RM4L2020 International Conference **Paper number: 1231**
20-22 September 2021
Online

Bacterial Cellulose as a Building Material: Identifying opportunities, limitations and challenges

Heran Yang[1,3], Ruth Morrow[1,3], Ben Bridgens[1,3], Meng Zhang[2,3], Joshua Loh[2,3], Meng Zhang[2,3], Martyn Dade-Robertson[1,3]

1: School of Architecture, Planning and Landscape, Newcastle University, Newcastle, NE1 7RU, UK

2: Department of Applied Sciences, Northumbria University, Newcastle, NE1 8ST, UK

3: Hub for Biotechnology in the Built Environment

Abstract
Bacterial cellulose (BC), a bacteria-synthesised cellulose material, has been intensively researched in biomedical, food and packaging over several decades. However, its application in the built environment (BE) has received less attention. This paper scopes out BC's original properties and the methods used to modify them. This capability to modify the properties of BC offers exciting possibilities for creating building components with low environmental impact, enhanced properties and targeted performance. In its unprocessed hydrogel state, BC yields promising strength and durability. This biodegradable material's production process can be sustained by several waste streams, making it a promising material for the circular economy. When used in composites, BC can act as a scaffold for multiple nanoparticles and polymers, extending its properties to, for example, provide electrical conductivity or antimicrobial surfaces. However, to support BC's application in the BE, the material must be studied at multiple scales, namely nano-, micro- and macro-scale. Standardised tests need to be developed and tailored to measure BC behaviour under complex BE scenarios. Its interaction with humidity, durability and its regenerative properties are identified as potentially fruitful areas for further investigation.

Introduction
Bacterial cellulose, usually generated as a pure cellulose gelatinous mat, secreted by a genus of bacteria known as Komagataeibacter, has garnered increased attention over recent years. Its first appearance in scientific paper dates to 19th century. Since then, traditional modification methods applicable to other cellulosic materials have been tested on BC, such as acetylation: a chemical surface treatment that makes this hydrophilic hydrogel repellent to water [1]. Other modification methods followed, attempting to add additional functionality or to optimise its performance. Hu et al., has made BC membranes that are antimicrobial or resistant to water [2]. Due to its high purity and biocompatibility, BC has been the focus of biomedical research, as a drug delivery substrate or as artificial tissue [3]. It has also been studied as a bio-degradable material source for packaging [4]. To date, the only BE-related application identified for BC has been as a reinforcing admixture for concrete [5].
BC is a product of a distinctive group of bacteria. Its formation, or fermentation, is typically sustained in a liquid nutritious culture medium in the presence of oxygen. The culture medium provides the bacteria with carbon and nitrogen sources, both indispensable to support the producer bacteria's metabolism. Several additives can be used in the culture medium to alter the BC membrane property, embedding extra functionality or interfering with its formation. The cellulose-genesis process will initiate once the required conditions are met, the carbon source will be consumed and extruded into β-1,4-glucan chains, a polysaccharide [6]. During extrusion, the cellulose-producing bacterium cell divides, creating numerous entangled and interconnected branches of polysaccharide chains, forming cellulosic ribbons, approx. 40 – 60 nm wide [7]. With hydroxyl groups interacting with each other and with the water, these ribbons form a 3D meshed polysaccharide network in the form of a hydrogel mat that floats on the medium-to-air interface [8].
This paper draws on an extensive body of BC research. Over 250 sources from both fundamental science, applied science and DIY experimentation were reviewed, with only the most significant sources cited in this abstract. The paper reflects on the demands and requirements of BC as a building material in terms of production efficiency (yield), mechanical properties, durability, aesthetics and

functionality. Chemical substances, treatments and growing methods are reviewed in terms of their utility and efficiency. The paper also looks for a trajectory of research that indicates possible application of BC in the built environment.

