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Bacterial Cellulose Production from Agro-Industrial Waste for Food-Grade Edible Coating: A Systematic Review

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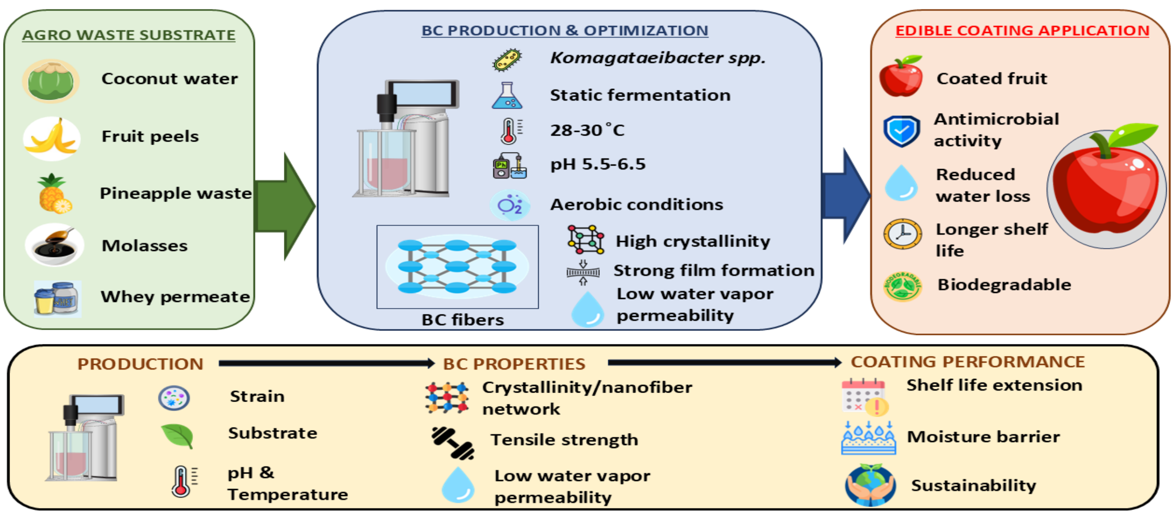
Abstract

Food losses after harvesting amounting to 1.3 billion tonnes each year pose a threat to achieving the United Nations Sustainable Development Goals, including SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 9 (Industry, Innovation and Infrastructure). Bacterial cellulose (BC) is a purified and crystallized extracellular polysaccharide with excellent mechanical properties and barrier behavior applicable as a food coating. Despite these benefits, wider application of BC in the food industry remains limited due to high production costs in Hestrin-Schramm medium cultivation technology. This paper addresses a research gap in the bibliography on BC production optimization for edible coating development, focusing not only on production yield but on other relevant aspects. Bibliometric analysis based on the Scopus database of indexed papers from 2014 to 2026 using the Bibliometrix R-package was performed. Through narrative synthesis based on a novel production-property-performance (PPP) framework, this research proves that fermentation conditions during the initial phase of BC production play a key role in determining coating-related properties such as crystallinity index, moisture permeation rate, and film-forming ability. Ideal fermentation conditions include *Komagataeibacter* bacteria, stationary culture, fruit-derived waste material, a temperature of 28–30°C, pH 5.5–6.5, yielding crystallinity indices of 70–90%.

Graphical Abstract



1.Introduction

The post-harvest loss is among the biggest problems of modern-day food security, with FAO stating that about a third of the food produced globally for consumption or around 1.3 billion tonnes per year is lost or wasted (Gustavsson *et al*., 2011). Fruits and vegetable losses after harvesting are especially high in developing nations, usually between 25% and 50%, owing to inadequate storage and absence of cold chain logistics (Bancal & Ray, 2022).Consumer preferences for natural preservative techniques coupled with strict regulation, such as the European Union Packaging and Packaging Waste Regulation (PPWR) requiring biodegradable packaging by 2030, has led to increased attention towards eco-friendly, edible coatings made using bio-based feedstocks (European Commission, 2022: Hassan *et al*., 2018).

Bacterial cellulose (BC) has become an especially attractive option amongst the wide variety of biopolymer systems that have been studied for their potential use in food coatings due to the outstanding properties associated with BC. BC is an extracellular polysaccharide, produced by bacteria from multiple genera, including the *Komagataeibacter* (previously known as *Gluconacetobacter*) group. In contrast to the cellulose obtained from plants, BC is synthesized in a state of chemical purity with no lignin, hemicellulose, or pectin present, thereby producing a highly crystalline material, excellent water retention capabilities and unique three-dimensional structure of nanofibrils (Absharina *et al*., 2025; Sozcu *et al*., 2025; Turganova *et al*., 2025).

However, despite all its exceptional properties, the mass uptake of BC in food applications, especially its use as an edible coating, was hindered by a very basic economic problem: the very high price associated with BC media used for traditional production techniques. In fact, the HS medium, which is considered a basis for fermentation cultures in BC production, uses pure glucose and peptone that amount to 30% of the overall cost and provide BC yields in amounts below 20 g/L of the medium under static conditions (Catarino *et al*., 2025). Thus, many studies have been conducted regarding new sources of cheap culture substrates made of agricultural wastes.

In this regard, a considerable number of studies have been conducted that demonstrate the successful production of BC from various agro-industrial waste sources like coconut water, sugarcane bagasse hydrolysate, fruit peels, corn steep liquor, cheese whey, and rice washing water. Meanwhile, considerable improvement in the efficiency of producing BC can be attributed to progress in areas such as the selection of microbial strains, genetic manipulation of microorganisms, and optimization of fermentation process parameters using statistical approaches like response surface methodology (RSM) and Box-Behnken design (El-Gendi *et al*., 2022). Yet there is one important omission in the literature; all the available studies analyzing the optimization of BC production focus exclusively on the efficiency of process and do not consider an important aspect – the suitability of BC for producing edible coatings.

In this sense, this review paper tries to bridge the research gap by applying the food-grade perspective while examining the scientific literature related to BC production and optimization. This paper examines the scientific literature related to BC production and optimization not only in terms of yield (g/L), which is a conventional measure, but also considering those characteristics that make BC ideal as an edible coating agent. These characteristics include crystallinity index, water vapor permeability, tensile strength, water holding capacity, and film-forming property.

2. Methodology

2.1 Bibliometric Analysis Framework

This review adopts a dual-track methodology, combining a systematic bibliometric analysis of the global scientific landscape with a structured narrative synthesis of primary research findings. The bibliometric component was performed using the Bibliometrix R-package (R version 4.5.1) and its companion web application Biblioshiny, which provide an integrated suite of tools for scientometric mapping, thematic clustering, and co-occurrence network visualization (Aria & Cuccurullo, 2017).

Peer-reviewed literature was retrieved exclusively from the Scopus database using two independent Boolean search strings applied to Title, Abstract, and Keywords (TITLE-ABS-KEY) fields. Two separate strings were designed to capture the two distinct research dimensions of this review: (i) BC production and substrate optimization, and (ii) BC applications in edible coatings and food preservation.

