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Bacterial cellulose in sustainable agriculture: bibliometric map and critical review of agronomic applications and waste-valorised production

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Abstract. Bacterial cellulose (BC) is a lignin-free nanofibrillar hydrogel with high water-binding capacity, mechanical strength, and biodegradability. Despite these properties, a Scopus bibliometric survey of 738 publications (2015–2025) showed that agricultural applications accounted for only 17% of BC research, while biomedical and materials-science applications dominated. This review contributes a bibliometric quantification of that imbalance; a four-function synthesis of BC as a cultivation substrate, soil amendment, seed or biological carrier, and agrochemical platform; and a production route-property-application matrix linking waste feedstocks to agronomic functions. Direct crop evidence remains limited. In a controlled tomato-seedling study, 0.01% BC increased substrate water-holding capacity by up to 14% and improved survival, root development, and nutrient availability under restricted irrigation. Supporting evidence from plant-derived cellulose and other biopolymer hydrogels demonstrates improved germination and soil moisture regulation, but should not be interpreted as direct validation of BC. Feedstock selection affects production cost, material properties, and application fit simultaneously. Multi-season field trials, matched comparisons with commercial substrates and hydrogels, standardised characterisation, and life-cycle and techno-economic assessments remain priorities.

Keywords: bibliometric analysis; biotechnology; material science; soilless system; circular bioeconomy; nanofibers

Agriculture faces sustained pressure to feed a global population projected to reach 9.7 billion by 2050 without exceeding the planetary boundaries for land, water, and nutrient use (United Nations 2022, Francaviglia et al. 2023). The yield gains of the twentieth century depended on intensive synthetic inputs and deep tillage, practices that are now linked to soil degradation, erosion, and agrochemical contamination of water bodies (Francaviglia et al. 2023, Jiang et al. 2025). Sustainable intensification, which seeks to raise output from the same resource base without further ecological damage, has since gained importance in research and policy (Jiang et al. 2025).

Controlled-environment agriculture (CEA), including hydroponics, is a well-established example of this shift; it reduces water consumption, improves land-use efficiency, and reduces dependence on pesticides (Rajendran et al. 2024). However, CEA and other soilless systems depend on growth substrates that carry their own ecological costs. Rockwool

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is energy-intensive to manufacture and generates non-biodegradable waste, peat extraction destroys carbon-rich wetlands, and coconut coir must travel long distances and varies in quality (Grass Ramírez et al. 2023, Farvardin et al. 2024). The absence of high-performance biodegradable alternatives limits the environmental credentials of advanced soilless systems and their integration into circular production models (Bueno et al. 2023).

Bacterial cellulose is a candidate material. Produced by non-pathogenic acetic-acid bacteria, principally *Komagataeibacter xylinus*, through the self-assembly of cellulose nanofibres of exceptional purity (Wu et al. 2023), BC contains no lignin, hemicellulose, or pectin and therefore does not require harsh chemical purification (Potočnik et al. 2023). The resulting nanofibrillar structure achieves a tensile strength of 150–200 MPa and a water-binding capacity of 100–200 times its dry weight (Lu et al. 2024), properties relevant to drought buffering, root-zone aeration, nutrient-use efficiency, and substrate biodegradability in agricultural contexts (Datta 2024).

However, BC research remains concentrated in the biomedical and materials sciences. Wound dressings, tissue engineering, and structural composites account for more than 80% of the Scopus corpus of 738 publications (2015–2025), while agricultural applications represent less than 20% (Campano et al. 2025, Venturelli et al. 2025). This disproportion is the gap that this review addresses.

This review makes three contributions not found in prior BC reviews: (*i*) a bibliometric quantification of BC's marginal position within its own research field (17% agricultural share across 738 publications); (*ii*) a four-function evidence synthesis structured around five evidence tables, including the first production route-property-application matrix linking waste-stream feedstock to specific agronomic use; and (*iii*) a critical trade-off assessment distinguishing what the evidence supports from what remains undemonstrated. The discussion is structured around four guiding questions.

1. What are the physicochemical and biological properties of BC, and how do they suit soil-based and soilless systems?
2. What agronomic functions can BC fulfil as a substrate, soil conditioner, seed coat, or agrochemical carrier, and what trade-offs are associated with each?
3. What is the impact of various production strategies, particularly waste-based fermentation, on BC yield, quality, and scalability?
4. Which research and innovation priorities would enable BC to develop into a circular, high-performance agricultural biomaterial?

METHODOLOGY

This review comprises two stages: a bibliometric analysis that defines the scope and thematic structure of BC research applicable to agriculture and a qualitative synthesis of experimental agronomic studies that link production routes and material properties to plant and soil performance.

