Bacterial cellulose: purer and stronger than plant cellulose

Grandma: What is that giant squid floating in the vinegar you made?

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Cellulose produced from bacteria

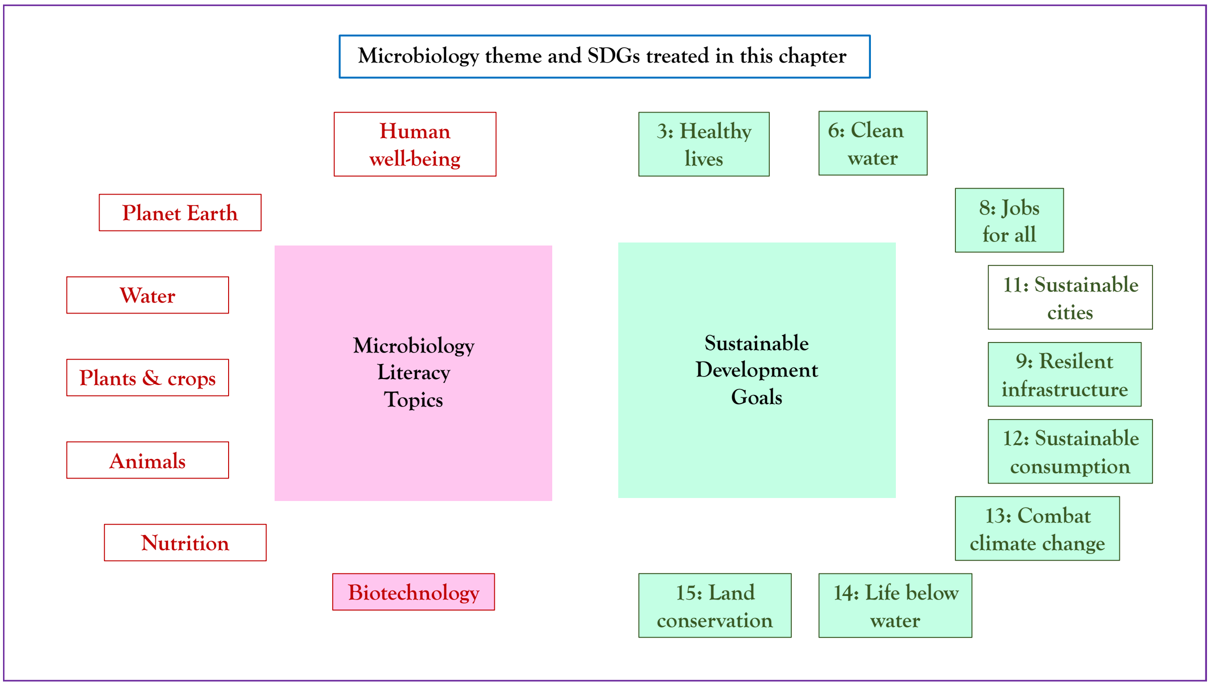
Storyline

Bacterial cellulose (BC) was first discovered in 1886 by a scientist named A.J. Brown. While studying bacteria in vinegar, he noticed that some of them produced a thin, jelly-like film on the liquid's surface, which reminded him of the texture of squid. This film turned out to be a material made entirely of cellulose — a substance usually found in plants. But unlike plant-based cellulose, this new type came from bacteria, and it had some unique properties that intrigued scientists.

At first, BC might have seemed like a small discovery, but over the decades, researchers began to realize its enormous potential. BC stands out as a purer, stronger alternative to plant-based cellulose, offering the advantage of being produced more sustainably without the need for deforestation, the depletion of other natural resources and chemical extraction. The damage caused by logging hurts both the planet and our health, making it even more important to find alternatives. BC can be grown simply by providing the right conditions for bacteria. That is why BC has become such an exciting material for areas like medicine, environmental science, and technology.

The Microbiology and Societal Context

The microbiology: sugar fermentation; extracellular production; architectural organic work; sustainable biotechnology; vinegar production; acidification. *And, peripherally for completeness of the storyline*: non-agricultural resource attribution; biomedicine scaffolds. *Sustainability issues:* health; economy and employment; environmental pollution; global warming.