Search String 1: BC Production & Substrate Optimization:

TITLE-ABS-KEY ("bacterial cellulose") AND TITLE-ABS-KEY ("production" OR "biosynthesis" OR "yield") AND TITLE-ABS-KEY ("waste" OR "low-cost" OR "substrate")

Search String 2: BC in Edible Coatings & Postharvest Applications:

TITLE-ABS-KEY ("bacterial cellulose") AND TITLE-ABS-KEY ("edible coating" OR "food packaging" OR "postharvest" OR "shelf life" OR "fruit" OR "coating" OR "biopolymer film")

Results for both sets were obtained individually before being combined, and duplicates eliminated, resulting in one combined corpus. The literature search involved documents published between the years 2014 and 2026, and the combined dataset was refined to contain only original research papers and reviews in the English language. Conference papers, editorials, book chapters, and documents in languages other than English were excluded from the final refined set, which then served as the data source for all bibliometric analyses shown here.

2.2 Annual Scientific Production and Growth Trend

The yearly output of scientific publications was shown as the annual number of indexed papers (2014-2026) to examine the temporal dynamics of the scientific field (*Figure 1*). The scientific field displayed an obvious growth tendency, rising from around 75 papers in 2014 to a maximum of around 255 papers in 2024, with a rise of about 3.4 times in the last decade. This tendency demonstrates the integration of rising concern about sustainable food packaging, biodegradable products according to EU legislation (PPWR 2030), and developments in affordable BC fermentation from agricultural waste streams. A slight decrease in 2025-2026 was expected due to bibliometric indexing delays at the end of the period (*Figure 2*).

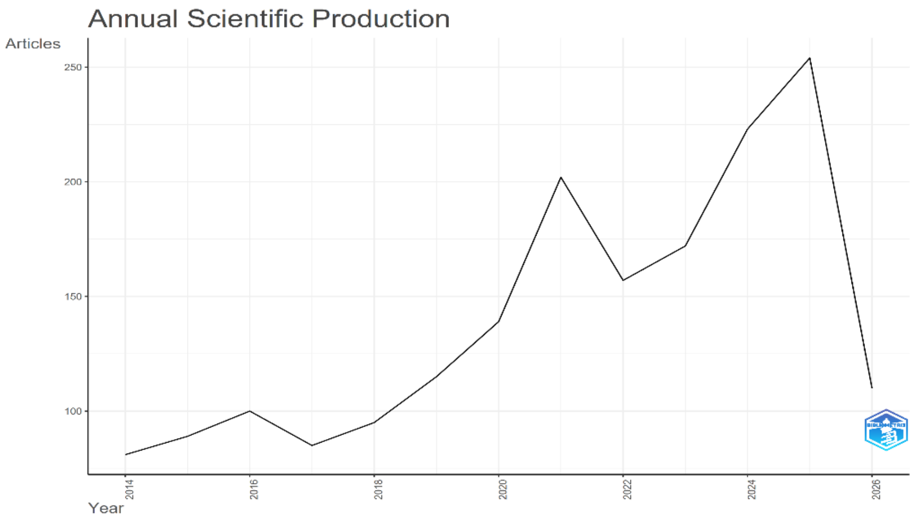


Figure 1: *Annual Scientific Production in bacterial cellulose research related to edible coatings and food applications (2014–2026). Data retrieved from Scopus using two targeted search strings (String 1: production/substrate; String 2: coating/postharvest applications); visualization generated using Biblioshiny (Bibliometrix R-package).*

2.3 Thematic Mapping

Thematic clusters were identified using the co-word analysis module in Biblioshiny, which applies the (Callon *et al*., 1991) methodology of mapping themes by their centrality (Relevance degree) and density (Development degree) onto a two-dimensional strategic diagram (*Figure 2*). This partitions the research landscape into four thematic quadrants as summarized in *Table 1*.

Table 1: Thematic quadrant classification from co-word analysis of the BC literature corpus (2014–2026). Quadrant definitions follow Callon et al. (1991). Theme labels extracted from Biblioshiny output (Figure 2).

Quadrant	**Characteristics**	**Identified Themes**	**Implication for This Review**
Motor Themes (High centrality, high density)	Well-developed, central to the field	nonhuman, article, metabolism	Core research focus; most studied aspects of BC biology and production

Niche Themes (Low centrality, high density)	Specialized; internally developed but not mainstream	—	Emerging sub-disciplines requiring targeted synthesis
Emerging/Transversal Themes (High centrality, low density)	Cross-cutting but underdeveloped	bacteria, bacterium, biomass	Transition zone — substrate & organism optimization studies
Declining Themes (Low centrality, low density)	Marginal; losing research momentum	cellulose, chemistry, bacterial-cellulose	Foundational topics now considered established; reviewed briefly in Section 3

The thematic mapping revealed that while metabolism and BC biology (motor themes) remain the dominant and well-consolidated research axes, topics directly relating BC to food packaging and edible coating performance remain underrepresented in the high-centrality zones. This confirms the principal research gap addressed by the present review: the need to systematically connect BC production optimization with food-grade coating functionality.

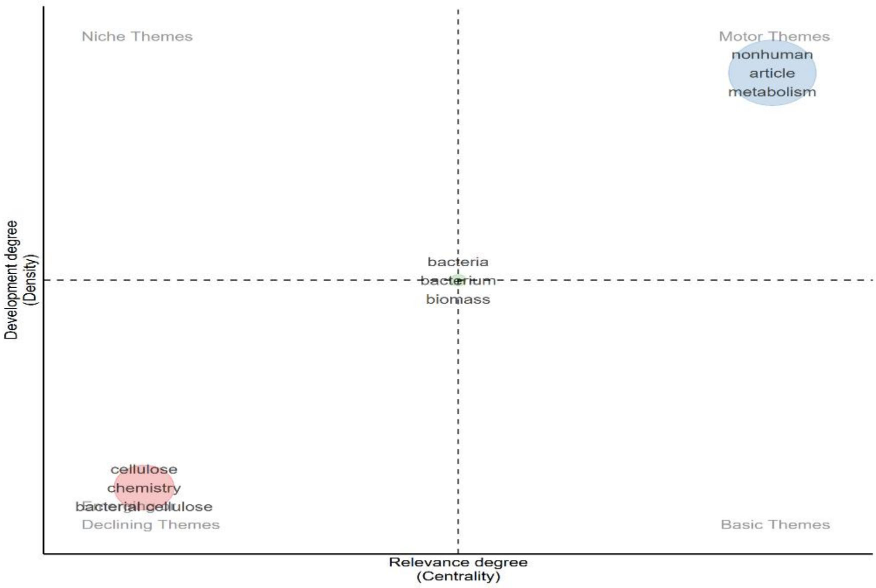


***Figure 2**: Strategic thematic map of bacterial cellulose research (2014–2026), showing distribution of research themes by centrality (x-axis) and density (y-axis). Generated using Biblioshiny co-word analysis module.*

2.4 Keyword Co-occurrence Network Analysis

A keyword co-occurrence network was also constructed based on author's keywords (*Figure 3*). The keywords were treated as nodes, with their size being proportional to their occurrence frequency and with edge width denoting strength of co-occurrence. Network clustering was done using the community detection algorithm (Louvain), where different network thematic clusters were delineated based on the color scheme displayed (*Figure 3*). Network analysis showed the presence of a main core network centered on bacterial cellulose, *Komagataeibacter xylinus*, fermentation, crystallinity, and nanofibers, thus validating the conclusion regarding high popularity of research focused on the production-structure axis. Other network clusters identified included:

- Substrate & waste valorization cluster (orange/yellow nodes): coconut water, agro-waste, sugarcane, fruit waste, media optimization
- Coating application cluster (blue nodes): chitosan, alginate, edible coating, postharvest, shelf life, fruit preservation
- Characterization & properties cluster (green nodes): XRD, FTIR, tensile strength, water vapor permeability, film-forming
- Food safety & regulatory cluster (purple nodes): GRAS, food-grade, purification, endotoxin

It is worth mentioning that relatively few connections were noted between the coating application cluster and the production optimization cluster, thus reiterating the gap identified during bibliometric analysis and addressed herein.