Bibliometric search method and dataset construction

Scopus was selected as the primary data source because it provides broad peer-reviewed coverage, rich bibliographic metadata, and strong support for multidisciplinary research in biotechnology, material science, and agriculture (Pranckutė 2021). The search retrieved literature at the intersection of BC and agriculture using a Boolean query combining two conceptual groups of terms: material terms ("bacterial cellulose", "microbial cellulose", "biocellulose", "nanocellulose") and application terms ("sustainable agriculture", "hydrogel", "nutrient delivery", "agricultural substrate"), linked by OR operators within each group.

The search was limited to 2015–2025 and restricted to research and review articles in English. Titles, abstracts, and keywords were screened to remove duplicate and off-topic records, including publications confined to biomedical, cosmetic, electronic, textile, packaging, or energy-storage applications (Natukunda and Muchene 2023). After screening, 738 publications were retained and exported from Scopus in CSV format. The selection procedure is reported narratively because the bibliometric mapping provides contextual evidence rather than a systematic-effect estimate. Exclusion of Web of Science is acknowledged as a limitation; a future dual-database search may identify additional records.

Bibliometric analysis and science mapping

The Bibliometrix R package (Aria and Cuccurullo 2017) was used to analyse annual publication trends, citation impact, and author and institution contributions. Science-mapping outputs comprise keyword co-occurrence networks (identifying emergent theme clusters;

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Saleh et al. 2024), co-citation networks (identifying foundational knowledge pillars; Muiruri et al. 2023, Wang et al. 2024), and thematic evolution maps (Rodrigues et al. 2024, Taokaew 2024). Author names, affiliations, and keywords were standardised for network construction (Aria and Cuccurullo 2017, Santosa 2023). Together, these outputs contextualise the critical agronomic synthesis that constitutes the primary contribution of this review.

Experimental studies: agronomic evidence synthesis

Direct agronomic evidence comprised laboratory, greenhouse, or field experiments in which BC or a BC-based composite was applied to a plant, cultivation substrate, or soil, and at least one plant or soil response was measured. Because direct evidence was sparse, mechanistically relevant experiments using plant-derived cellulose or other biopolymer hydrogels were also examined as analogue evidence. These studies are explicitly labelled as non-BC analogues in Tables 1 and 2 and were not treated as direct validation of BC performance.

Reported outcomes included germination, plant survival, biomass or yield, substrate or soil water retention, nutrient availability, and soil biological responses. Biomedical, cosmetic, packaging, textile, and energy-storage articles, modelling-only studies, and papers that reported neither a plant nor a soil response were excluded from the direct agronomic evidence set (Raut et al. 2023). Material-characterisation studies were retained only where their measured properties were directly relevant to cultivation-substrate performance and are identified as such in Table 3.

The qualitative synthesis therefore separates three evidence levels: direct BC agronomic experiments, BC material studies relevant to agricultural use,

Table 1. Direct bacterial cellulose (BC) and explicitly labelled cellulose-analogue studies relevant to soil conditioning

Study	Crop and soil or test matrix	Material and application	Verified outcome	Evidence status and comparator
De la Cruz Gómez et al. (2024)	*Solanum lycopersicum* L. cv. Marmande; commercial organic horticultural substrate + vermiculite (3:1, *v*/*v*); no soil taxonomic class applicable	BC from *K. sucrofermentans* CECT 7291; 0.01% (*w*/*w*)	water-holding capacity increased by up to 14%; survival, root development and P/K availability improved under restricted irrigation	direct BC; matched substrate without BC; controlled 14-day pot experiment
Qin et al. (2022)	*Triticum aestivum* L. and *Lactuca sativa* L.; artificial harsh-soil systems including saline-alkali and sandy conditions; taxonomic class not reported	wood-pulp-derived gel-glycerol; cellulose analogue, not BC; application rate not reported in the article abstract	wheat germination increased by 21.88%, leaf number by 100% and water uptake by 94.7%; lettuce germination improved relative to water-only and potassium-polyacrylate controls	laboratory/pot analogue evidence
Bueno et al. (2023)	no crop; characterised greenhouse pot soil; texture, pH, nutrients, organic matter and moisture measured; taxonomic class not reported	coffee-kombucha-derived BC sheets buried below soil for 8 weeks	approximately 75% mass loss; fungal abundance increased, and bacterial-community composition changed during decomposition	direct BC biodegradation evidence; nylon-membrane and soil-only controls
Jong et al. (2025)	no crop in soil-conditioning assay; sand, topsoil, gley soil and clayey soil; *Brassica chinensis* var. *parachinensis* tested separately in germination assay	wastepaper-derived cellulose hydrogels plasticised with alginic acid, NaCMC, glycerol or PEG; 50% hydrogel-soil mixture; not BC	soil moisture increased, and pH was maintained at ≥ 5 over 15 days; electrical-conductivity responses depended on plasticiser and soil type	laboratory/pot analogue evidence; each soil without a hydrogel as a control

NaCMC – sodium carboxymethyl cellulose; PEG – polyethylene glycol

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Table 2. Experimental evidence for seed germination and microbial-carrier functions; direct bacterial cellulose (BC) seed-coating trials were not identified