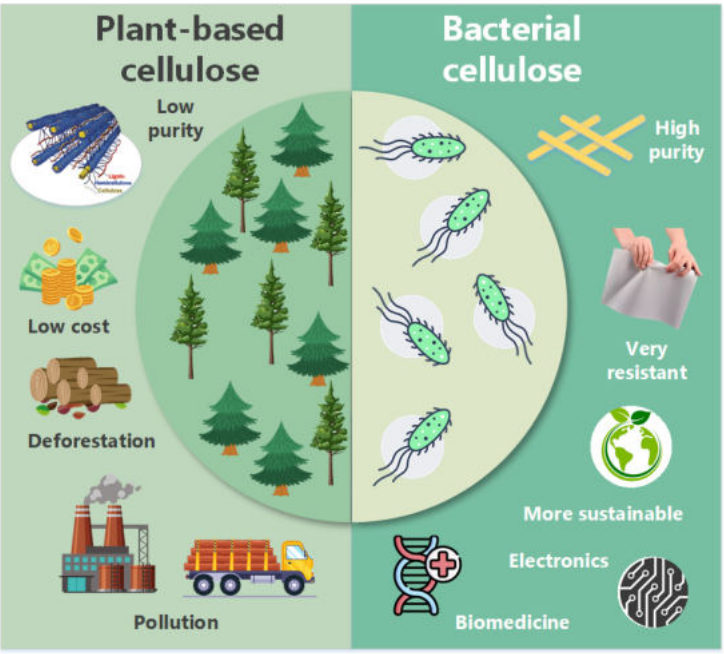
Bacterial cellulose: purer and stronger than plant cellulose

1. ***Obtaining cellulose from wood is very cheap but… is it a sustainable and environmentally beneficial practice?*** Cellulose, the main component of wood, is widely used in industries such as textiles, paper, and packaging, due to its affordability and versatility. However, concerns about sustainability and environmental impact accompany its low cost. The large-scale logging required for cellulose production can lead to **deforestation**, habitat destruction, **biodiversity** loss, reduction in forest-mediated carbon capture, and deterioration and loss of soil, contributing to environmental degradation if not properly managed. Additionally, the chemical processes used to extract cellulose can release pollutants into water and air.

Sourcing wood from sustainably managed forests, where logging is regulated and reforestation is enforced, can make the cellulose industry more **eco-friendly**. In such cases, wood-based cellulose may align with sustainability principles, as trees, when responsibly harvested, act as renewable resources that help absorb carbon dioxide and mitigate **climate change**.

Thus, while wood-based cellulose is economically attractive, its sustainability hinges on responsible forest management and eco-conscious production. Transitioning to more sustainable practices, such as using recycled materials or cellulose from non-wood sources like agricultural waste, could provide greener alternatives.

2. ***Is it possible that tree bark is a hindrance for plant cellulose to be used, for example, in medicine?***

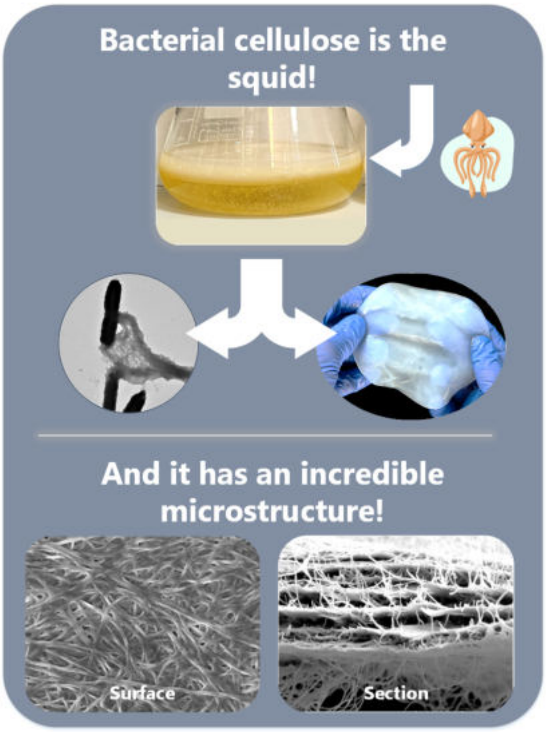


One of the main issues with plant cellulose is its structural irregularity and lower purity. Plant-based cellulose contains other components like **lignin** and **hemicellulose**, which can affect its performance in applications requiring high purity and uniformity. Moreover, plant cellulose fibers are relatively thick and lack the fine nanostructure required in applications like medical materials, wound dressings, or certain high-performance composites. Its rigidity can also be a drawback when flexibility is needed, such as in **flexible electronics** or delicate **biomedical scaffolds**.

In contrast, BC offers several advantages in these contexts. It is produced by certain bacteria, such as *Komagataeibacter xylinum*, through fermentation, resulting in a purer form of cellulose that doesn't contain lignin or other plant-based contaminants. Its nanofiber network is much finer and has greater **tensile strength**, providing exceptional mechanical properties.

Its ability to form thin, flexible, yet strong films makes it suitable for uses in high-tech areas such as flexible displays or advanced filtration systems. Additionally, because it can be grown in controlled environments, BC production can be more sustainable, with fewer chemical inputs and less environmental harm compared to traditional plant cellulose extraction.