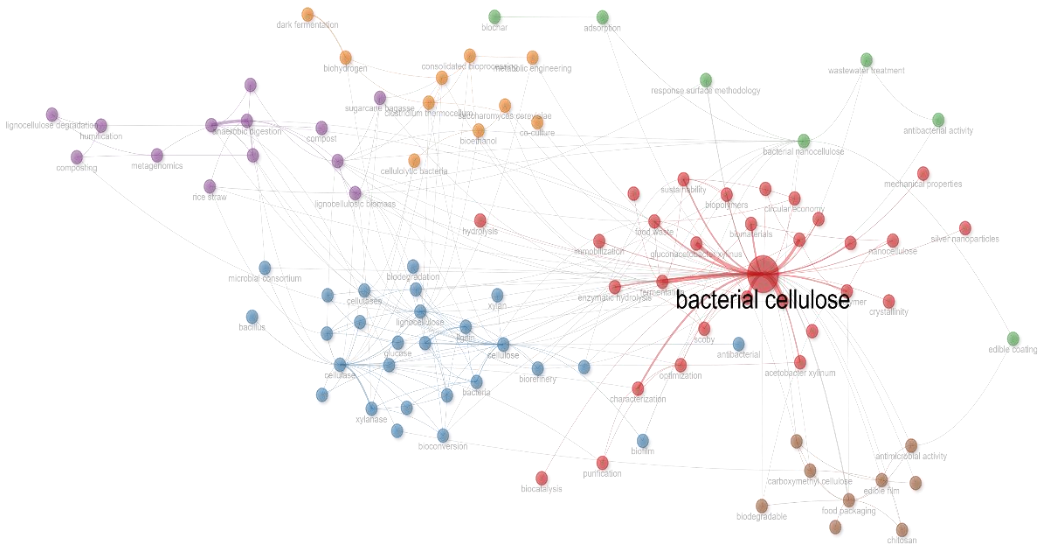


***Figure 3**: Keyword co-occurrence network of bacterial cellulose research literature (2014–2026). Node size ∝ keyword frequency; edge thickness ∝ co-occurrence strength. Color-coded clusters identified via Louvain community detection. Generated using Biblioshiny.*

2.5 Literature Selection Criteria for Narrative Synthesis

Following the bibliometric analysis, articles were screened for inclusion in the narrative review using the following PICO-adapted criteria:

Table 2: Inclusion and exclusion criteria applied to the literature corpus for narrative synthesis in this review.

Criterion	Inclusion	Exclusion
Subject	BC production, optimization, characterization, edible coating application	Plant/nano-cellulose not from bacterial origin
Organism	*Komagataeibacter* spp. and GRAS-recognized BC producers	Non-food-safe organisms (e.g., *A. tumefaciens*) unless explicitly contrasted
Substrate	Defined media (HS), agro-industrial waste substrates	Studies using undefined or proprietary media with no composition disclosure
Outcome	BC yield (g/L), crystallinity index (CI%), WVP, tensile strength, postharvest efficacy	Studies reporting weight alone without food-grade quality parameters
Publication type	Original articles, review articles, 2014–2026	Conference abstracts, book chapters, grey literature
Language	English	Non-English publications

The data collected from the selected studies were tabulated based on the following dimensions: (i) microbe strain and food safety; (ii) substrate used and its pre-treatment; (iii) fermentation parameters and optimization techniques; (iv) bacterial cellulose characteristics and yield; and (v) results from the coating process when applicable. The information thus collected was used to prepare the comparative tables shown in sections 3-8 of this review paper.

2.6 Conceptual Framework

This review follows a production-property-performance (PPP) approach (*Figure 3* in Section 7.1), under which production factors such as strain, substrate, and process optimization are seen as key factors influencing BC properties. Properties, in turn, define the performance of BC films as edible coating materials used in post-harvest products. The PPP framework makes this review different from other reviews where production optimization and film application have been treated separately.

All bibliometric analysis was performed using R v4.3+ and Bibliometrix ; network analysis was carried out using Biblioshiny. Experimental data used for statistical optimization were obtained from literature and analyzed by table synthesis. No new experimental data was generated.

3.BC-Producing Microorganisms: Strain Selection and Food Safety

3.1 Taxonomy and diversity of BC producers

The production of BC occurs among an array of different bacteria belonging to either Gram-positive or Gram-negative categories. In Gram-negative bacteria, the family *Acetobacteraceae*, which includes the genus *Komagataeibacter* (previously *Gluconacetobacter*), is known to be one of the most proficient groups for BC formation. Among these bacteria, *K. xylinus* (previously *Gluconacetobacter xylinus*, or *Acetobacter xylinum*) has been determined to be a model organism for BC studies. Other notable members of the *Komagataeibacter* genus include *K. sucrofermentans*, *K. hansenii, K. medellinensis,* and *K. rhaeticus* (Huang *et al*., 2016)

Apart from *Komagataeibacter*, other BC producers include *Agrobacterium tumefaciens*, *Sarcina ventriculi* (Gram-positive), *Rhizobium leguminosarum*, *Pseudomonas putida*, and lately, non-traditional BC producers such as some species of *Bacillus* and genetically modified *E. coli* (Al-Janabi *et al*., 2022; Almihyawi *et al*., 2024; Bektas & Yildirim, 2025; Potočnik *et al*., 2023). Nevertheless, considering the potential application of BCs in foods, one should look at the variety of BC producers through the lens of food safety, which is whether the producer has GRAS (Generally Recognized As Safe) designation by the United States Food and Drug Administration (US FDA) or is food contact approved by EFSA or FSSAI (Gama *et al*., 2021; Kumar *et al*., 2024).

3.2 Food-safe strain selection — GRAS considerations

The safety aspect of the producing organism in BC production is another vital consideration that is often ignored in scientific literature (Girard *et al*., 2024; Kumar *et al*., 2024). In cases where the BC will be used for edible coating purposes, it is important to consider whether the producing organism is GRAS-listed or characterized enough to guarantee the absence of toxins and other dangerous by-products from the process. The strains *K. xylinus* and *K. sucrofermentans* are the best-characterized strains for food-grade use, owing to a well-known metabolic pathway in which acetic acid fermentation byproducts are GRAS-listed (Gama *et al*., 2021; Santos *et al*., 2024). A comparative overview of major BC producing strains is provided in *Table 3*.

Food-safe BC obtained from Kombucha SCOBY is one such candidate, since the production culture has a long history of use as a fermented food product and hence is known to be safe. BC produced through Kombucha fermentation has been found to exhibit qualities similar to those of BC isolated in the laboratory using HS medium, the additional benefit being that the BC originates from an accepted food-fermentation process (Moreno-Díaz *et al*., 2024).