Intrinsic properties

The key properties of BC are hydrophilicity, high crystallinity, high purity, excellent biocompatibility and probable UV-resistance. BC hydrogel membrane has a high water holding capacity, thanks to the hydroxyl groups on the entangled cellulose chains [8]. The consistently repeating biosynthetic process also gives BC a high crystallinity, as well as purity [6]. Its high crystallinity indicates higher tensile strength in comparison with other cellulosic materials [9]. Some researchers have suggested that BC is formed by the producer bacteria as a protection mechanism against UV radiation, whilst allowing liquid culture media to access oxygen [8]. Whilst these properties show potential for a range of applications in the built environment, a deeper understanding of both BC properties and the functional requirements of different building components is required to identify beneficial applications. In terms of the tensile strength and elastic modulus of BC, there is considerable variation, across scientific papers due to the varied nature of BC and means of testing. For example, following some simple loading experiments Cazón et al, record them as 20 MPa and 1GPa respectively [10]; Dayal and Catchmark report the elastic modulus to be around 7.55 MPa [11]; and according to Damsin, an unsterilised wet BC pellicle has an elastic modulus of 25 MPa, compared to 100 MPa for a sterilised, dried BC pellicle [12]. The literature search revealed little data regarding durability against chemical, biological or atmospheric corrosive agents, all of which are present in external BE applications. As a biopolymer, BC is considered to have low resistance to photo-degradation, similar to petrol-chemical-based polymers, which usually exhibit low UV-resistance in the absence of antioxidants or stabilizers [13]. Furthermore, BC mechanical performance, UV resistance and insulative properties are reported to be humidity-sensitive [10].

Properties enhanced through modifications

In-situ modification methods can be carried out through selecting producer bacteria, co-culturing, choosing nutritional sources, additives and bioreactors.

The type of **producer bacteria** can influence production efficiency and BC grown form, among them Komagataeibacter is the most productive genus, producing long, consistent fibrils in the form of a gelatinous mat [14]. As the core concept of engineered living materials, the producer bacteria can be edited at a genetic level [15] and material microstructural patterns can be generated through a genetic strategy [16]. Levantis, a biodesigner, has proposed editing bacteria in a way that allows their production to be activated by light, enabling localised control of cellulose production, similar to a 3D printer [17]. This method could potentially be used to *grow* BC with complex geometry.

Co-culturing is a process whereby multiple microorganisms are hosted in a single culture medium. This method can be used to increase the yield or build in additional functions. It was proved feasible by Liu and Catchmark, who co-cultured *Escherichia coli* to produce a yield-boosting substance for BC producer bacteria [18]. Das et al. have co-cultured BC with photosynthesising microalga, exploring their symbiotic relationship to fabricate a new type of living biomaterial [19].

Carbon and nitrogen sources are indispensable as **nutrition** and, in many cases, influence the yield and mechanical properties. Some carbon sources can boost the production, such as arabitol [20]. In comparison, lactose and sucrose are less effective [6]. Some are reported to increase mechanical performance, like mannose [21]. An increased fire-resistance can be achieved by using glucose phosphate as carbon source [22]. Typical nitrogen sources include yeast extract and peptone and among them, substances like vitamins and nicotinic acid can increase yield [23]. It should be noted, however, that the use of refined chemicals, involves intensive energy and material input [24].

Additives can affect production efficiency, mechanical properties and functionality. Antibiotics, such as nalidixic acid, are reported to interfere with cell division and protein activities, influencing mechanical properties [7]. Some, including agar, can alter the viscosity of the medium, and influence the yield and mechanical properties [25]. Starch can also change the medium viscosity, causing reduced crystallinity and changes in mechanical properties in different water content [26]. Sodium carboxymethyl cellulose can inhibit the formation of nanofibril bundles, changing the material crystallisation and internal stress [27]. Caffeine is reported to stimulate the BC growth, increasing the yield [23]. Vegetable oil is reported to signficantly increase the yield and water-holding capacity and potentially the mechanical strength [28]. Metal and metal oxides have been used in the biomedical context to add functions, such as antibacterial [29].

Bioreactors, reviewed by Campano et al., are the containers where the BC biosynthesis process occurs. Increasing the air transfer ratio is critical for biodesigners, who often use tray-like containers to produce large BC membranes [30]. Multiple designs of airlift bioreactors have also been proposed [31].