3. ***Bacterial cellulose is an architectural work constructed by bacteria working in an organized way, as if they were an orchestra.*** This fascinating material is formed through an intricate and highly organized process yielding a fiber web. Bacteria responsible for the net construction work in perfect unison, much like musicians in an orchestra, each contributing to the complex structure in a coordinated and rhythmic mode.



Each bacterial cell produces fine cellulose fibrils from pores that forms ribbons, which, through the simple movements of individual cells, become entangled into a robust network. This dynamic interaction of bacteria constantly moving and extruding fibrils results in the formation of the BC pellicle. As the bacteria construct the net on the surface of the liquid they inhabit, they create tunnels with a crucial purpose: they can move upward, toward the air, in search of oxygen, and downward, toward the liquid, in search of nutrients.

Through this collective effort, BC takes shape layer by layer, forming a durable, flexible, and resilient material. Each bacterium plays its part, contributing to a biologically engineered masterpiece—a living architectural work.

This process results in a material with extraordinary properties, including high tensile strength, flexibility, and an ability to retain moisture, making BC ideal for applications ranging from wound dressings to environmentally friendly packaging. The ability of the bacteria to organize themselves and produce a functional, adaptable structure exemplifies the precision and beauty of natural processes.

4. ***The microbiology behind the bacterial artists, with a diet based on sugar, nitrogen and oxygen.*** BC production in *Komagataeibacter* species is a well-coordinated process driven by several key genes. BC is not just a structural component in biofilms but also plays ecological roles, such as protecting bacteria from UV light and helping them survive in low-oxygen environments.

The core machinery for producing BC is conserved among bacteria, but some key components in *Komagataeibacter* gene cluster (*bcs*) give their cellulose unique properties. These *bcs* genes encode the proteins involved:

- BcsABC complex: This complex comprises the enzymes responsible for linking sugar molecules (UDP-glucose) together to form cellulose chains (BcsA), translocation along the peptidoglycan (BscB) and secretion through the outer membrane, acting as a pore so that the cellulose can be released outside the cell (BcsC).
- The *Komagataeibacter* species are characterized by the presence of a genus-specific gene (*bcs*D) encoding a crystallinity-related protein. BcsD, together with its complementing factor (BcsH), is involved in setting the distances between synthase complexes (BscABC)

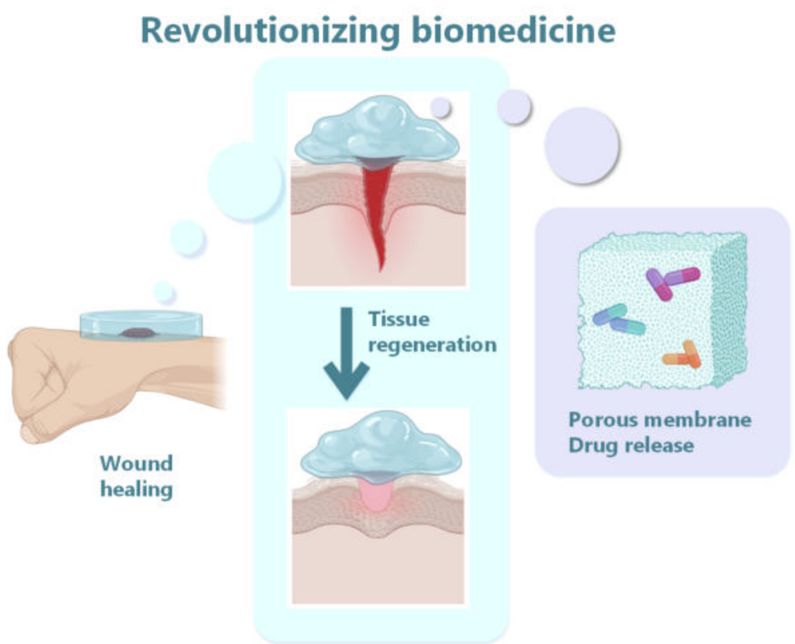
to allow for the crystallization of the polymer outside the cell, ensuring they are spaced correctly to form highly crystalline and strong cellulose.

5. ***Can bacteria be made to produce cellulose with the properties we want?*** Synthetic biology treats DNA as modular code, allowing for extensive biotechnological advancements since 2000, particularly in microbes like *E. coli* and *S. cerevisiae*. These organisms have rich genome data, enabling the creation of modular DNA toolkits that allow for novel genetic programs. While BC-producing organisms like *Komagataeibacter* lag behind, progress has been made in applying synthetic biology to engineer new functionalities in these bacteria.