Study	Crop species and test setting	Formulation	Verified outcome	Evidence status and comparator
Jong et al. (2025)	*Brassica chinensis* var. *parachinensis* (Choy Sum); Petri-dish germination without external watering	wastepaper-derived cellulose hydrogel plasticised with alginic acid, NaCMC, glycerol or PEG; non-BC cellulose analogue	glycerol hydrogel produced 65% germination *versus* 27% on watered cotton; every hydrogel treatment produced ≥ 40% germination	soilless analogue evidence; watered and unwatered cotton controls
Feng et al. (2025)	*Brassica napus* L. cv. Zhongshuang 11; pakchoi (*Brassica rapa* subsp. *chinensis*) cv. Jinzhi 30; *Arabidopsis thaliana* Col-0; pot soil from Shilin County and field site in Chongqing, China	carboxymethyl chitosan/sodium alginate/Ca^{2+} hydrogel carrying *Ensifer* sp. C5; non-BC biopolymer analogue	improved PGPR persistence and plant growth; *B. napus* pod number and yield increased by 30.74% and 28.01% relative to free bacteria; activity retained at pH 5.5	plate, pot and field analogue evidence; hydrogel alone, free C5 and untreated controls

NaCMC – sodium carboxymethyl cellulose; PEG – polyethylene glycol; PGPR – plant growth-promoting rhizobacterium

and non-BC cellulose or biopolymer analogues. A formal meta-analysis was not appropriate because crop species, soil and substrate matrices, materials, application rates, comparators, and outcome definitions were heterogeneous. Quantitative values are consequently reported only in relation to their original experimental conditions.

BIBLIOMETRIC CONTEXT: BC IN AGRICULTURE AS AN EMERGING RESEARCH FIELD

A Scopus survey of 738 publications (2015–2025) confirmed that BC research is dominated by materials science and biomedicine, with agricultural applications accounting for only 17% of the corpus (Venturelli et

Table 3. Direct and material-level evidence relevant to bacterial cellulose (BC) in hydroponic and soilless cultivation

Study	Crop or test system	BC material and source	Verified outcome	Evidence scale and comparator
De la Cruz Gómez et al. (2024)	*Solanum lycopersicum* L. cv. Marmande; hydroponic safety assay and organic-substrate pot assay	BC from *Komagataeibacter sucrofermentans* CECT 7291; 0.01% (*w*/*w*) in commercial organic substrate + vermiculite (3:1, *v*/*v*)	non-phytotoxic; substrate water-holding capacity increased by up to 14%; survival, root growth and P/K availability improved under restricted irrigation	direct BC evidence; matched substrate without BC; controlled hydroponic and 14-day pot experiments
Szymańska et al. (2022)	no crop or soil tested; BC synthesis and material characterisation	BC pellicles produced with a silicone polyether surfactant	BC synthesis and water-holding capacity increased; no plant response or commercial-substrate comparison was reported	laboratory material evidence; BC produced without surfactant as a comparator
Drosos et al. (2024)	no crop or soil tested; BC material characterisation	*Komagataeibacter sucrofermentans* DSM 15973T; water-purified liquid-*versus* solid-inoculum BC	liquid-inoculum BC had greater porosity, swelling and water-holding capacity; maximum 116 g water/g cellulose on day 4	laboratory material evidence; liquid-*versus* solid-inoculum BC

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al. 2025). Annual output grew steadily from 2018, and the highest citation rates were observed for integrative studies from 2018–2019 (Figure 1), suggesting that a recognisable knowledge base is forming even as the field continues to expand. In keyword co-occurrence networks, agronomic terms, soil amendment, hydroponics, and seed coating appeared as small, sparsely connected nodes on the periphery of the material science and biomedical cluster (Figure 2). Thematic evolution mapping shows that BC-agriculture connections have strengthened progressively since 2020, with the terms water retention, circular bioeconomy, and biopolymer scaffold gaining co-occurrence weight (Taokaew 2024). Two conclusions follow. Agricultural applications of BC are under-researched relative to the available evidence, and the field is slowly moving towards the convergence of BC materials science with agronomic practice.

BC PRODUCTION AND VALORISATION OF AGRI-FOOD WASTE

Despite BC's suitability for agricultural use, large-scale implementation is constrained by production costs (Khan et al. 2023). High-purity BC produced from refined sugars and yeast extracts is too expensive for agricultural applications (Kamal et al. 2022). Subsequent research has optimised fermentation conditions and replaced refined carbon sources with agri-food residues, thereby reducing costs and aligning BC production with circular bioeconomy principles (Quijano et al. 2024).

BC production routes and process parameters

Komagataeibacter xylinus and *Komagataeibacter hansenii*, both acetic-acid bacteria, produce BC by extruding cellulose nanofibres at the air-liquid interface or throughout the medium, depending on the cultivation system (Wahid and Zhong 2021). BC is commonly produced in two operational modes: static and agitated culture.