Strategies, such as intermittent feeding, can make use of limited volume to effectively interact with air [32]. Agitation or air-pumping can increase oxygen exchange and the yield at the cost of forming a disrupted BC mass [33]. Plastics such as polyvinylchloride can be used as substrate or scaffold to host BC growth [34].

Ex-situ methods involve sterilisation, drying, chemical and mechanical treatment.

Typically the BC hydrogels discussed in the literature are **sterilised** in boiling sodium hydroxide solution, thus disabling its bacterial activity. **Drying** can be achieved using air-convection, heat-press-drying, vacuum-drying and freeze-drying, though properties of BC are subject to change [35]. **Chemical treatment** on the surface or through impregnation has been found to change BC's water-resistance, thermal stability or structure performance and ethylene glycol etc. can alter the BC mechanical properties [12]. For example, BC impregnated with glycerol is reported to develop long-term water resistance [36]. And application of chitosan acetic acid solution allows BC to develop resistance against thermal degradation [37]. Chemical grafting is a common surface treatment to make BC antibacterial, water-repellent or transparent [38]. **Mechanical treatments** can alter physical appearance and form. Dry moulding results in shrinkage [39] and hot pressing alters the physical appearance, making it brittle but stiffer [12]. Grinding and casting BC is commonly used by designers, where BC is first shredded and a chemical binder added, before being added to a mould [40]. Stitching BC components together also appears to be durable enough for use in clothing[36].

Opportunities and Reflection

BC can be modified at multiple scales and at many stages within the manufacturing process, but to date its behaviour and performance has been investigated in limited contexts. However the growing body of research indicates that BC has characteristics that are conducive to BE applications, in terms of production efficiency (yield), durability, mechanical properties, aesthetics and potential other unique functionalities.

Large scale BC production faces challenges, in terms of energy and material input, when using refined substances to support BC growth. However, research indicates that utilisation of waste streams offer potential nutritional alternatives for BC growth [38]. More data is needed to reveal its durability in outdoor environments, but given its similarity to other polymers, its exterior applications might be evaluated as a trade-off between decomposability and durability. However, it should be noted that when used as a blood vessel substitute, BC is relatively durable with only negligible degradation [41]. Vegetable oil offers an interesting path for further investigation, given its protective nature and ability to boost production and since some types of oil are used as wood stabilisers, this might also inform future weathering strategies [28]. Oil might also turn out to be an interesting method to achieve insulative performance, interfering with BC mesh formation and entrapping air bubbles. BC is likely to exhibit low UV-resistance, a similar challenge faced by many polymers, especially in the absence of antioxidants or stabilizers [13]. Its mechanical performance and UV resistance are also reported to be humidity-sensitive, which is a significant issue for external built environment applications [10]. In addition BC's reaction to water may offer unique strategies to manage water-related aspects. Its mechanical and aesthetic properties are demonstrated through apparel designs [42]. Although exhibiting limited strength and stiffness in its raw form, this can be compensated for by selecting the right nutrition, additives, in-situ and ex-situ composites and treatment. Notably, similar to an elastomer, BC's microstructure can realign to applied load [43]. Without sterilisation, the bacteria are likely to remain alive, maintaining a certain level of self-healing for the material. BC's unique properties, in relation to changes over time and in respect to built environmental context, need further study.