From 2016, some researchers introduced a modular DNA toolkit and CRISPR-based tools for BC-producing *K. rhaeticus*, enabling controlled gene expression and spatial patterning in growing cellulose pellicles. This work demonstrated how external signals like acyl-homoserine lactone (AHL) could regulate gene expression, resulting in self-sensing materials that alter gene expression based on cell boundaries.

Researchers have also explored the production of composite materials and BC copolymers by introducing genes from other organisms. For instance, chitin-cellulose copolymers and protein-based materials with enhanced properties have been produced. Synthetic biology holds potential for creating BC materials with new functional properties, such as biosensing, pollutant degradation, and programmable cell behavior. However, future work is still needed to further engineer *Komagataeibacter* strains for protein secretion, which could enable cellulose materials embedded with functional proteins, opening possibilities in fields like water filtration and regenerative medicine.

6. ***Bacterial cellulose-based dressings have revolutionized biomedicine, especially for wound healing.*** Based on the described properties, BC can confidently be regarded as having vast potential for **biomedical applications**. In this field, the application of this biopolymer in the controlled release of drugs, such as BC capsules for oral intake, and in wound healing, such as antibiotic or silver dressings applied to burns to facilitate skin regeneration, stand out. This is facilitated by the porosity of the BC, which helps to load various drugs, such as antibacterial, anticancer, antioxidant and/or anti-inflammatory agents, and by the chemical modifications that can be made, which can increase control over drug release, with adaptations that may even respond to pH, temperature or electromagnetism.



Similarly, the biocompatibility of BC, its mechanical strength and ability to absorb exudates while maintaining a moist environment make it ideal for wound healing applications. BC dressings act as physical barriers against microbes while allowing gas exchange and can be removed painlessly. Optical transparency also allows for non-invasive imaging of wound healing. BC-based dressings have proven effective for full-thickness wounds, burns and bleeding control, and studies highlight the importance of BC's nanostructure in accelerating tissue recovery.

Through tissue engineering, BC has been shown to serve as a scaffold for human cells by mimicking the extracellular matrix of human cells. In addition, modifications such as the incorporation of keratin promote cell adhesion and the maintenance of cell morphology.

As proof of the success achieved with this material, we can provide the example of several brands that have marketed dressings based on BC for the treatment of burns: Biofill, XCell, Suprasorb X, Nanoderm™ and Membracel.

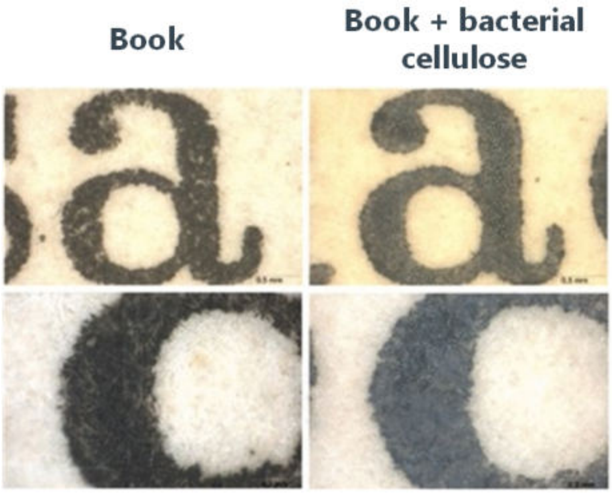
7. ***Well then, can we make clothes out of bacterial cellulose, just like cotton?*** Yes, it is possible to make clothes from BC, offering unique benefits compared to cotton. BC holds great promise for textile innovation, particularly in promoting more sustainable and eco-friendly manufacturing practices, an essential step in addressing the fashion industry's status as the second-largest polluter after the petroleum sector.

British designer Suzanne Lee pioneered this concept with her BioCouture project. By growing BC from kombucha and applying traditional garment construction techniques, she successfully created wearable items like jackets and gloves. This grown, not woven, material presents a more sustainable alternative to fibers like cotton, which require extensive water and land resources.

Another initiative, Malai, produces vegan leather using BC cultivated in a medium of coconut water and industrial byproducts. Malai's biodegradable and durable material is used to make fashion accessories in various colors, offering long-lasting wearability with proper care.

BC also holds potential in functional clothing, thanks to its breathability, moisture absorption, and antimicrobial properties. These characteristics make it ideal for performance textiles like sportswear, medical garments, and protective clothing. Unlike synthetic fibers, BC is eco-friendly and offers functional enhancements that improve comfort, hygiene, and sustainability.