Static culture: bacteria form a BC pellicle over the air-liquid interface in shallow trays or flasks. This method yields highly crystalline, mechanically robust BC with well-organised nanofibrillar networks; however, only the uppermost layer is active, leading to low volumetric productivity (El-Gendi et al. 2022).

Agitated (stirred-tank) culture: bacteria grow in suspension within the medium and produce dispersed

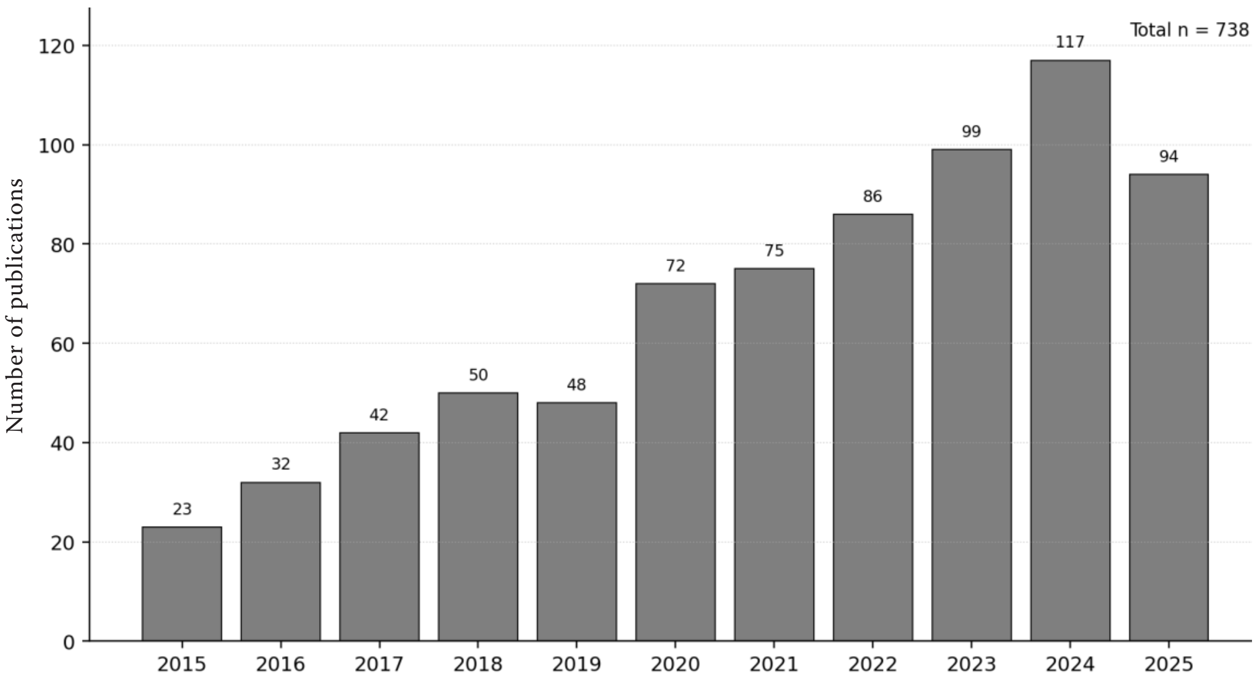

Figure 1. Annual scientific production of bacterial cellulose (BC) publications in sustainable agriculture. Output grew consistently from 2018, with agricultural applications accounting for only 17% of the 738-publication dataset (2015–2025). The highest citation rates correspond to the anchor studies from 2018–2019 (Venturelli et al. 2025)

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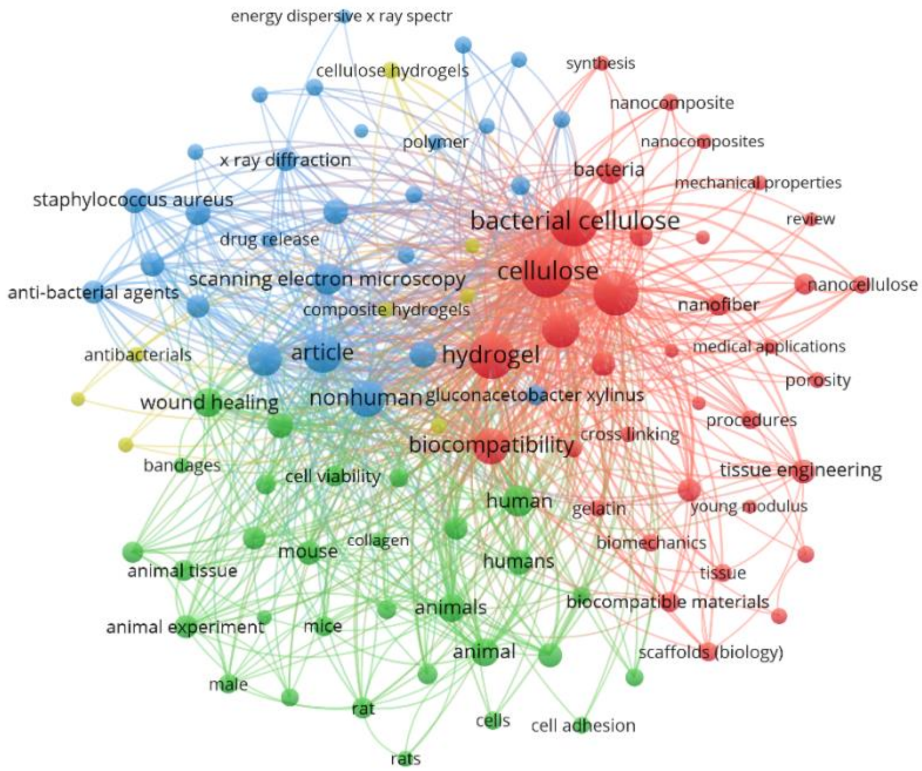

