Bacterial cellulose: functions, applications and prospects

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Abstract. Cellulose is a β-1,4 glucose polymer of polysaccharide derived from bacterial or plant cells and the structural backbone of plant cell walls. Compared with plant cellulose, bacterial cellulose's uniqueness is its higher purity, unique structure, and strong nanoscale properties, making it particularly suitable for applications ranging from wound dressings to high-performance materials in industrial manufacturing. While the biosynthesis of plant cellulose has been studied sufficiently, the synthesis of bacterial cellulose, in particular its kinetic parameters and enzymatic processability, remains poorly understood. This study provides an explanation of the molecular details of the process, including the initiation, elongation, and termination.

Keywords: Bacterial cellulose; Biocompatibility; Nanocomposites; Application.

1. Introduction

Gluconacetobacter hansenii and Rhodobacter sphaeroides produce derivative biopolymers with the properties of high crystallinity, tensile strength, and excellent biocompatibility. Results show the potential of bacterial cellulose as a biopharmaceutical and packaging substrate, but also for the development of nanocomposites, offering new ideas for industrial and medical application of synthetic abilities.

A. J. Brown was the first people found out that a type of bacteria called Acetobacter xylinum made a squishy, gel-like fiber outside its cells. This was the first time bacterial cellulose, or BC, was discovered. The very first thing people did with BC was to make a yummy treat called coconut gel, or nata de coco. This clear, jelly-like snack comes from fermenting coconut water using bacteria. This method of making it first became really popular in the Philippines back in 1973. Since then, nata made from BC has become a hit in lots of Asian countries like Vietnam, Indonesia, and Japan. In fact, in 1993, the Philippines was sending 90% of its nata to Japan! People started to think of nata as a super healthy food, and that helped it become even more popular. Plus, because it's pretty easy to make, it's helped lots of little businesses in rural parts of Southeast Asia to grow. Nowadays, BC is being used for more than just food. It's starting to show up in all kinds of commercial and medical stuff, like glue for paper, a base for clothes, and even as a material for dressing wounds. With all these uses, BC is definitely getting more attention in the market.

Plant cellulose, which comes from traditional sources like cotton, has been a go-to material in medicine for a long time. We often see it as cotton gauze bandages that help stop bleeding. Even if it's not perfect, it's still widely used. These gauzes, made from a special kind of cotton, were invented by a guy named Frantz during World War II. They're good at stopping bleeding and keeping things from sticking together. There's also a sponge made from plant cellulose that's been used in wound healing. It helps to stimulate the growth of new tissue in wounds after an injury. Some studies have looked at putting in hydrogels made from cellulose and found that they work well with the body's connective tissues and stay stable over time. Other lab tests have shown that these cellulose hydrogels are great for bone cells to stick to and grow on, making them a promising material for bone-related treatments. Furthermore, processability analysis can provide insight into the ways in which bacterial enzymes manipulate cellulose production toward more sustainable materials.

2. Synthesis of bacterial cellulose

Bacterial cellulose (BC) is produced by many bacteria including Gluconacetobacter hansenii and Rhodobacter sphaeroides, characterized by a cellulose synthase complex and differentiation into initiation, elongation, and termination. The first phase consists, after uridine diphosphate glucose, known as UDP glucose, is the substrate of cellulose synthase, this enzyme will catalyze the polymerization of the glucose. We demonstrate that BC synthesis is primed-independent, unlike other glycosyltransferases like glycogen synthase which require preexisting oligosaccharide primers [5]. A famous study by McManus et al. showed that BC synthesis is primer-independent by radiolabeling glucose. This was a very significant breakthrough to prove that cellulose synthase directly starts polymerization from UDP-Glc. And without a primer, which is of great utility in enabling the high versatility of BC synthesis. The elongation phase, once initiated, then does the cyclic addition of glucose units to the growing cellulose chain.