8. ***Bacterial cellulose has also been used to restore old books.*** Most historical paper documents, especially those from the mid-19th to the late 20th century, suffer from



degradation by acidification, oxidation and fiber breakdown due to exposure to harmful environmental factors and the inherent instability of paper materials. Given the limitations of current conservation techniques, which use either synthetic or natural polymers, BC presents a superior alternative because of its biocompatibility, structural similarity to paper fibers, and high bonding strength. By using BC solutions applied through ultrasonic atomization, not only the mechanical properties of aged paper are improved—such as tensile strength, tear resistance, and folding endurance—but also enhances the paper's pH stability and resistance to further aging. The ability of BC to form strong inter-fiber bonds results in prolonged durability, even under stressful aging conditions. Furthermore, the non-invasive nature of this application ensures that it preserves the original appearance of paper, which is crucial for the authenticity of historical documents.

9. ***Food and industrial waste: low-cost nutrients to focus bacterial cellulose production towards a circular economy.*** The use of industrial wastes for BC production is not only cost-effective but also environmentally beneficial. For instance, agro-industrial residues such as corn stalk hydrolysates, wheat straw, and fruit peels provide an abundant source of sugars for microbial growth. Brewery and sugar industries also generate by-products like molasses, which have been used as carbon sources to produce BC. These waste streams not only lower production costs but also contribute to circular economy practices by transforming waste into valuable materials, thus promoting sustainable production and waste reduction.

This approach maximizes the use of readily available biomass, minimizes waste disposal costs, and provides a renewable feedstock for BC production. Through this integration, industries reduce their environmental footprint while supporting the large-scale commercialization of BC-based products in biomedical, food packaging, and engineering applications.

Relevance for Sustainable Development Goals and Grand Challenges

The microbial dimension of producing and using BC relates to several SDGs (*microbial aspects in italics*), including

- **Goal 3. Ensure healthy lives and promote well-being for all at all ages** (*improve health and prevent from infections).* BC's high biocompatibility, non-toxicity, and ability to promote faster wound healing make it a key material in healthcare. For example, BC dressings are used in burn treatments, promoting moisture retention and faster tissue regeneration without causing irritation. Additionally, BC can be used as a scaffold for drug delivery systems, allowing for controlled and targeted medication release, making healthcare treatments more effective. By producing BC from waste, these healthcare products become more affordable, making them accessible to wider populations, contributing to better health outcomes.
- **Goal 6. Ensure availability and sustainable management of water and sanitation for all** (*assure safe drinking water, improve water quality, reduce pollution, protect water-related ecosystems,*

improve water and sanitation management). BC's nanofiber network can be utilized in filtration systems to remove contaminants from water, making it suitable for clean water applications. Recent studies have shown BC membranes can be functionalized for heavy metal adsorption, which can purify water from pollutants like lead or mercury. By producing BC from agricultural residues or industrial by-products, the overall cost and environmental impact of water filtration systems are significantly reduced, making it easier for communities, particularly in developing regions, to access clean drinking water.

- **Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all** (*fostering sustainable economic activities and job creation).* Utilizing industrial and agricultural residues, BC production promotes green employment opportunities in sectors like biotechnology, waste management, and materials science. This supports innovation, driving industries to develop eco-friendly products like sustainable textiles and biomedical devices. BC production also empowers small and medium-sized enterprises (SMEs) in developing regions by turning waste into valuable products, thus promoting inclusive economic growth and reducing inequalities. Through this circular economy model, BC production helps industries grow sustainably, ensuring long-term economic resilience.
- **Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation** *(sustainable industrial practices and promotes innovation).* BC derived from residues like fruit peels and brewery by-products helps industries reduce dependency on raw materials while minimizing environmental impact. This process enables more efficient resource use, driving the circular economy and strengthening industrial resilience. BC's applications in textiles, packaging, and biomedicine push industries to innovate and develop eco-friendly alternatives. Additionally, BC production creates opportunities for small and medium enterprises (SMEs) to utilize local waste, enhancing inclusive and sustainable industrialization at a global scale
- **Goal 12. Ensure sustainable consumption and production patterns** *(achieve sustainable production and use/consumption practices, reduce waste production/pollutant release into the environment, attain zero waste lifecycles, inform people about sustainable development practices).* The use of agro-industrial waste, such as fruit peels, corn stalks, and brewery residues, for BC production is a prime example of responsible production. It helps industries transition to a circular economy by repurposing what would otherwise be discarded as waste. This method not only reduces waste disposal costs but also lessens reliance on natural resources, making the production cycle more sustainable and eco-friendlier. As BC is biodegradable, its use in packaging and textiles contributes to reducing the environmental footprint of industries heavily dependent on non-renewable resources like plastics.
- **Goal 13. Take urgent action to combat climate change and its impacts** *(reduce greenhouse gas emissions, reduce carbon footprint).* BC production from waste helps mitigate climate change by reducing greenhouse gas emissions. Traditional waste disposal methods, such as landfilling and burning, contribute to carbon emissions. By utilizing these waste streams for BC production, industries significantly reduce their carbon footprint. Moreover, BC production requires fewer chemicals and less energy compared to traditional cellulose extraction from trees, further lowering environmental impact. Importantly, transition away from tree-based cellulose reduces deforestation and helps maintain carbon-capturing forests. All of this will contribute to global efforts to combat climate change through innovative, low-carbon technologies.
- **Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development** *(reduce pollution of marine systems like plastics).* Since BC is biodegradable, it can serve as an eco-friendly alternative to traditional plastics in packaging,