Table 3: Comparative overview of major BC-producing strains with food safety status and production characteristics

Strain	Family	Food safety status	BC yield (g/L)	Preferred substrate	References	Notes
Komagataeibacter xylinus	*Acetobacteraceae*	GRAS / food-grade	4–18	Glucose, sucrose, agro-waste hydrolysates	Peng *et al.*, 2024; Sumini *et al.*, 2025	Most studied BC producer
K. sucrofermentans	*Acetobacteraceae*	GRAS / food-grade	6–22	Fructose, glucose, fruit juices, raisin extract	Adamopoulou *et al.*, 2024; Liu *et al.*, 2025	High yield up to ~19 g/L
K. hansenii	*Acetobacteraceae*	Food-associated	3–12	Glucose, glycerol, ethanol	Chaussé *et al.*, 2024; Khiabani *et al.*, 2024	Common in SCOBY
K. rhaeticus	*Acetobacteraceae*	Food-associated	5–14	Sucrose, whey, brewing waste	Tsouko *et al.*, 2024; Uğurel & Öğüt, 2024	Good agro-waste utilisation
Levillactobacillus brevis DSS.01	*Lactobacillaceae*	GRAS	1.56	Pear pomace + rice bran	Mongkolchat *et al.*, 2026	Novel LAB BC producer
Kombucha SCOBY consortium	Mixed	GRAS	3–9	Tea, sugar, fruit waste	Cubas *et al.*, 2023; Khiabani *et al.*, 2024	Mixed microbial system
Agrobacterium tumefaciens	*Rhizobiaceae*	Not food-safe	3–8	Glucose, sucrose	Kumar *et al.*, 2024; Potočnik *et al.*, 2023	Plant pathogen
Komagataeibacter intermedius	*Acetobacteraceae*	Food-associated	5–15	Tea extracts, plant substrates	Avcioglu, 2024b, 2024a	~14.5 g/L on green tea

Komagataeibacter europaeus KFET1	*Acetobacteraceae*	Food-associated	15–21	Rice bran hydrolysate	Xu *et al*., 2025	~20.7 g/L at scale
Novacetimonas hansenii	*Acetobacteraceae*	Food-associated	1.5–3.2	Pomegranate waste, rice straw	Saleh *et al*., 2025; Sathianathan *et al*., 2025	High crystallinity BC
Gluconacetobacter xylinus LYP25	*Acetobacteraceae*	Food-associated	10–17	Chestnut pericarp hydrolysate	Lee *et al*., 2024	Improved mutant strain
Bacillus spp. (B. siamensis, B. subtilis)	*Bacillaceae*	GRAS (strain dependent)	2–3	Glucose, sucrose	Bektas & Yildirim, 2025	Non-traditional BC producers
Achromobacter S3	*Alcaligenaceae*	Not established	0.52–1.22	Mango peel hydrolysate	Hasanin *et al*., 2023	Novel isolate

3.3 Strain improvement strategies

Natural strains that produce BC generally suffer from low efficiency, instability (spontaneous inability of synthesizing cellulose in non-cellulose mutant strains), and a narrow substrate range. Various methods for strain optimization have been tested to enhance production efficiency. Classical approaches based on physical or chemical agents (UV radiation, ethyl methane sulfonate, nitrosoguanidine) led to the generation of BC super-producer mutants of *K. xylinus* (Potočnik *et al*., 2023).

Most recently, metabolic engineering and synthetic biological strategies have facilitated the fine-tuning of the BC production pathway. In the *Komagataeibacter* genus, the operon for BC synthesis is composed of four primary genes – bcsA, bcsB, bcsC, and bcsD – coding for the cellulose synthase complex and regulating genes like bglAx and bcsI. The upregulation of bcsA and bcsB, coding for the catalytic and regulatory units of the cellulose synthase complex, has been shown to lead to a considerable improvement in BC production (Belkozhayev *et al*., 2025). Another strategy that involves blocking competing pathways, especially those involving the metabolism of glucose to gluconic acid and acetan, has been found to increase BC yield by up to 40% (Cruz *et al*., 2024)

4. Agro-Industrial Waste as Low-Cost Substrates

4.1 Rationale for agro-waste valorization

The economic feasibility of producing BC is highly dependent on the cost of media used during fermentation processes. The cost of preparation of standard HS medium (glucose – 2%, yeast extract – 0.5%, peptone – 0.5%, Na_2HPO_4 – 0.27%, citric acid – 0.115%) in laboratory settings amounts to about USD 8-15 per litre (Chen *et al*., 2013; Kamal *et al*., 2022). The current expenses associated with the generation of bacterial cellulose via the traditional HS medium continue to pose a serious impediment towards commercialising its production. The techno-economic evaluation of the BC production process has indicated costs in the range of about USD 63.83 per kg for conventional fermentation conditions, whereas pure bacterial cellulose sells at up to USD 120 per kg on the biotech market – levels well above those which would make BC economically viable for use in food packaging (Behera *et al*., 2022; Kamal *et al*., 2022)On the other hand, substituting HS medium with agro-industrial waste biomass as fermentation feedstock offers a promising strategy with threefold advantages: lowering the costs of medium by as much as 90% (Henry *et al*., 2024) ,reusing waste products, and embracing the concept of bio-based circular economy (Belkozhayev *et al*., 2025; Khan *et al*., 2023).

4.2 Carbon sources from agro-waste

Criteria that guide the choice of an appropriate carbon source include its sucrose content and bioavailability, non-inhibition to fermentation, most importantly, lack of contamination from heavy metals, pesticides, and mycotoxins which may affect safety in BC products meant for use in foods. Fruit-derived wastes have proven to have the greatest potential in producing BC (Belkozhayev *et al*., 2025; El-Gendi *et al*., 2022a; Khan *et al*., 2023)

The use of coconut water obtained as a waste product from coconut-processing industries constitutes, perhaps, the most researched agro-waste medium for producing BC. The intrinsic nature of coconut water, which is rich in glucose (3.5 – 5.5 %), fructose (2.8 – 4.0 %), sucrose, vitamins, and minerals, makes it close to a perfect fermenting medium, necessitating little or no additional ingredients. BC grown on coconut water media has been found to have crystallization indices and tensile strengths that are similar to those of HS medium grown BC (Fei *et al*., 2024; Lin *et al*., 2022; Thongsuk *et al*., 2025).

Sugarcane bagasse and sugarcane molasses are significant volumes of agricultural wastes resulting from sugarcane sugar and ethanol industries. Following appropriate pretreatment through dilute acid hydrolysis or enzyme saccharification to liberate fermentable sugars from cellulosic biomass, sugarcane hydrolysates have shown production rates of biocontrol agents ranging from 4.2 to 8.7 g/L under optimal static culture conditions (Akintunde *et al*., 2022; Belkozhayev *et al*., 2025). Nevertheless, the presence of fermentation inhibitors such as furfural, HMF, and phenolics in hydrolysates from acid-treated sugarcane bagasse necessitates additional measures for detoxification (Candido *et al*., 2020; X. Lin *et al*., 2022). The major agro-industrial waste substrates evaluated for BC production are classified in *Table 4*.

