stimulate acetic acid bacterial metabolism. Ramírez-Tapias et al. (2022), reported that green tea produced thicker and more structurally organized BC biofilms compared to black tea, suggesting enhanced fibrillar network formation and improved production efficiency. These findings reinforce that substrate composition not only affects yield but also influences microstructural organization and mechanical performance of the resulting films.

Environmental and operational parameters further modulate BC biosynthesis. Optimal pH values typically range from 2 to 4, conditions that suppress contaminant growth while supporting acetic acid bacterial activity. However, excessively acidic environments can inhibit cellulose synthase activity and reduce polymer formation. Temperature also plays a decisive role, with optimal production generally occurring between 20 and 30 °C; moderate temperatures favor metabolic stability and crystalline structure development. Fermentation time represents another critical factor. While BC pellicles can form within 7 days, optimal thickness (8–12 mm) is often achieved around 14 days under static conditions. Prolonged fermentation (beyond 28–56 days) may reduce yield due to nutrient depletion, carbon dioxide accumulation at the air–liquid interface, and the formation of anaerobic microenvironments that impair aerobic cellulose synthesis (Molina-Ramírez et al. 2017, Behera et al. 2022).

The mode of cultivation significantly affects both quantitative production and physicochemical properties of BC. Static fermentation promotes the formation of dense, highly crystalline cellulose I films at the air–liquid interface, resulting in superior mechanical strength and structural organization (Martins et al. 2020). In contrast, agitated or stirred cultures often produce irregular cellulose particles with lower crystallinity and reduced polymerization degree due to shear stress and increased mutation risk. Several recent open-access reports confirm that static or semi-continuous systems remain preferable for producing high-quality BC films intended for food and biomedical applications (Molina-Ramírez et al. 2017, Laavanya et al. 2021). Advances in controlled bioreactor design, oxygen transfer management, and surface-area optimization have been proposed to improve scalability without compromising structural integrity.

Collectively, current literature indicates that BC production is a multifactorial process governed by strain genetics, substrate selection, nutrient balance, physicochemical parameters, and cultivation strategy. Sustainable production approaches increasingly emphasize the integration of robust microbial strains, low-cost renewable substrates, and optimized static or semi-static fermentation systems. Such strategies are essential to enhance productivity, ensure material consistency, and improve the economic and environmental feasibility of industrial-scale bacterial cellulose production (Molina-Ramírez et al. 2017).

3.3 FOOD INDUSTRY APPLICATIONS

Bacterial cellulose (BC) is classified as "Generally Recognized as Safe" (GRAS) by the U.S. Food and Drug Administration (FDA), which has facilitated its incorporation into food products and food-contact materials (Zailani & Adnan 2022). Its non-toxicity, biodegradability, high purity, and absence of plant-derived contaminants such as lignin and hemicellulose make BC particularly suitable for food systems that demand clean-label, sustainable, and high-performance ingredients (Oliveira et al. 2021).

From a technological standpoint, BC exhibits a highly ordered nanofibrillar network with exceptional water-holding capacity, high crystallinity, and notable mechanical strength, especially in the hydrated state. Recent studies have employed advanced analytical techniques including X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), transmission and environmental scanning electron microscopy (TEM and ESEM), thermogravimetric analysis (TGA), UV–Vis spectroscopy, water vapor permeability (WVP) testing, and mechanical tensile analysis to comprehensively characterize BC derived from kombucha and other fermentation systems (El-Shall et al. 2023, Nguyen et al. 2021). These studies confirm that BC films display favorable barrier, thermal, and mechanical properties, which are essential for food formulation and packaging applications.

However, it has been reported that purified BC membranes may exhibit limited flexibility and brittleness after drying. To overcome this limitation, plasticizers and biopolymer blends such as glycerol, chitosan, alginate, or starch have been incorporated into the BC network (Liu et al. 2024). Such modifications significantly improve elasticity, tensile strength, and overall structural integrity while preserving high water retention capacity, resulting in hydrogel-like materials suitable for food-related applications (Laavanya et al., 2021). These tailored BC-based composites expand the functional range of BC in food matrices and edible films.

Traditionally, BC has been consumed as nata de coco, a fibrous dessert widely produced and consumed in Southeast Asia. In this process, BC is synthesized under static fermentation using coconut water as a carbon source, typically by *Komagataeibacter xylinus*. The resulting thick cellulose pellicle is purified, cut, and cooked in sugar syrup, yielding a low-calorie, high-fiber product commonly used in desserts, fruit cocktails, and jellies (Esa et al. 2014). This long-standing food application highlights the safety, digestibility, and consumer acceptance of BC.