Figure 2. Keyword co-occurrence network for the 738-publication bacterial cellulose dataset. The dominant cluster is anchored by materials-science terms; agronomic keywords (soil amendment, hydroponics, seed coating) appear as small, weakly connected peripheral nodes, confirming that bacterial cellulose (BC)-in-agriculture occupies a niche within the broader research field (VOSviewer, Scopus dataset)

fibres or irregular particles. As shear stress disrupts fibre production, agitation enhances volumetric yield and scalability, reduces crystallinity, and changes fibre morphology (Avcioglu 2022, Cruz et al. 2024).

The media composition and processes strongly influence BC yield and structure. Glucose or sucrose is the predominant carbon source in typical Hestrin-Schramm (HS)-type media, and yeast extract and peptone provide nitrogen and growth factors (Kolesovs and Semjonovs 2020, Mitri et al. 2022, Almihyawi et al. 2024). BC-producing strains can utilise various carbohydrates, organic acids, and alcohols; thus, agricultural waste hydrolysates can substitute for refined sugars (Kamal et al. 2022, Saberi Riseh et al. 2024). The optimal culture pH is 4.5–6.0, and the temperature is 28–30 °C with sufficient oxygen, especially in a still culture, where interface diffusion is the limiting factor for BC production (Manan et al. 2022). Any deviation from these optima can decrease productivity or alter the porosity, degree of polymerisation, or mechanical strength of BC, which affects water retention, soil aggregation, and seed-coating performance (Muiruri et al. 2023).

These process considerations demonstrate that BC production is a tunable phase, with feedstock selection, fermentation mode, and operating conditions influencing material properties relevant to plant-soil systems. Improved reactor designs (e.g., rotating disc or mesh-disperser bioreactors) and strain engineering are targeting higher productivity and agronomically tailored BC structures (Loh et al. 2025, Venturelli et al. 2025).

Valorisation of agri-food residues as production feedstocks

Numerous studies have used agri-food residues as BC feedstocks in circular production systems, thereby reducing costs. BC-producing bacteria metabolise sugars and nutrients from fruits, vegetables, and agro-industrial by-products. Commonly studied categories include fruit and vegetable waste (pineapple peel, citrus pomace, and mango peel), lignocellulosic residues (sugarcane bagasse, maize stover, and rice straw), dairy by-products (whey, whey permeate, and brewery spent grain), and urban feedstocks such as

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stale bread (Mitri et al. 2022, Cubas et al. 2023, Khan et al. 2023, Saberi Riseh et al. 2024).

Mild acid or enzymatic hydrolysis, size reduction, and filtration enhance the availability of fermentable sugars and remove inhibitory compounds (Tan et al. 2025). Waste-derived media can sustain BC yields that are similar to or exceed those obtained with the standard HS medium. Rice bran, apple pulp, and paper sludge provide 12–20 g/L, substantially higher than the ~0.5–2 g/L typically found in HS medium (Cubas et al. 2023). Media based on dairy whey and molasses have achieved yields comparable to pure glucose media at lower feedstock costs (Kamal et al. 2022). In some solid-state fermentation systems, agricultural residues have been shown to increase BC production by 20–25% and reduce medium costs by up to 90% (Henry et al. 2024) (Table 4).

Effect of feedstock on BC properties and agronomic performance

The choice of feedstock shapes both the economics and microstructure of BC, with direct agronomic consequences. Sweet fruit and vegetable residues promote the formation of thick, hydrated pellicles with porous networks that retain water effectively and support high yields (Güzel and Akpınar 2020). This type of BC is suitable for hydroponic substrates and soil conditioners, where moisture-buffering capacity is the primary requirement (Sorze et al. 2023).

BC with higher crystallinity is better suited for structural applications, seed coatings, or composite substrates that must withstand handling and repeated wetting-drying cycles (Srivastava and Mathur 2022). Incomplete hydrolysis or residual lignin can impede processing and introduce impurities. Dairy-derived media, which contain lactose and proteins, can alter BC surface chemistry in ways that may improve interactions with microbial inoculants or nutrients when BC is used as a carrier (Kolesovs and Semjonovs 2020) (Table 5).

