BACTERIAL CELLULOSE: A REVIEW FOCUSED ON TECHNOLOGICAL OPPORTUNITIES IN INDUSTRIAL PRODUCTION AND BIOMEDICAL APPLICATIONS

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ABSTRACT

Bacterial cellulose (BC) is a versatile and sustainable biopolymer with significant industrial and biomedical applications. Produced by bacteria like *Komagataeibacter xylinus*, BC boasts higher purity and better mechanical properties compared to plant cellulose. The main production challenges include high cultivation costs and low industrial productivity. Advances in genetic modification and fermentation technologies, such as CRISPR and automated bioreactors, aim to overcome these hurdles. Additionally, BC's applications span diverse fields as: creating dressings, biomedical devices, food packaging, and biodegradable straws.. The growing interest in BC is driven by the need for eco-friendly materials in response to environmental challenges. Continued research and innovation in production processes are essential for maximizing BC's potential in contributing to environmental sustainability and technological advancements across multiple sectors.

Keywords: Metabolic engineering. Sustainable materials. Biomaterials. *Komagataeibacter*

1 INTRODUCTION

Due to the global impacts caused by human activities, especially environmental problems, there has been a growing interest in society and particularly within the scientific community for the development of environmentally friendly materials.[1]

Cellulose is the most abundant polymer in nature and has significant industrial applications. It can be found in the cell walls of plant cellulose along with lignin and hemicellulose, and can also be synthesized by certain types of bacteria such as *Komagataeibacter xylinus* and *Acetobacter xylinum*.[2]

Cellulose produced from microorganisms has higher purity compared to plant cellulose, and is easier to purify, involving only the use of dilute sodium hydroxide solutions. Additionally, it has high crystallinity and nanometric fibers, which provide it with good mechanical properties.[2]

In recent years, much research has been conducted on the use of bacterial cellulose (BC) for the creation of new technologies, such as in the development of dressings, grafts, biomedical devices, food packaging, and biodegradable straws.[1,3,16] The main difficulties in the production of bacterial cellulose are associated with the high cost of the cultivation medium and the low productivity on an industrial scale, which stimulates numerous research efforts to find alternative sources.[4]

The continuous advancement in the research and application of bacterial cellulose represents a promising field in both industry and the biomedical area. This article aims to explore the emerging trends and various applications of this versatile and sustainable biopolymer.

2 MATERIAL & METHODS

A literature review was conducted aiming to identify relevant and updated studies on the subject in question. The search was performed in electronic databases such as "Google Scholar", "SciELO", "ScienceDirect" and the "Virtual Health Library", with publications from the period 2017 to 2024.

3 DISCUSSION

The most efficient microorganisms for the production of bacterial cellulose are Gram-negative bacteria belonging to the genus *Acetobacter*, *Acetobacter hansenii* and *Acetobacter pasteurianus,* and especially *Komagataeibacter xylinus* (formerly *Gluconacetobacter xylinus*).[15,22]

Bacterial cellulose can be produced in static, agitated, or stirred conditions by the fermentation process; each different production conditions lead to different forms of cellulose,[18] providing diverse characteristics depending on the conditions to which it is subjected. BC is produced intracellularly in the form of β-1,4-glucan chains (1Å). Each intracellularly synthesized β-1,4-glucan chain is comprised of about 15,000 glucose monomers. The abundance of these chains are secreted to the extracellular environment, where these are organized at a rate of up to 200,000 glucose molecules per second and form 2-4 nm diameter protofibrils, also termed sub-elementary fibrils, which are comprised of 12-16 glucans. Glucans are aligned and stacked to form cellulose microfibrils (1 nm) which then form micro- and macro-fibrils, bundles (3-4 nm), and finally ribbons (30-100 nm). Ribbons represent a 3D network structure comprised of up to 1000 glucans, which form a pellicle of varying thickness (2-10 mm). The produced cellulose fibrils within the culture medium form pre-mature cellulose, cellulose pellicle, and cellulose sheet through a self-aggregation process involving hydrogen bonding. The sheet becomes thicker when more pellicles are added to it.[10]

The main challenge in scaling up the production of bacterial cellulose is the lack of cost-effectiveness due to low productivity. One of the major disadvantages is the significant variation in nutritional requirements and production efficiency among different strains of *Komagataeibacter*, as well as the spontaneous formation of unstable Cel-negative mutants (non-bacterial cellulose-producing mutants) in shaken cultures, which leads to the consumption of nutrients for cell growth and multiplication without cellulose production.[21]

Due to the issues in large-scale bacterial cellulose production, various methodologies such as homologous recombination, heterologous gene expression, and new techniques like *CRISPR* have been employed by researchers to modify the genome of bacterial cellulose-producing bacteria. The recent sequencing of genomes of some *Komagataeibacter* strains has provided the necessary impetus for this research direction.[21]

It was only in 2019 that metabolic engineering emerged as a way to improve the yield of bacterial cellulose production. In an impressive set of works conducted by a team of researchers based at Samsung and KAIST in South Korea, a genome-scale metabolic model of a *K. xylinus* strain was constructed for the first time by collecting data from genome sequencing and metabolome analysis of this strain.[20] Figure 1 represents a general scheme of genetic modification.