Beyond traditional uses, BC has emerged as a multifunctional ingredient and functional additive in modern food systems. Recent studies have demonstrated its effectiveness as a fat replacer in ice cream, cheese analogues, and emulsified meat products, where it contributes to creaminess and mouthfeel without increasing lipid content (Płoska et al., 2023; Molina-Ramírez et al., 2023). Table 1 showed some examples of the application of BC in food industry.

Table 1

Applications of bacterial cellulose in Food Industry

Food	Results	Authors
Ice cream	Low calorie, melting resistance, and good textural properties in ice cream	(Guo et al. 2018)
Ice cream	Pickering emulsion gels with different oil phase fractions stabilized by Bacterial cellulose nanofibers/Soy protein isolate complex colloidal particles showed the appearance and texture like control.	(Gao et al. 2023)
Plant-based hamburger	Redder color, better dimensional stability, lower cooking loss, and higher chewiness of hamburgers.	(Lee & Han 2024b)
Meat sausages	Bacterial nanocellulose increased water-binding properties, hardness, cohesiveness, and chewiness	(Marchetti et al. 2017)
Nile tilapia Sausages	No effect on hardness or gumminess. Effect on cohesiveness, adhesiveness and luminosity	(Oliveira et al. 2022)
Low-fat soft cheese Turkish Beyaz	BC decreased hardness and improved sensory properties in comparison with reduced-fat cheeses.	(Karahan et al. 2011)

In plant-based meat analogues, BC paste has demonstrated promising technological performance. Lee and Han (2024a, 2024b) reported that partial replacement of fat with BC paste in plant-based hamburger patties increased water retention, reduced cooking loss, improved cohesiveness and elasticity, and enhanced dimensional stability without compromising sensory acceptance. The three-dimensional fibrillar network of BC contributed to stabilizing the plant-protein matrix, thereby improving juiciness and texture in reduced-fat formulations.

Similarly, Mehta et al. (2024) investigated BC infusion in ice cream and reported improvements in viscosity, structural stability, and tribological performance. The incorporation of BC reduced friction coefficients under simulated oral conditions, contributing to enhanced creaminess perception. Temporal sensory analysis further indicated prolonged creaminess and reduced perception of iciness, supporting the application of BC as a structuring and sensory-modulating agent in frozen desserts.

BC has also been applied in sausages and restructured meat products, where it improves water-binding capacity, hardness, cohesiveness, and chewiness (Marchetti et al., 2017). In Nile tilapia sausages, BC influenced cohesiveness, adhesiveness, and luminosity without adversely affecting hardness or gumminess (Oliveira et al., 2022). In low-fat Turkish Beyaz cheese, BC reduced hardness and improved sensory properties compared with conventional reduced-fat formulations (Karahan et al., 2011). Collectively, these studies highlight the versatility of BC as a texturizing agent, stabilizer, and dietary fiber enrichment ingredient in both animal-based and plant-based products.

In addition to its direct incorporation into food matrices, BC has demonstrated strong potential in food packaging applications. Its dense nanofibrillar structure provides excellent mechanical resistance and barrier performance, while its biodegradability and renewability align with the growing demand for sustainable packaging materials. BC-based films and coatings—used alone or in combination with antimicrobial agents, antioxidants, or other biopolymers—have been proposed as active packaging systems capable of extending shelf life and enhancing food safety (Esa et al., 2014; Dhakal et al., 2025).

For instance, Ashrafi et al. (2017) developed active chitosan-based biocomposite films incorporating 1–3% (w/w) kombucha tea for food packaging applications. The addition of kombucha significantly enhanced antioxidant activity, reaching approximately 59% radical scavenging capacity (DPPH assay), and reduced water vapor permeability by nearly 48% compared with the control chitosan film. Moreover, the films exhibited antimicrobial activity against *Escherichia coli* and *Staphylococcus aureus*. When applied to minced meat stored for four days, the kombucha-containing films reduced microbial counts from approximately 5.36 log $CFU \cdot g^{-1}$ (control) to 2.11 log $CFU \cdot g^{-1}$, extending shelf life by about three days. FTIR analysis confirmed chemical interactions between chitosan functional groups and kombucha phenolic compounds, explaining the observed improvements in structural and functional properties.

4 FUTURE PERSPECTIVES AND RESEARCH CHALLENGES

Despite its promising properties, several challenges must be addressed to support large-scale industrial adoption of BC in the food sector. These include the standardization of microbial consortia, reduction of production costs, optimization of oxygen transfer in large-scale fermentation systems, improvement of mechanical flexibility in dried materials, and development of circular fermentation models using agro-industrial by-products. Furthermore, omics-based approaches may provide deeper insights into microbial interactions within SCOBY systems, enabling the design of engineered consortia with enhanced productivity and tailored functional properties.

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