Table 4: *Classification of major agro-industrial waste substrate categories for bacterial cellulose production, with reported BC yield ranges, crystallinity indices, and relative food safety assessments. Fruit-derived substrates are identified as most suitable for food-grade edible coating applications.*

Category	Substrate	Yield (g/L)	Crystallinity Index (%)	Key Advantages	Limitations	References
Fruit-derived	Coconut water (pre-fermented)	~3–4	64.8–69.4	Rich in simple sugars; enhances yield vs control	Composition variability	X. Lin *et al.*, 2022
	Pineapple waste	3.24	NR	Low-cost agro-waste	Lack of CI data	Mardawati *et al.*, 2023
	Fruits and vegetable wastes	4.09	~70–79	Good yield from fruit waste	Requires preprocessing	Zhao *et al.*, 2025
	Confectionery waste	5.7	77.9	High sugar → improved yield	Industrial variability	Efthymiou *et al.*, 2022
Cereal/Crop waste	Sugarcane bagasse (acid hydrolysate)	2.13	66.5	Abundant, low-cost	Requires pretreatment	Cheng *et al.*, 2016)
	Sugarcane bagasse (ACP treated)	1.68–1.88	NR	Improved sugar release	Lower yield	S.-P. Lin *et al.*, 2022b
	Sugarcane bagasse (enzymatic)	0.9–1.6	NR	Eco-friendly method	Lowest yield	Akintunde *et al.*, 2022
	Molasses + CSL	8.2	26-58	Industrial by-product utilization	Variable composition	Heydorn *et al.*, 2023
	Corn steep liquor (CSL)	~HS equivalent	High	Cost-effective nitrogen source	Needs supplementation	Costa *et al.*, 2017
Dairy/Food waste	Cheese whey permeate + β-galactosidase	6.77	82*	Highest yield; rich nutrients	Enzyme requirement	Rollini *et al.*, 2020
	Hydrolysed whey + CSL	6.97	71.1–85.9	Enhanced yield with nitrogen	Process complexity	Kolesovs *et al.*, 2024

	Cheese whey + side stream	Variable	Moderate	Industrial integration	Yield inconsistency	Lappa *et al*., 2021
Fermented beverages	Kombucha SCOBY (optimized)	2.94	59.89	Produces purified BC	Lower yield	Cubas *et al*., 2023
	Kombucha green tea (30 d)	6.5% (w/v)	90–95	Very high crystallinity	Long fermentation time	Charoenrak *et al*., 2023
	Kombucha food waste	~4.5	NR	Waste valorization	Limited data	Moreno-Díaz *et al*., 2024

4.3 Nitrogen sources and media supplementation

Although the presence of the carbon source determines the level of BC produced, the choice of nitrogen sources becomes very critical in determining the growth kinetics of bacteria and quality of BC produced. The traditional sources of nitrogen in HS medium (yeast extract and peptone) may be completely or partially replaced with agro-industrial sources of nitrogen, such as corn steep liquor, soy hydrolysate, rice bran extract, and spent brewery yeast. Corn steep liquor, being a waste product of wet corn milling, is especially suitable because it not only offers nitrogen, but also other vitamins required by *Komagataeibacter* to make cellulose (Absharina *et al*., 2025; Betlej *et al*., 2021).

5. Fermentors and Fermentation Parameter Optimization

5.1 Bioreactors and Fermenters for Bacterial Cellulose Production

Selection of a fermentation system constitutes a key determinant that will not only impact the quantity of BC produced but also the morphological, crystalline, and mechanical characteristics of the end product. As the standard fermentation approach for the synthesis of BC for food applications at laboratory scale, static tray fermentation continues to be the benchmark technique despite the limitations associated with oxygen transfer and scalability in static fermentation. Designing such fermentation approaches will require consideration of oxygen needs, shear effects on cellulose synthase complexes, maintenance of air-liquid interfaces, and applicability in fermentation with agro-industrial substrates (Cáceres *et al*., 2025; Cruz *et al*., 2024).

5.1.1 Stirred Tank Reactors (STRs)

STRs have become the most frequently used industrial fermenters for submerged fermentation due to their proven engineering principles, capacity for scale-up, and maintenance of homogeneity in conditions. In the case of BC production using STRs, better oxygen transfer occurs when compared with static systems, resulting in faster rates of bacterial growth. Nevertheless, the process of mechanical stirring causes shear stress, and therefore, BC does not develop a pellicle but produces irregular fibrous pellets/aggregates. The resulting change in BC morphological properties leads to a reduction in its crystallinity index from a 70-90% level characteristic of static culture to 45-65%. This is unacceptable in terms of using BC as an edible coating because the material must possess higher barrier properties (Buldum & Mantalaris, 2021; Singhania *et al*., 2022). Moreover, long-term use of STRs results in the selection of spontaneous acallulose mutants, which prevent BC production in further cultivations (Lee *et al*., 2024).Nonetheless, STRs should be considered a preferable method for producing BC for nanofiber/nanocrystals.

5.1.2 Airlift Bioreactors (ALBs)

The airlift type bioreactors ensure oxygenation via delivery of air/oxygen-rich gas into the fermentor from its bottom resulting in creation of circulatory flow with no need in mechanical stirring. The system minimizes shear stress to the bacteria significantly compared to STR systems while ensuring effective oxygenation – an important requirement for highly aerobic *Komagataeibacter* species. Thus, according to Żywicka *et al*., 2021 BC production of 3.8 g/L in 50 L internal-loop airlift reactor is achieved through the use of air supply, while oxygen-rich gas supply doubles yield (Chao *et al*., 2000) The use of airlift bioreactor with wire-mesh draft tube results in the production of membrane BC which has a higher water binding capacity than that in static cultures (a potential alternative to the trade-off between product quality and efficiency) (Wu *et al*., 2017). Finally, magnetically-assisted external-loop airlift bioreactors (EL-ALBs) with RMF generators were recently used successfully for increased metabolic activity of *K. xylinus* without causing acallulose mutations during 72-hour fermentations (Żywicka *et al*., 2021).

5.1.3 Rotating Disk Bioreactors (RDBs) / Rotating Biological Contactors (RBCs)

While the major drawback of static BC formation is the confined air–liquid boundary, RDBs overcome this limitation by constantly rotating partially submerged disks that keep the medium exposed to air and thus result in a bigger dynamic area of interaction between liquid medium and atmosphere. In particular, in the groundbreaking study, eight 7 cm PMMA disks rotating at 7–11 rpm yielded a fivefold higher BC output than the conventional static cultivation techniques. Furthermore, in more contemporary research, the use of coated silicone disks rotating at 7–9 rpm allowed the attainment of BC production levels as high as 2.72 g/L in synthetic media, whereas switching the substrate from HS to grape pomace extract as the source of carbon resulted in increased productivity up to 5.23 g/L (Cruz *et al*., 2024). Modelling oxygen mass transfer in RBC technology showed better mass transfer efficiency of RDBs over other fermentation technologies due to their disk rotation design which helps to bypass diffusion restrictions inherent to stationary tray fermenters (Hosseinzadeh *et al*., 2023).

5.1.4 Thin-Layer and Membrane-Scaffold Bioreactors

The latest kind of bioreactors developed to retain BC pellicle structure and promote scalability uses mesh or membrane scaffolding where the growing BC pellicle is suspended at the air-liquid interface. Loh *et al*., 2025 observed pellicle formation in the use of this bioreactor in a co-culture environment, resulting in enhanced glucose conversion efficiency by 3.4-fold and water usage efficiency compared to conventional static trays. The air-liquid interface bioreactor is especially effective for producing food-grade BC because of the minimal disruption to pellicle structure, although care must be exercised in managing feed and harvest (Mukherjee *et al*., 2024)

An overview of bioreactor configurations used for BC production, comparing their operational principles, BC yield ranges, crystallinity outcomes, and suitability for food-grade edible coating applications is provided in *Table 5*.