APPLICATION OF BACTERIAL CELLULOSE IN AGRICULTURE

The properties described in Section 4 support four proposed agronomic functions. However, the evidence is uneven. Tables 1–3, therefore, distinguish direct BC crop or soil experiments from BC material-characterisation studies and from non-BC cellulose or biopolymer analogues. This distinction

Table 4. Examples of waste feedstocks used for bacterial cellulose (BC) production and their implications for agricultural use

Representative studies (examples)	Feedstock type	Examples (typical)	Fermentation mode	BC yield *vs* HS (Hestrin-Schramm) medium	Key BC properties	Example agricultural uses
Güzel and Akpınar (2020), Cubas et al. (2023), Moreno-Díaz et al. (2024)	fruit and vegetable waste	pineapple, mango peels; citrus pomace; sweet lime pulp	static (mostly)	↑ 12–20 g/L (up to 3× *vs.* HS reference yield of 0.5–2 g/L)	very porous, high-water retention; soft pellicles	hydroponic substrates; soil conditioners (drought mitigation)
Potočnik et al. (2023), Henry et al. (2024), Saberi Riseh et al. (2024)	lignocellulosic residues	sugarcane bagasse; corn stover; rice straw	agitated/static (with pre-treat)	≈ / ↓ variable (0.3–1.5 g/L after hydrolysis; yield loss possible due to inhibitors)	dense, tough structure; variable crystallinity	seed coatings; biodegradable films; structural substrate blends
Kolesovs and Semjonovs (2020), Mitri et al. (2022), Almihyawi et al. (2024)	dairy side-streams	whey; whey permeates	static/agitated	≈ 1–5 g/L (comparable to HS medium; lower feedstock cost)	moderate porosity; enriched surface chemistry	BC carriers for agrochemicals or microbial inoculants
Khan et al. (2023)	kitchen/bakery waste	stale bread; mixed food waste	static/agitated	↑ up to 8–12 g/L (if pre-treated; variable depending on feedstock mix)	variable (depending on feed mix)	urban farming substrates; low-cost carrier materials

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Table 5. Production route-property-application matrix: matching bacterial cellulose (BC) feedstock and fermentation mode to agronomic function

Representative studies	Feedstock/ BC type	Fermentation mode	Key BC properties	Best agronomic application
Güzel and Akpınar (2020), Cubas et al. (2023), Moreno-Díaz et al. (2024)	fruit and vegetable waste (pineapple peel, citrus pomace, mango peel)	static culture	highly porous; very high water-holding capacity (WHC); soft pellicle; yield up to 3× HS medium	hydroponic substrate; soil conditioner for short-term drought buffering
Kolesovs and Semjonovs (2020), Mitri et al. (2022), Almihyawi et al. (2024)	dairy side-streams (whey, whey permeate, brewery wort)	static or agitated	moderate porosity; enriched surface chemistry; yield ≈ HS medium	agrochemical and microbial inoculant carrier; seed coating matrix
Potočnik et al. (2023), Henry et al. (2024), Saberi Riseh et al. (2024)	lignocellulosic residues (sugarcane bagasse, rice straw, corn stover, pre-treated)	agitated or static (after hydrolysis)	dense; high crystallinity; tough pellicle; variable yield (≈ or ↓ *vs.* HS); residual lignin possible	structural seed coatings; composite substrate blends; dense soil amendment for long-term aggregate stabilisation
Khan et al. (2023), Saleh et al. (2024)	kitchen/bakery waste (stale bread, mixed food waste, pre-treated)	static or agitated	variable (feed-dependent); ↑ yield if pre-treated; low production cost	urban farming substrate; low-cost carrier material for localised applications
Wahid and Zhong (2021), Manan et al. (2022), Lu et al. (2024)	standard HS medium (glucose + yeast extract, reference baseline)	static (high crystallinity) or agitated (dispersed fibres)	crystallinity 70–90%; tensile strength 150–200 MPa; WHC 100–200× dry WT; yield 0.5–2 g/L	all applications; preferred where product purity is critical (seed coatings, controlled-release carriers)

prevents material potential from being interpreted as demonstrated field performance.

BC in hydroponic and soilless cultivation systems

BC has high porosity and water-holding capacity, properties that are relevant to hydroponic and other soilless systems. Direct crop evidence is nevertheless limited in controlled experiments with *Solanum lycopersicum* L. cv. Marmande, BC, produced by *Komagataeibacter sucrofermentans* CECT 7291, was non-phytotoxic in hydroponic assays. When incorporated at 0.01% (*w*/*w*) into a commercial organic substrate mixed with vermiculite, BC increased substrate water-holding capacity by up to 14% and improved seedling survival and root development under restricted irrigation (De la Cruz Gómez et al. 2024).