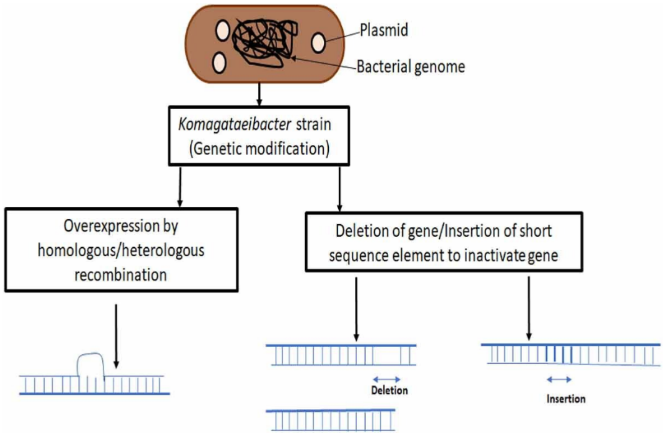

Figure 1 Genetic modification: A general scheme in *K. xylinus.*

Source: Singhania *et al*. 2021

Another promising direction to increase the productivity of the bacterial cellulose production process is the upgrading of fermentation equipment. Pilot-scale production under agitated conditions in a modified 50 L bubble column bioreactor using saccharified food waste as feedstock has been reported. Stirred tank bioreactors serve as a tool to increase production and lead to higher yields of bacterial cellulose.[2]

The majority of experiments within the dataset analyzed in the literature involved vial volumes smaller than 1 L. Therefore, it is necessary to increase studies on the optimization and scaling of bioreactors using new technologies such as Artificial Intelligence and Automation Systems to achieve results fully automatic and sustainable biointelligent manufacturing.[17]

As a result of its properties, bacterial cellulose has been increasingly utilized across various industrial sectors, either in its pure form or in combination with other compounds. The following Table 1 illustrates some of the applications of BC.

Table 1 Applications of BC across different industries based on its specific properties.
Source: Authors. 2024

Industry	Application	Properties of BC enabling application	References
Food Industry	Edible cellulose, food additive, functional film, packaging	Emulsifying properties, low digestible sugar content, antimicrobial properties	Jiang, Z., Cheung, K.M., Ngai, T. (2023)[15]
Textile	Shoes, purses, clothing, tents and camping equipment	High mechanical strength, hydrophilicity, moldability	Nayak, R., *et al*. (2024)[16]
Cosmeceuticals	Face masks, creams, tonics	Ability to absorb exudates during the inflammatory phase, antimicrobial properties	Pacheco, G., *et al*. (2017)[17]
Biomedical	Artificial skin for burns and ulcers, curative for wound care, electronic skin	Biocompatibility, low cytotoxicity	Jiang, G., *et al*. (2022)[18]

In the literature, reports are found on the applicability of BC for different purposes. A recent study addresses the applicability of bacterial cellulose in the preservation of chilled beef using active films based on bacterial cellulose and other components, presenting positive results.[11]

Researches are also conducted in the fashion industry, where studies about the improved mechanical properties of BC nanocomposites, resulting in robust and flexible materials with promising properties for applications in the textile and shoe industries.[5]

In the biomedical field, skin repair treatments such as biotechnological dressings based on BC are used in cases of burns, wounds, and ulcers, as BC membranes accelerate the healing process and prevent infections.[19]

Studies show that bacterial cellulose can also be associated with other components. In one study, bacterial cellulose was modified using cyclic anhydrides, both unsubstituted and long-chain substituted, as esterifying agents. This efficient and environmentally friendly method resulted in bacterial cellulose films with excellent mechanical properties, as well as barriers against water vapor, oxygen, and foodborne pathogenic bacteria. Additionally, the films show visible improvements in thermal stability and are biodegradable in soil within one month, demonstrating great potential to replace widely used petrochemical-based plastic food packaging materials.[15]

In recent research, BC is applied as a base material for the fabrication of ionogels, which are used in electronic skins (e-skin). These ionogels, developed from molecularized BC polymer fibers, combine high tensile strength and high ionic conductivity. The resulting e-skin can respond to stimuli such as pressure, touch, temperature, humidity, magnetic force, and astringency, showing great potential for soft robotics, artificial intelligence, and biomedical devices.[8]

These studies approach the versatility of bacterial cellulose as an innovative material with applications in multiple sectors. With the continuous advancement of research, it is expected that new applications and technological improvements will further consolidate the role of bacterial cellulose in industry.

4 CONCLUSION

The growing academic and industrial interest in bacterial cellulose (BC) is driven by the need for environmentally friendly solutions in response to increasing global environmental problems caused by human activities. Exploring alternative sources of substrates, such as food waste, and integrating emerging technologies like Artificial Intelligence offer viable pathways to overcome the current limitations of BC production.The studies reviewed in this article show that with continuous advances in the understanding and genetic manipulation of cellulose-producing bacteria, as well as innovation in production processes, bacterial cellulose has the potential to become a widely used material. This material can significantly contribute to environmental sustainability and technological innovations across various industries.

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