which are a significant contributor to marine waste. By producing BC from agricultural and industrial residues, industries reduce the reliance on synthetic polymers that often end up in oceans. Additionally, BC can be used in water filtration systems, contributing to cleaner oceans by removing contaminants and pollutants from industrial wastewater. This supports efforts to minimize the release of harmful chemicals and materials into marine ecosystems, promoting healthier aquatic environments and supporting biodiversity. Through its biodegradable properties and sustainable production processes, BC offers a solution for reducing ocean pollution and protecting marine life.

- **Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss** (*reducing deforestation, preserving biodiversity*). By reducing the need for deforestation through the use of waste-based cellulose production, BC helps preserve biodiversity and ecosystems. Traditional cellulose extraction from trees often leads to habitat destruction and ecosystem disruption. BC's production from renewable waste sources minimizes environmental degradation, promoting a balance between industrial development and ecosystem conservation. This sustainable practice supports the protection of terrestrial ecosystems, essential for maintaining the planet's biodiversity.

Potential Implications for Decisions

1. ***Individual***

a. Individuals may weigh the sustainability benefits of using BC over plant cellulose. BC is produced without deforestation and is biodegradable, making it eco-friendlier. However, considerations like cost and availability may influence personal decisions. Do the environmental benefits of supporting BC outweigh the financial costs?

b. People may prefer products made from BC if they are eco-conscious, as BC has applications in medical devices, packaging, and textiles. They may need to consider if the durability, flexibility, and environmental impact align with their values, particularly in contexts such as buying sustainable clothing or medical supplies.

c. BC is highly biocompatible and non-toxic, which may influence decisions in healthcare settings (e.g., choosing BC-based wound dressings). For individuals focused on health and sustainability, BC presents a safe and environmentally sound option.

2. ***Community policies***

a. Local governments may consider policies encouraging the use of BC in place of traditional materials like plastic in packaging to reduce waste in landfills and water systems. Since BC is biodegradable, communities might encourage or incentivize industries to adopt it, reducing pollution and contributing to cleaner ecosystems.

b. As BC has applications in healthcare (e.g., wound dressings, tissue scaffolds), communities could benefit from the local production of medical supplies using BC, especially in areas lacking access to high-cost medical materials. This could lower healthcare costs and improve the availability of more sustainable medical products.

c. Communities can promote the use of BC by supporting small businesses engaged in eco-friendly production, such as those creating packaging, textiles, or other goods from BC. Policies that incentivize sustainable manufacturing would foster a circular economy.

3. ***National policies***

a. National policies could be developed to promote BC as a sustainable material to reduce deforestation, pollution, and greenhouse gas emissions. BC could be positioned as a key material in the fight against climate change by reducing reliance on wood-derived cellulose and plastics.

b. Policies encouraging the use of waste materials to produce BC (e.g., agricultural by-products, industrial residues) could advance circular economy goals. These policies would incentivize industries to use low-cost, readily available resources to produce BC, reducing both environmental impact and production costs.

c. BC has revolutionized biomedicine, especially in wound healing and tissue engineering. National healthcare systems could support the production and use of BC-based medical devices, which are cost-effective and environmentally friendly. This could lead to better healthcare outcomes while promoting sustainability.

d. Governments could provide funding and support for R&D into BC applications, further expanding its use in high-tech fields like electronics, water filtration, and biodegradable packaging. Encouraging innovation in BC production methods would strengthen national industries focused on sustainability.

Pupil Participation

1. ***Class discussion of the issues associated with cellulose production***

a. What are the differences between BC and plant cellulose?

b. How do the environmental impacts of wood-derived cellulose compare to BC production?

c. Why is BC considered more sustainable?

2. ***Pupil stakeholder awareness***

a. BC has advantages in sustainability, but it also has limitations in cost and scalability. Which aspects of its production or application are most important to you as a class?

b. Can you think of ways we can encourage the use of BC in industries such as textiles and medicine?

c. What personal actions could you take to support more sustainable material choices in your daily life?