Table 5*: Comparative overview of bioreactor and fermentor configurations for bacterial cellulose production. BC yield, morphology, and crystallinity index (CI%) values are representative ranges compiled from literature. Suitability for food-grade edible coating is assessed based on BC pellicle morphology and CI% threshold of ≥70% recommended for high barrier performance.*

Bioreactor Type	**Operating Principle**	**BC Yield (g/L)**	**BC Morphology**	**Suitability for Food-Grade Coating**	**Key References**
Static Tray / Tray Fermentor	BC pellicle forms at static air–liquid interface; no agitation	2–15	Continuous flat pellicle / membrane	High (Reference method)	Buldum & Mantalaris, 2021; Moreno-Díaz *et al*., 2024
Stirred Tank Reactor (STR)	Mechanical impeller agitation; continuous oxygen supply via aeration sparger	2–8	Fibrous pellets; irregular masses; no pellicle	Low (BCNF/BCNC only)	Singhania *et al*., 2022
Airlift Bioreactor (ALB)	Air/O_2-enriched gas injected from base; no mechanical stirring; draft tube guides circulation	3.8–7.2	Fibrous / pellet-like; modified ALB can produce membranes	Moderate (Modified ALB preferred)	Chao *et al*., 2000; Żywicka *et al*., 2021

Bioreactor Type	Operating Principle	BC Yield (g/L)	BC Morphology	Suitability for Food-Grade Coating	Key References
Rotating Disk Bioreactor (RDB) / Rotating Biological Contactor (RBC)	Partially submerged rotating disks expose culture to air; expanded dynamic air–liquid interface	5.32	Semi-organized fibrillar; intermediate between pellicle and fiber	Moderate–High (Good agro-waste compatibility)	Cáceres *et al.*, 2025; Hosseinzadeh *et al.*, 2023
Thin-Layer / Mesh-Scaffold Bioreactor	Mesh scaffold suspends BC at air–liquid interface; vertically expanding pellicle; minimal disturbance	High (pellicle >80 mm thick)	Thick continuous pellicle; excellent structural integrity	High (Preserves pellicle morphology)	Loh *et al.*, 2025; Mukherjee *et al.*, 2024
Bubble Column Bioreactor	Air bubbled through sparger at column base; no draft tube; gentle mixing	2.14	Spherical / irregular pellets	Low (Limited scalability, low CI)	Páez *et al.*, 2024

For food-grade production purposes, static tray fermentation and mesh-scaffold bioreactors continue to be the most appropriate configurations for BC intended to act as coating material owing to the retention of continuous pellicle structure and the requisite crystallinity index of ≥70%. The rotating disk bioreactor system can be considered an appropriate intermediate stage in the production of BC that is capable of providing acceptable crystallinity levels as well as greater scalability compared to static trays and compatibility with agro-waste carbon sources. Both STRs and bubble column bioreactors, despite being widely used industrially, generate BC with poor crystallinity and morphology for use as coating material and would therefore be more appropriate for BCNC/BCNF production routes. Bioreactor designs for future food-grade BC production should aim to optimize oxygen transfer while maintaining high crystallinity levels without compromising scalability and film-forming capacity.

5.2 Fermentation Parameter Optimization

5.2.1 Temperature

Temperature is one of the most important abiotic factors regulating BC synthesis, influencing bacterial proliferation, cellulose synthase activity, BC nanofiber structure, and crystallinity. Most *Komagataeibacter* species are optimal at temperatures from 28 to 30 °C; however, the BC synthesis decreases drastically when temperature levels are lower than 20 °C or higher than 35 °C owing to enzyme denaturation and increased formation of acetic acid as an energy source. Moreover, temperature does not impact BC productivity alone; its synthesis at 28 °C versus 30 °C results in BC with a significantly distinct water-retention ability and crystallinity, directly influencing BC applicability as an edible coating. For food-grade BC coatings, the optimum temperature range of 28 to 30 °C is an ideal solution for both BC productivity and quality (Ribas, 2026; STROBIN *et al*., 2003).

5.2.2 pH

The pH at the beginning and throughout the fermentation process plays a very important role in the synthesis of BC because the activity of cellulose synthase complex in the *Komagataeibacter* species is best suited within the pH range of 4.5 to 6.5. At pH less than 4.0, due to increased acetic acid concentration, cellulose synthase enzyme gets inhibited. Moreover, when pH is more than 7.0, bacteria cannot survive (Huang *et al*., 2016). The control of pH continuously by using buffering or pH-adjustment methods can provide yield improvement.In the case of agro-waste substrates having pH variability due to their organic acid composition, adjusting the pH before inoculation to 6.0 to 6.5 becomes essential (N. Kumar *et al*., 2025).

5.2.3 Dissolved oxygen and agitation

Because of being an obligate aerobe, sufficient oxygen availability is needed to perform the oxygen-dependent enzymatic reaction of cellulose synthase, which occurs within cell membranes. Cultivation regime such as static versus agitated cultivation regime is one of the most vital factors influencing BC production because it defines the morphological characteristics of BCs produced, as well as their physicochemical characteristics. The static regime of cultivation provides BCs that are obtained in form of thick layers on the air-liquid interface; they have a high degree of crystallinity (70-90%), fiber organization, and better mechanical properties; thus, the static cultivation regime is preferable in case of application in foods (Moreno-Díaz *et al*., 2024). In turn, agitated cultivation can significantly increase the productivity of BCs but decreases crystallinity (45-65%) as well as the regularity of fiber's arrangement (Buldum & Mantalaris, 2021).

5.2.4 Statistical optimization: RSM and design of experiments

The one variable at a time (OVAT) optimization methods are constrained in their capacity to account for interactions among the fermentation process variables. Response Surface Methodology (RSM), especially central composite design (CCD) and Box-Behnken Design (BBD), has proven to be the most efficient statistical approach for optimizing multiple parameters simultaneously for BC production. The yield obtained using RSM optimization techniques is always higher than that from OVAT methods by a factor of 30-150% (Abdel-Fattah *et al*., 2024; El-Gendi *et al*., 2022a). Key optimization studies are summarized in *Table 6*.

***Table 6**: Summary of fermentation parameter optimization studies for BC production from agro-industrial substrates*

Substrate	**Strain**	**Optimization Method**	**Key Optimized Parameters**	**BC Yield (g/L)**	**References**
Coconut water	*K. xylinus*	RSM-CCD	pH 6.0, 30°C, 12 days static	12.13	Thongsuk *et al.*, 2025
Sugarcane molasses	*K. sucrofermentans*	Box-Behnken RSM	pH 5.5, 28°C, sugar optimization	8.7	Adamopoulou *et al.*, 2024; Belkozhayev *et al.*, 2025
Pineapple juice waste	*K. saccharivorans*	Plackett-Burman + RSM	Ammonium sulphate, ethanol, incubation optimized	9.3	Patel *et al.*, 2024
Pear pomace + rice bran	*L. brevis* DSS.01	Box-Behnken RSM	85% HS medium substitution	1.56	Mongkolchat *et al.*, 2026
Kombucha SCOBY medium	SCOBY consortium	RSM-CCD	Starter volume, glucose, temperature	Variable	Contreras-Chávez *et al.*, 2026
Papaya peel extract	*K. sucrofermentans*	Physico-chemical parameters have been optimized	pH 5.5, 30°C	3.48	Tseng *et al.*, 2023

***Note**: RSM = Response Surface Methodology; CCD = Central Composite Design.*

6. Downstream Processing for Food-Grade BC

6.1 Purification methods

Crude BC pellicles after fermentation consist of substantial amounts of bacteria, culture media constituents, and metabolic wastes that need to be eliminated before being applied to food products. In the traditional purification process, the pellicle is subjected first to repeated washing with boiling distilled water, and then treated with 0.1-1% NaOH solution between 80 and

100° C for 15-30 minutes. This process eliminates the remnants of bacteria, proteins, and lipopolysaccharides (Girard *et al*., 2024; Menegasso *et al*., 2022; Santos *et al*., 2024). To use BC for food applications, an additional step is washing the treated product with neutralized water and/or diluted acetic acid.