Material studies support the physical plausibility of this function but do not constitute crop validation. Water-purified BC produced from *Komagataeibacter sucrofermentans* DSM 15973T by liquid inoculum reached a maximum water-holding capacity of 116 g water/g cellulose and showed greater porosity and swelling than BC produced from a solid inoculum (Drosos et al. 2024). Likewise, surfactant-assisted synthesis increased BC production and water-holding capacity, but no crops, nutrient solutions, or commercial substrates were tested (Szymańska et al. 2022).

No replicated crop trial directly comparing BC with rockwool, peat, or coir was identified. The existing evidence, therefore, supports BC as a candidate substrate component rather than as a proven commercial substitute. Multi-season comparisons should report crop species and cultivar, substrate composition, BC dose and physical form, nutrient solution chemistry, irrigation frequency, root zone aeration, yield, material reuse, degradation, and cost (Khan et al. 2023, Ferrarezi et al. 2024).

BC as a soil conditioner and amendment

Direct evidence for BC as a soil or substrate amendment is currently limited to a small number of con-

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trolled studies. In the tomato experiment, 0.01% BC increased the water-holding capacity of an organic substrate-vermiculite mixture by up to 14% and improved survival, root development, and phosphorus and potassium availability under restricted irrigation (De la Cruz Gómez et al. 2024). This result should not be generalised to field soils because neither a WRB nor a USDA soil taxonomic class applied to the commercial horticultural substrate.

The strongest direct soil evidence concerns biodegradation rather than crop productivity. Coffee-kombucha-derived BC buried in characterised greenhouse pot soil lost approximately 75% of its mass over eight weeks. Fungal abundance increased, and bacterial-community composition changed during decomposition, whereas nylon membranes showed no comparable physical loss (Bueno et al. 2023). The source measured soil texture, pH, nutrients, organic matter, and moisture but did not report a WRB or USDA taxonomic class in the accessible record.

Plant-derived cellulose hydrogels provide useful analogue evidence but must be distinguished from BC. A wood-pulp gel-glycerol amendment improved germination of wheat and lettuce in experimentally prepared harsh-soil systems. In contrast, a wastepaper-derived cellulose hydrogel improved moisture, pH, and electrical conductivity in sand, topsoil, gley soil, and clayey soil (Qin et al. 2022, Jong et al. 2025). These studies support mechanisms relevant to BC, but they do not establish BC application rates, persistence, or yield effects.

Accordingly, the critical next experiment is a matched comparison of chemically and physically characterised BC with an incumbent superabsorbent or commercial substrate across defined soil classes. Such studies should report dry-mass application rate, water-retention curves, bulk density, aggregate stability, nutrient leaching, microbial responses, crop yield, degradation half-life, and cost. Until these data are available, claims of superiority over polyacrylamide or polyacrylate hydrogels remain untested.

BC as a seed coating and seedling enhancer

BC can be processed into thin films and porous matrices, but no direct crop trial of a BC seed coating was identified in the reviewed evidence. The available experimental support comes from plant-derived cellulose and other biopolymer hydrogels. These analogues demonstrate relevant water-delivery and microbial-carrier mechanisms, but their performance cannot be attributed directly to BC.

A wastepaper-derived cellulose hydrogel supported germination of *Brassica chinensis* var. *parachinensis* without external watering; the glycerol-plasticised formulation produced 65% germination compared with 27% on the watered cotton control (Jong et al. 2025). This was a soilless germination medium rather than a conformal seed coating, and the material was not bacterial cellulose.

For microbial delivery, a carboxymethyl chitosan-sodium alginate-Ca^{2+} hydrogel protected *Ensifer* sp. C5 and improved its growth-promoting effect in *Brassica napus* L., pakchoi, and *Arabidopsis thaliana* (L.) Heynh. In field-grown *B. napus*, pod number and yield increased by 30.74% and 28.01%, respectively, relative to free-bacteria treatment, and the carrier retained activity at pH 5.5 (Feng et al. 2025). This is a non-BC biopolymer analogue and is included only to define performance targets for a future BC carrier.

Future BC seed-coating studies should therefore report crop species and cultivar, film thickness, BC source and crystallinity, coating mass per seed, water-uptake kinetics, emergence synchrony, mechanical abrasion, storage stability, microbial or agrochemical release, and comparison with an established commercial coating. Until such trials are available, BC seed-coating claims should be presented as a research proposition rather than demonstrated agronomic performance.

Emerging and prototype applications

BC's structural versatility has led to several emerging agricultural applications, each currently at the prototype or conceptual stage.

Biodegradable sensors: functionalised BC films containing pH-responsive dyes, conductive materials, or moisture-responsive materials can be used as low-cost, disposable sensors for soil moisture or nutrient concentrations (Bao et al. 2025). These sensors degrade in service, avoiding plastic waste and enabling precision irrigation and fertilisation.

Water purification membranes: BC aerogels and fine-pore membranes can remove heavy metals, organic pollutants, and pathogens from water (Tran et al. 2025). They can be deployed in farming systems to treat irrigation water or surface runoff, and selectively retain nitrate or phosphate *via* BC's charged nanofibre matrix (Tran et al. 2025).