3. ***Exercises***

a. In groups, research the environmental impacts of traditional cellulose production (e.g., deforestation, pollution) and present alternatives, such as BC, that reduce these impacts.

b. What other applications can you envision for BC outside of medicine and textiles? How could these innovations reduce environmental harm?

c. How does BC production align with different Sustainable Development Goals (SDGs) like climate action (SDG 13), sustainable consumption (SDG 12), and life below water (SDG 14)?

d. Students should create a sustainable city plan, integrating BC and its production processes to reduce pollution and waste in various sectors (e.g., water filtration, packaging).

The Evidence Base, Further Reading and Teaching Aids

Risks arising from deforestation

- Position of European Union: https://environment.ec.europa.eu/topics/forests/deforestation_en
- EU action to Protect and Restore the World's Forests: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1565272554103&uri=CELEX:52019DC0352
- Regulation of EU in 2023 on Deforestation-free Products: https://environment.ec.europa.eu/topics/forests/deforestation/regulation-deforestation-free-products_en
- Why deforestation matters—and what we can do to stop it (with explicative video): https://www.nationalgeographic.com/environment/article/deforestation
- Report on Deforestation fronts, by WWF: https://files.worldwildlife.org/wwfcmsprod/files/Publication/file/ocuoxmdil_Deforestation_fronts___drivers_and_responses_in_a_changing_world___full_report__1_.pdf

Cellulose from plants

- A board game of cellulose: https://youtube.com/shorts/AduyU-Phmy8?si=bgqstyN2NlkRU7-A
- How paper is made from cellulose: https://youtu.be/-XdwsChJTwU?si=8oNlEyRawogpvNZd
- Videos of cellulose: https://www.bbc.co.uk/bitesize/articles/z2d2gdm#zxpmm39
- Is Cellulose Fiber Safe to Eat? https://www.healthline.com/nutrition/cellulose-fiber
- Gopi, S., Balakrishnan, P., Chandradhara, D., Poovathankandy, D., & Thomas, S. (2019). General scenarios of cellulose and its use in the biomedical field. Materials Today Chemistry, 13, 59-78. https://doi.org/10.1016/j.mtchem.2019.04.012

Bacterial cellulose (BC)

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- Images of bacteria extracting cellulose fibrils by each pore: https://link.springer.com/article/10.1023/A:1020195205030

Internal structure of bacterial cellulose

- How bacteria produces layers and tunnels: Campano, C., Rivero-Buceta, V., Fabra, M. J., & Prieto, M. A. (2022). Gaining control of bacterial cellulose colonization by polyhydroxyalkanoate-producing microorganisms to develop bioplasticized ultrathin films. International journal of biological macromolecules, 223, 1495-1505. https://doi.org/10.1016/j.ijbiomac.2022.11.120

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Genetic mechanism of bacterial cellulose producers

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Engineering bacterial cellulose by synthetic biology

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Bacterial cellulose for wound healing

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How to make clothes from bacteria

- Suzanne Lee: https://youtu.be/u9u_m_QzXSI?si=fWoUPIP__y8Xby-v
- TED talk of Suzanne Lee: https://youtu.be/3p3-vl9VFYU?si=I4b6QOeR3mozvL-s
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Food valorization

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Glossary

- **Aging (paper):** Paper aging refers to the gradual chemical and physical deterioration of paper over time. This process is influenced by several factors, including the composition of the paper, environmental conditions (like light, humidity, and temperature), and exposure to pollutants. Aging often results in visible changes to the paper, such as yellowing, brittleness, and fading of printed or handwritten text.
- **Agro-industrial residues:** Agro-industrial residues are the by-products or waste materials generated during the processing of crops, plants, or livestock products in various industries. These residues include organic materials such as husks, peels, stalks, bagasse, and manure, which remain after the main products have been extracted or processed.
- **Biocompatibility:** Ability to be in contact with a living system without producing an adverse effect.
- **Biodiversity:** the variety of animals, plants, fungi, and even microorganisms like bacteria that make up our natural world.
- **Biofilm:** a community of microorganisms attached to an inert or living surface by a self-produced polymeric matrix.
- **Biomass:** Biomass is renewable organic material that comes from plants and animals.
- **Biomedical scaffold:** A scaffold serves as a structural template for cell attachment and tissue formation, and it is designed to define the shape, size, and structural properties of the forming tissues.
- **Biomedicine:** is a branch of medical science that applies biological and physiological principles to clinical practice.
- **Cellulose:** a polysaccharide consisting of a linear chain of several hundred to many thousands of $\beta(1\rightarrow4)$ linked D-glucose units. Cellulose is an important structural component of the primary cell wall of green plants, many forms of algae and the oomycetes, and some species of bacteria secrete it to form biofilms. It is the most abundant organic polymer on Earth.