The LPS compounds adhere to BC nanofibers very strongly, thus making it difficult to remove all of them from the surface; alkaline cleaning coupled with water washing several times has been shown to lower endotoxins to a level appropriate for food contact applications by regulatory agencies (Girard *et al*., 2024; Tang *et al*., 2011). Other BC purification methods that could be employed include enzymatic purification using cellulase-free proteases and ultrasound cleaning (Menegasso *et al*., 2022; Santos *et al*., 2024).

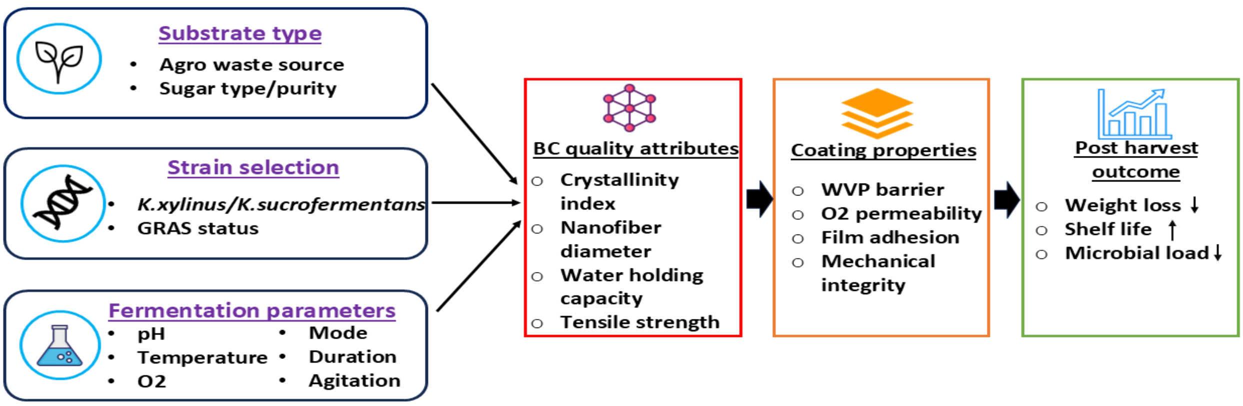
6.2 Food-grade quality parameters

Quality evaluation of BC used for coating should not be limited to traditional tests like crystalline structure via XRD, tensile strength, and water holding capacity, but also cover food related factors such as microbiological safety (determination of total plate count and presence of pathogens), presence of metals especially in case of BC obtained using agricultural waste materials, presence of chemicals like NaOH and bleaching agents, and finally the critical ability of coating (Girard *et al*., 2024; Wasoh *et al*., 2025).

7. BC Properties Relevant to Edible Coating Performance

7.1 How production conditions determine coating properties

The functional properties of BC based edible coatings are not only a function of post-production processing; rather, their formation is primarily dependent upon the preceding production process. The interdependency of production and property on performance is the central theme of this paper which constitutes the most critical gap that exists in the current body of research pertaining to BC. The BC film made under ideal static conditions of pH 6.0 and temperature of 30°C using coconut water as the substrate would be significantly different from the one made under dynamic conditions using sugarcane bagasse hydrolysate as the substrate



in terms of its structural, mechanical, and transport properties (Ningsih *et al*., 2025). The production-property-performance pathway is conceptually illustrated in *Figure 4*.

***Figure** 4: Conceptual framework illustrating the production-property-performance pathway in BC-based edible coatings. Upstream fermentation decisions (substrate, strain, parameters) determine BC quality attributes, which in turn govern edible coating functional properties and ultimately determine postharvest preservation outcomes.*

7.2 Crystallinity and barrier properties

One of the most important parameters defining the barrier capacity of BC is its crystallinity index (CI) determined via X-ray diffraction (XRD) technique. BC characterized by the crystallinity index higher than 70% demonstrates a pronounced reduction in the water vapor permeability (WVP) in comparison with the low-crystallinity BC due to the dense hydrogen bonded structure of the nanofibers providing a more difficult path for the water vapor transport (Girard *et al*., 2024; Jiang *et al*., 2024; Santos *et al*., 2024). For statically cultivated BC, the CI will be between 70% and 90%, but for BC obtained from agitated cultivation, there will be a decrease in CI to about 45-80%, as the result of mechanical interference with fibril formation (Tang *et al*., 2011). As an additive to edible coatings, high-CI BC is highly recommended for application to composite films, as crystallinity has a direct impact on the performance properties of the barrier layer. Increased crystallinity of BC means that the hydrogen bonds in the fibrous network become tighter, thus decreasing the space for oxygen and water vapor molecules to migrate, hence improving the performance of composite film WVP and oxygen resistance (Hubbe *et al*., 2017; Jiang *et al*., 2023).

7.3 Film-forming ability and coating adhesion

The ability of BC to generate continuous films on the surface of fruits is primarily dictated by the extent of BC dispersion and the flow characteristics of the BC film-forming suspension. In contrast to cellulose derivatives isolated from plants (CMC, HPMC), BC is insoluble in aqueous solutions but forms stable suspensions after mechanical disruption. At concentrations of 0.3-1.0%, BC nanofiber suspensions in biopolymer matrices (chitosan) show excellent film-forming properties, with strong adherence of the coating layer to the surface of fruits determined by scanning electron microscopy (Santos *et al*., 2024; Yazdi *et al*., 2024).

8. Applications in Edible Coatings: Evidence from Literature

BC and BCNC in composite edible coating systems

There have been three different modes of use of BC in edible coatings. The first mode is the most widely researched one. Here, bacterial cellulose nanocrystals (BCNC) formed by the acidic hydrolysis of BC films, are used as nanofillers (0.3-2.0 wt.%), in combination with various biopolymeric matrices (chitosan, alginate, starch, and gum tragacanth). Due to their rod-like structure (dimensions, 100-500 nm × 5-20 nm) and high aspect ratio, BCNC can form efficient reinforcing networks in the composite matrices due to hydrogen bond formation with the matrix polymers, thus leading to increased tensile strength

(30-120%) and decreased water vapor permeability (WVP) (15-45%) (Popa *et al*., 2025; Wang *et al*., 2025).Evidence from the literature on these coating systems is summarized in *Table 7*.

In the second method, bacterial cellulose nanofibers (BCNFs), derived from either the homogenization or ultrasonication process of BC pellicles, are added in amounts between 0.5 and 3.0% to serve as reinforcing and emulsion stabilizing materials in Pickering emulsion based edible coatings. Due to their large surface area and amphiphilic nature, BCNFs can be utilized for creating highly stabilized oil-in-water emulsions incorporating essential oils or plant extracts, allowing the delivery of antimicrobial/antioxidant materials in a manner greatly superior to conventional emulsion systems (Cai *et al*., 2026; Wardana *et al*., 2025; Zhang *et al*., 2022).