Deleted: ¶

References

[1] Kim DY, Nishiyama Y, Kuga S Surface acetylation of bacterial cellulose. Cellulose, 2002 9:361–367
[2] Hu W, Chen S, Yang J, Li Z, Wang H Functionalized bacterial cellulose derivatives and nanocomposites. Carbohydr Polym, 2014. Carbohydr. Polym.
[3] Heßler N, Klemm D Alteration of bacterial nanocellulose structure by in situ modification using polyethylene glycol and carbohydrate additives. 2009 899–910
[4] Cazón P, Velázquez G, Vázquez M Bacterial cellulose films: Evaluation of the water interaction. Food Packag Shelf Life, 2020 25:100526
[5] Akhlaghi MA, Bagherpour R, Kalhori H Application of bacterial nanocellulose fibers as reinforcement in cement composites. Constr Build Mater, 2020 241:118061
[6] El-Saied H, Basta AH, Gobran RH Research progress in friendly environmental technology for the production of cellulose products (Bacterial cellulose and its application). Polym - Plast Technol Eng, 2004 43:797–820
[7] Yamanaka S, Sugiyama J Structural modification of bacterial cellulose. Cellulose, 2000 7:213–225
[8] Gama M, Gatenholm P, Klemm D Bacterial NanoCellulose: A Sophisticated Multifunctional Material J Chem Inf Model, 2012
[9] Lee KY, Tammelin T, Kiiskinen H, Samela J, Schlufter K, Bismarck A Nano-fibrillated cellulose vs bacterial cellulose: Reinforcing ability of nanocellulose obtained topdown or bottom-up. ECCM 2012 - Compos Venice, Proc 15th Eur Conf