- **Chitin:** the second most abundant polysaccharide in nature (behind only cellulose); it is a primary component of cell walls in fungi (especially filamentous and mushroom-forming fungi), the exoskeletons of arthropods such as crustaceans and insects, the radulae, cephalopod beaks and gladii of molluscs and in some nematodes and diatoms.
- **Circular economy:** is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible.
- **Climate change:** Climate change refers to long-term shifts and alterations in temperature, precipitation patterns, and other atmospheric conditions on Earth. These changes can be natural, due to processes like volcanic eruptions and variations in solar radiation, but in recent decades, human activities—especially the burning of fossil fuels, deforestation, and industrial emissions—have significantly accelerated the rate of change. This rapid shift impacts ecosystems, sea levels, weather patterns, and biodiversity, leading to consequences like more frequent extreme weather events, rising global temperatures, and disruptions in natural habitats.
- **Copolymer:** is a polymer derived from more than one species of monomer.
- **CRISPR-based tools:** are genetic engineering technologies that use the CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) system to precisely edit, modify, or regulate DNA in living organisms. Originally discovered as a natural defense mechanism in bacteria, CRISPR allows for targeted cutting and altering of specific gene sequences. By guiding specialized enzymes, like Cas9, to exact DNA locations, these tools enable scientists to add, delete, or change genetic material with high accuracy.
- **Crystalline polymer:** a polymer with partial alignment of its molecular chains.
- **Deforestation:** is the removal and destruction of a forest or stand of trees from land that is then converted to non-forest use.
- **Eco-friendly:** not harmful to the environment, or trying to help the environment.
- **Enzyme:** a substance produced by a living organism which acts as a catalyst to bring about a specific biochemical reaction.
- **Exudates:** is fluid that leaks out of blood vessels into nearby tissues. The fluid is made of cells, proteins, and solid materials. Exudate may ooze from cuts or from areas of infection or inflammation. It is also called pus.
- **Kombucha:** a drink produced by fermenting sweet tea with a culture of yeast and bacteria.
- **Flexibility:** refers to a material's ability to deform without sustaining damage or permanent change when subjected to external forces.
- **Fibrils (cellulose):** a linear chain of covalently linked glucose residues extracted by each bacteria pore.
- **Flexible electronics:** also known as flex circuits, is a technology for assembling electronic circuits by mounting electronic devices on flexible plastic substrates, such as polyimide, PEEK or transparent conductive polyester film.
- **Hemicellulose:** Hemicelluloses are a group of complex polysaccharides found in plant cell walls, where they work alongside cellulose and lignin to provide structure and support. Unlike cellulose, which consists of long, linear chains of glucose molecules, hemicelluloses are shorter, branched, and made up of various sugar monomers, such as xylose, mannose, and arabinose. They are more easily broken down than cellulose and play an important role in plant flexibility and strength.
- **Hydrolysate:** Hydrolysate refers to any product of hydrolysis. Protein hydrolysate has special application in sports medicine because its consumption allows amino acids to be absorbed

by the body more rapidly than intact proteins, thus maximizing nutrient delivery to muscle tissues. It is also used in the biotechnology industry as a supplement to cell cultures.

- **Lignin:** is a complex organic polymer found in the cell walls of plants, particularly in wood and bark, where it provides rigidity, strength, and resistance to decay. It binds with cellulose and hemicelluloses to create a sturdy, protective structure, allowing plants to stand upright and transport water efficiently. Lignin is highly resistant to decomposition.
- **Living architecture:** consist of cells embedded in self-regenerating matrices of their own or artificial scaffolds.
- **Modular DNA toolkit:** is a collection of standardized, interchangeable DNA sequences and molecular tools designed to facilitate genetic engineering and synthetic biology. Each module, or DNA "part," performs a specific function, such as promoting gene expression, regulating protein production, or tagging molecules, and can be combined in various ways to construct new biological pathways or modify existing ones.
- **Self-sensing materials:** are advanced materials that can detect and respond to changes in their environment by monitoring their own condition, such as stress, strain, temperature, or damage. These materials have built-in sensing capabilities, often through embedded sensors or conductive components, allowing them to provide real-time feedback on structural integrity
- **Skin regeneration:** is the natural process by which the body repairs and renews damaged or lost skin tissue, typically after an injury, burn, or surgical procedure. This process involves the activation of skin cells, including keratinocytes and fibroblasts, as well as stem cells, to produce new cells, collagen, and other structural components needed to restore the skin's integrity and function.
- **Synthase:** is an enzyme that catalyzes the formation of chemical bonds to produce new molecules, often without requiring energy input in the form of ATP.
- **Synthetic biology:** is a multidisciplinary field of science that focuses on living systems and organisms, and it applies engineering principles to develop new biological parts, devices, and systems or to redesign existing systems found in nature.
- **Tensile strength:** is the maximum stress that a material can withstand while being stretched or pulled before breaking.