The third and "A novel technique is the use of entire bacterial cellulose dispersion in very low amounts within polysaccharide gum coating liquids, in which BC nano-fibers act as reinforcing components to strengthen both the physical and barrier qualities of the coating material (Li *et al*., 2023; Wardana *et al*., 2025; Zhou *et al*., 2024). Although this is a relatively simple and less expensive process compared to BCNC or BCNF production, the homogeneity of BC dispersions and proper viscosity control for coating solutions should be considered.

***Table** 7: Summary of BC and BC nanoform applications in edible coating systems for postharvest preservation of fruits and vegetables.*

BC Form	Coating Matrix	Bioactive Additive	Produce	Key Findings	References
BCNC (0.5–4%)	Chitosan (1%)	Apple polyphenols (0.25%)	*Ficus carica* (Fig)	Respiration ↓50.1%; weight loss ↓47.9%; shelf life 15 days; TS ↑61.5%; WVP ↓45.7%	Wang *et al*., 2025
BCNFs (0-3%)	Gelatin (2%)	None	Fresh-cut apple	Improved crystallinity & thermal stability; reduced microbial load; firmness retained	Li *et al*., 2023
BCNFs	Konjac glucomannan	Thyme EO + Ag NPs	Tangerine	Pickering emulsion; antimicrobial activity; sustained release	Zhou *et al*., 2024
CNC (0.24%)	Sodium alginate (1%)	Ylang-ylang EO	Mandarin (*Citrus reticulata*)	Pickering emulsion; reduced weight loss; improved firmness; antifungal activity	Nkede *et al*., 2024

BCNW (0.5–15 wt%)	Whey protein concentrate (WPC)	None	Food packaging (circular economy)	TS ↑32%; Young's modulus ↑80%; WVP ↓33.9% at 0.5% BCNW; BCNW produced from orange peel fermentation; high crystallinity (XRD confirmed)	Papadaki *et al*., 2022
BCNC (Sakacin-A conjugated)	Paper-based packaging	Sakacin-A (anti-Listeria bacteriocin)	Fresh soft cheese (stracchino)	BC yield 6.77 g/L from cheese whey; BCNCs conjugated with Sakacin-A (75 AU/mg); coating at 25 AU/cm²; effective Listeria reduction in storage trials; circular economy approach	Rollini *et al*., 2020
BNC (1-2%)	Sodium alginate + grape seed extract (GSE)	Grape seed extract (GSE)	General food packaging / fruit	BNC ↑ tensile strength + Young's modulus of alginate film; GSE provides antioxidant activity; FTIR confirms BNC-alginate H-bonding; biodegradable sustainable packaging	Vrabič-Brodnjak & Ružič, 2025

Note: *BCNC = bacterial cellulose nanocrystals; BCNFs = bacterial cellulose nanofibers; TS = tensile strength; WVP = water vapor permeability; EO = essential oil; Ag NPs = silver nanoparticles.*

9. Challenges, Research Gaps and Future Directions

9.1 Scale-up and economic challenges

The transfer from lab-scale BC production to large-scale industrial BC manufacturing in order to use it as a food coating material involves various challenges. Firstly, the static culture method for BC production that provides the highest degree of crystallinity and best properties suitable for coatings production is hard to scale up past tray-format production since BC pellicle formation takes place only at the air/liquid boundary because of the limitations on oxygen diffusion into the liquid . Special bioreactors developed for BC production, such as horizontal rotating disk bioreactors, airlift bioreactors, and thin-layer bioreactors showed encouraging results regarding BC productivity but their implementation requires large initial investments and was not confirmed commercially when agro-waste was used (Belkozhayev *et al*., 2025; Mukherjee *et al*., 2024).

The second challenge related to using agro-waste for BC production is high batch-to-batch variability caused by differences in agro-industrial waste composition depending on its geographical origin, time of the year, and waste treatment methods. Such variability leads to significant inconsistencies in BC yield and quality and causes difficulties in creating a homogeneous product needed in food-grade coating.

9.2 Food safety and regulatory considerations

There is great variation between regions regarding the regulatory path for BC as either a food ingredient or a food contact material. The production of BC from food-grade strains of *Komagataeibacter* species on a food-grade substrate in the USA is classified as Generally Recognized as Safe (GRAS) under the fermentation-derived polysaccharide heading. In the EU, BC would need Novel Food status under Regulation (EU) 2015/2283 unless there are existing authorizations for food additives, which has been a major regulatory hurdle limiting commercial development.

9.3 Research gaps and future perspectives

Several research gaps were uncovered after analyzing all the articles used in this literature review. The first key finding concerns the lack of assessment of the qualities of BCs obtained through optimization procedures that may be utilized in creating food coatings, namely crystallization index, water-holding capacity, film-forming ability, and food contact safety. The failure to address the problem of production versus application is the most urgent research gap identified in this review, which is why a food-grade BCs perspective must be considered here.

Secondly, there is a geographical limitation associated with the research on optimization of bacterial cellulose (BC). The bibliometric analysis shows that the research on BC optimization is geographically biased in favor of only a few nations. China appears to be the leading producer of BC research, while Brazil is regarded as the leading country in Latin America. Similarly, South Korea has been reported as an important research site for investigating BC (El-Gendi *et al*., 2022b; Fernandes *et al*., 2020; Infante-Neta *et al*., 2024). Lastly, in terms of future research directions, an area that would be both novel and impactful would be exploring BC-reinforced polysaccharide matrices with previously unexplored bioactives from plants that possess proven antimicrobial/antioxidant properties based on traditional medicinal systems like Ayurveda. For instance, *Cyclea peltata* is one plant that has been demonstrated to exhibit antimicrobial properties against food spoilage pathogens like Staphylococcus aureus, E. coli, and Pseudomonas aeruginosa owing to its tetrandrine and polyphenols. This kind of research area is very novel and highly impactful due to the limited amount of literature currently available (Sukanya BCV & Bhat PR, 2019).

10. Conclusion

The current systematic review analyzes the optimization of bacterial cellulose production using agro-industrial wastes in relation to the achievement of food-grade safety standards, a perspective that, to our knowledge, has not yet been applied in the context of BC production research. The important conclusions drawn from this study based on the analysis of relevant articles are as mentioned. The most efficient strains that can produce safe BC are *K. xylinus* and *K. sucrofermentans*. Fruits are sources of waste materials with which the highest-quality BC can be obtained for use in the preparation of edible food-grade coatings; specifically, the most effective material is derived from coconut water and papaya peel extract.

More importantly, through this review, it has been identified that production of BC-based edible coating is directly linked with the property and performance of the coating in post-harvest storage; and therefore, the decisions made during the process of fermentation become very important since it determines crystallinity, water vapor transmission rate, and film formation capability of the BC, thereby its ability to enhance the shelf-life of the produce. Static fermentation at 28-30°C temperature range and pH 5.5-6.5 using fruit waste biomass with food-grade *Komagataeibacter* species provides the highest crystallinity (70-90%).

Indeed, the area finds itself on the verge of a very interesting inflection point, one at which the progress made within each of these respective domains would allow for BC to shift roles from being an experimental material to being one that is suitable for use as an economic and scalable food-grade coating agent. As a consequence, future studies in the area should aim to develop food-grade BC production procedures, utilize locally available and underexploited agricultural waste materials, and examine BC-composite coatings supplemented with unique natural compounds with antimicrobial and antioxidant activity.

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Author Contributions (CRediT taxonomy):

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