Compos Mater, 2012 24–28
[10] Cazón P, Velazquez G, Vázquez M Characterization of mechanical and barrier properties of bacterial cellulose, glycerol and polyvinyl alcohol (PVOH) composite films with eco-friendly UV-protective properties. Food Hydrocoll, 2020 99:105323
[11] Dayal MS, Catchmark JM Mechanical and structural property analysis of bacterial cellulose composites. Carbohydr Polym, 2016 144:447–453
[12] Damsin B Bacterial Cellulose: New bio-composites based on bacterial cellulose for architectural membranes. 2019. Vrije Universiteit Brussel
[13] Ashby M, Shercliff H, Cebon D Engineering , Science , Processing and Design 2007
[14] Jonas R, Farah LF Production and application of microbial cellulose. Polym Degrad Stab, 1998 59:101–106
[15] Nguyen PQ, Courchesne NMD, Duraj-Thatte A, Praveschotinunt P, Joshi NS Engineered Living Materials: Prospects and Challenges for Using Biological Systems to Direct the Assembly of Smart Materials. Adv Mater, 2018 30:1–34
[16] Walker KT, Goosens VJ, Das A, Graham AE, Ellis T Engineered cell-to-cell signalling within growing bacterial cellulose pellicles. Microb Biotechnol, 2019 12:611–619
[17] Levantis I Project:JuicyPrint. 2014. https://biohackspace.org/projects/juicyprint/
[18] Liu K, Catchmark JM Enhanced mechanical properties of bacterial cellulose nanocomposites produced by co-culturing Gluconacetobacter hansenii and Escherichia coli under static conditions. Carbohydr Polym, 2019 219:12–20
[19] Das AAK, Bovill J, Ayesh M, Stoyanov SD, Paunov VN Fabrication of living soft matter by symbiotic growth of unicellular microorganisms. J Mater Chem B, 2016 4:3685–3694
[20] Mikkelsen D, Flanagan BM, Dykes GA, Gidley MJ Influence of different carbon sources on bacterial cellulose production by Gluconacetobacter xylinus strain ATCC 53524. J Appl Microbiol, 2009 107:576–583
[21] Liu K, Catchmark JM Effects of exopolysaccharides from Escherichia coli ATCC 35860 on the mechanical properties of bacterial cellulose nanocomposites. Cellulose, 2018 25:2273–2287
[22] Basta AH, El-Saied H Performance of improved bacterial cellulose application in the production of functional paper. J Appl Microbiol, 2009 107:2098–2107
[23] Fontana JD, Franco VC, De Souza SJ, Lyra IN, De Souza AM Nature of plant stimulators in the production of Acetobacter xylinum ("tea fungus") biofilm used in skin therapy. Appl Biochem Biotechnol, 1991 28–29:341–351
[24] de Araújo e Silva R, Santa Brígida AI, de Freitas Rosa M, da Silva Neto RM, Spinosa WA, Benício de Sá Filho E, Brito de Figueirêdo MC An approach for implementing ecodesign at early research stage: A case study of bacterial cellulose production. J Clean Prod, 2020. J Clean Prod.
[25] Ishida T, Sugano Y, Nakai T, Shoda M Effects of acetan on production of bacterial cellulose by acetobacte xylinum. Biosci Biotechnol Biochem, 2002 66:1677–1681
[26] Grande CJ, Torres FG, Gomez CM, Troncoso OP, Canet-Ferrer J, Martínez-Pastor J Development of self-assembled bacterial cellulose-starch nanocomposites. Mater Sci Eng C, 2009 29:1098–1104
[27] Chen HH, Chen LC, Huang HC, Lin S Bin In situ modification of bacterial cellulose nanostructure by adding CMC during the growth of Gluconacetobacter xylinus. Cellulose, 2011 18:1573–1583
[28] Żywicka A, Junka AF, Szymczyk P, Chodaczek G, Grzesiak J, Sedghizadeh PP, Fijałkowski K Bacterial cellulose yield increased over 500% by supplementation of medium with vegetable oil. Carbohydr Polym, 2018 199:294–303
[29] Shah N, Ul-Islam M, Khattak WA, Park JK Overview of bacterial cellulose composites: A multipurpose advanced material. Carbohydr Polym, 2013 98:1585–1598
[30] Õun R Crafting organic waste for fashion. 2019. https://www.riinao.com/lab
[31] Lee KY, Buldum G, Mantalaris A, Bismarck A More than meets the eye in bacterial cellulose: Biosynthesis, bioprocessing, and applications in advanced fiber composites. Macromol Biosci, 2014. Macromol Biosci.
[32] Hsieh YC, Yano H, Nogi M, Eichhorn SJ An estimation of the Young's modulus of bacterial cellulose filaments. Cellulose, 2008. Cellulose.
[33] Damsin B Higher BC yield with aquarium air filter. 2019
[34] Cacicedo ML, Castro MC, Servetas I, Bosnea L, Boura K, Tsafrakidou P, Dima A, Terpou A, Koutinas A, Castro GR Progress in bacterial cellulose matrices for biotechnological applications. Bioresour Technol, 2016 213:172–180
[35] Clasen C, Sultanova B, Wilhelms T, Heisig P, Kulicke WM Effects of different drying processes on the material properties of bacterial cellulose membranes. Macromol Symp, 2006 244:48–58
[36] Kamiński K, Jarosz M, Grudzień J, Pawlik J, Zastawnik F, Pandyra P, Kołodziejczyk AM Hydrogel bacterial cellulose: a path to improved materials for new eco-friendly textiles. Cellulose, 2020 27:5353–5365
[37] Cai Z, Chen P, Jin HJ, Kim J The effect of chitosan content on the crystallinity, thermal stability, and mechanical properties of bacterial cellulose-chitosan composites. Proc Inst Mech Eng Part C J Mech Eng Sci, 2009 223:2225–2230
[38] Andriani D, Apriyana AY, Karina M The optimization of bacterial cellulose production and its applications: a review. Cellulose, 2020 27:6747–6766
[39] Bloch K Micro - Design Potential of Microbial Cellulose in Growing Architecture Master. 2019. Chalmers School of Architecture
[40] Iguchi M, Mitsuhashi S, Ichimura K, Nishi Y, Uryu M, Yamanaka S, Kunihiko W Bacterial Cellulose-Containing Molding Material Having High Dynamic Strength. United States Pat, 1988. United States Pat.
[41] Pértile RAN, Moreira S, Gil Da Costa RM, Correia A, Guardão L, Gartner F, Vilanova M, Gama M Bacterial cellulose: Long-term biocompatibility studies. J Biomater Sci Polym Ed, 2012 23:1339–1354
[42] Suzanne Lee, Congdon A, Parker G, Borst C UNDERSTANDING " BIO " MATERIAL INNOVATIONS : a primer for the fashion industry. 2020
[43] Gao X, Sözümert E, Shi Z, Yang G, Silberschmidt V V. Mechanical modification of bacterial cellulose hydrogel under biaxial cyclic tension. Mech Mater, 2020 142:103272