Engineered living materials (ELMs): BC networks incorporating live microorganisms can serve as responsive soil supplements that secrete growth-

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promoting or protective compounds in response to environmental stimuli or root signals (Zhou et al. 2025).

Each application is still in the prototype stage. The main gaps are the lack of multi-season field validation under agronomic conditions, the lack of techno-economic analyses comparing these approaches with established alternatives, and the absence of any published integration of these approaches with waste-based BC production pathways. All three need to be resolved before any of these applications can be considered agronomically viable at scale.

COMMERCIALISATION OBSTACLES AND CHALLENGES

The scientific case for BC as an agricultural biomaterial is strong; however, translating it from laboratory to farm practice faces real economic, technical, and regulatory barriers. The following subsections identify these challenges.

High production cost and economic viability

Production cost remains the primary constraint. Even with low-cost waste feedstocks, the full manufacturing chain, pretreatment, fermentation, harvesting, purification, and formulation, exceeds the cost of most conventional substrates even with low-cost waste feedstocks (Mouro et al. 2025). Static cultures yield high-quality BC but at low volumetric productivity; stirred-tank reactors are more productive but require capital investment, energy, and complex process control (Avcioglu 2022). BC production in conventional systems costs approximately US$22/kg (Mouro et al. 2025), compared with approximately US$1–3/kg for rockwool and US$3–8/kg for polyacrylamide hydrogels (Kamal et al. 2022, Quijano et al. 2024). As an illustrative example, a 1 000 m^2 NFT hydroponic unit requires approximately 2–5 kg of substrate per growing module; at US$22/kg, BC substrate costs would reach approximately US$44–110/$m^2$, compared with under US$5/m^2 for rockwool, a differential that cannot be offset by agronomic performance gains alone without waste-stream feedstock integration and scale-up (Mouro et al. 2025).

Routes to lower costs include fed-batch or continuous fermentation, improved oxygen transfer, strain engineering, and integrated biorefineries that co-produce BC with other value-added products (Dong et al. 2023). Using local waste streams reduces feedstock procurement and waste management costs; however, these savings depend on the context and require a proper techno-economic assessment (Kamal et al. 2022, Quijano et al. 2024). No published LCAs compare BC production with the manufacturing footprints of rockwool or PAM hydrogels; establishing BC's net ecological position is a priority for journals focused on soil and the environment.

Evidence gaps, regulatory frameworks, and farmer adoption

Beyond cost, three further obstacles affect BC adoption.

First, the evidence base is limited. Most agronomic research uses short-term pot or greenhouse experiments, and multi-season field trials across diverse climates and soils are rare. The long-term effects of BC on soil structure, nutrient cycling, microbial communities, and soil organic carbon remain poorly characterised.

Second, regulatory clarity is required. BC-based substrates, soil amendments, and seed coatings must meet safety, quality, and performance standards before commercial use (Neuhoff et al. 2024). Standardised characterisation protocols covering water-holding capacity, tensile strength, crystallinity, and impurity levels would support consistent product quality and help regulators make informed decisions.

Third, farmer adoption depends on practical guidance and demonstrable values. Clear application rates, handling protocols, and productivity gains large enough to justify the cost are all required (Xu et al. 2025). Participatory trials and demonstration farms offer the most direct route for adoption.

CONCLUSION AND STRATEGY OUTLOOK

BC is a promising but insufficiently validated biomaterial for sustainable agriculture. Its purity, nanofibrillar structure, water-holding capacity, and mechanical properties justify continued investigation, while the available evidence from crops remains limited to short-duration controlled studies (Potočnik et al. 2023, De la Cruz Gómez et al. 2024). Bibliometric evidence likewise shows that agricultural applications remain peripheral to the broader biomedical and materials science literature.

The central finding is that production science, material characterisation, and agronomic validation must be evaluated together. Feedstock selection af-

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fects BC cost and structure, but application claims require direct testing in clearly identified crops, substrates, and soil classes. Plant-derived cellulose and other biopolymer hydrogels offer useful mechanistic benchmarks; they should not be cited as direct proof of BC performance (Quijano et al. 2024, Mouro et al. 2025).

The strategic priorities are as follows:

- establishment of scalable, cost-effective BC production systems utilising local agri-food residues;
- standardisation of BC characterisation and quality measures for agricultural applications;
- multi-season, multi-site trials comparing chemically characterised BC with incumbent substrates, soil conditioners, and seed-coating materials in explicitly classified soils;
- integration of BC research with agronomic, plant, and soil sciences to optimise agronomic performance;
- policy and market instruments supporting the circular bioeconomy and incentivising the adoption of BC-based agricultural products.

Progress on these fronts would provide BC with a realistic pathway from niche research materials to a biomaterial platform that underpins sustainable, resource-efficient, and circular agricultural systems.

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