Bacterial cellulose is made by a bunch of different bacteria. You've got Achromobacter, Alcaligenes, Aerobacter, Agrobacterium, Azotobacter, Gluconacetobacter, Pseudomonas, Rhizobium, Sarcina, Dickeya, and Rhodobacter—all capable of churning out BC. On top of that, there's a way to make BC without even using the bacteria themselves. Now, when we talk about the star bacteria for making BC, Gluconacetobacter is the one that really shines. Some scientists, like Yamada and his crew, have even given this bacterium a new name: Komagataeibacter. This particular species is a favorite in both research labs and factories because it's super efficient at making BC and can use a variety of carbon sources to do it. It's like the hardworking, versatile champ of bacterial cellulose production. Repeat the reaction of the enzyme with glucose incorporated multiple times, yielding elongated β-1,4 glucan chains. The elongation rate is strain-dependent between bacterial species. Typically, Rhodobacter sphaeroides incorporate glucose much more quickly than Gluconacetobacter hansenii. Gel permeation chromatography (GPC) experiments indicated that Gluconacetobacter hansenii AcsA AcsB elongated cellulose at 83 glucose units per second, while the amount of glucose elongated cellulose at 13 glucose units per second by Rhodobacter sphaeroides BcsA BcsB. Last year, Omadjela et al. did an experiment in which it actually helped in providing a hint of the cellulose synthase complex and how cellulose chains are translocated through the active site of the enzyme. Since every such increase in glucose is accompanied by a reorientation of the growing cellulose chain within the enzyme's active site, the transfer process is tightly controlled. Structural studies of the enzyme have revealed that the enzyme employs a glucose donor binding and cellulose chain transfer elongation mechanism, while the processivity of the enzyme represents the length of the product polymer. Termination with the release of the cellulose chain starts the extension process when the cellulose chain comes out. The final length of the cellulose polymer is determined by the processivity, the average number of glucose units added before chain release, of the enzyme. Gluconacetobacter hansenii produces longer cellulose chains with a higher degree of polymerization (DOP) than Rhodobacter sphaeroides. GPC analysis showed that Gluconacetobacter hansenii produced cellulose with DOP values from 11,000 to 23,000, while Rhodobacter sphaeroides produced shorter chains with DOP values ranging from 200 to 3,000 [1]. Termination is affected by the relative rates of extension and chain release, often with higher processivity resulting in longer cellulose chains. Researchers found that cellulose synthase's ability to terminate and restart synthesis is significant in determining the size distribution of cellulose fibers[2]. There is a large difference in the enzyme processing capabilities between different bacterial species was found by McManus and colleagues, which helps to explain the differences in the length of cellulose chains produced by different strains.

Overall, the synthesis of BC is a highly controlled sprucest of initiation, elongation, and termination. The molecular mechanisms of BC synthesis have been greatly enhanced by recent experimental studies of GPC, kinetic simulations, and crystallographic analysis. Optimizing BC production for these industrial applications into biomedical materials, food packaging, and high-performance nanocomposites is the next step. The favorable adaptability of BC, along with the amenability of synthesis, puts it in a good position to act as a future sustainable technological innovation material.

3. Functions and characteristics of bacterial cellulose

It is well known that the functionality of BC is greatly influenced by its unique structural properties. For BC, nanofibers are placed that are much smaller than those of plant cellulose, providing an extremely well-ordered crystalline structure with excellent mechanical performance. BC forms a porous matrix in which fibers bond to allow it to hold large amounts of water, making it an ideal choice for applications with major hydration needs, including biomedical products. The other strange thing about BC is its mechanical properties which distinguish it from plant cellulose. It is made of a high-tensile strength material that resists great mechanical stresses without breaking. Thus, it is a material well suited for use as wound dressings, or as tissue scaffolds, among other biomedical applications requiring strong, flexible materials. Moreover, BC is extremely biocompatible and nontoxic since it does not provoke an immune response when it interacts with body tissues, an important criterion for its use in biomedical applications.

The chemical properties show that BC is quite hydrophilic and can absorb and maintain large quantities of water. Its important property is enough of its capabilities in wound care, as water keeps the environment conducive to healing. More importantly, the properties of BC can be easily modified by chemical treatments and their structure turns from isotropic to anisotropic with the nanofiber structure of BC. Apart from its applications in biomedicine, BC has also been studied for fabricating nanocomposites. It is biodegradable and allows strong lightweight compositing combining it with graphene.

Biocompatibility is key when it comes to materials used in healthcare. It means the material can touch living tissue without causing harm or allergies. Studies have shown that a material made from porous plant cellulose is safe to be around bone and liver cells. When a cellulose sponge was implanted, it was found to break down slowly. Some experts even say it's practically non-degradable when used as a temporary bandage for a short time. Bacterial cellulose, unlike the kind from plants, doesn't have lignin or hemicelluloses. But it does need a strong cleaning with bases to remove any bacteria trapped in it. There have been several tests on animals using Bacterial cellulose. For instance, researchers put small pieces of it under the skin of rabbits and checked on them after a week and a month. The implants didn't cause any obvious inflammation, and when they looked closely at the samples, they only saw a few large cells and a thin layer of fibroblasts where the cellulose met the tissue.

Other positive results came from a lab study using mouse fibroblast cells. Another study put a hollow tube made of Bacterial cellulose into the carotid arteries of rats. In a thorough study, researchers implanted pieces of Bacterial cellulose into rats and checked on them after one, four, and twelve weeks. There were no signs of inflammation, no giant cells, and no chronic inflammation throughout the study. Instead, they saw new blood vessels forming around and inside the implanted cellulose. The researchers also noticed that cells, mostly fibroblasts, were able to move into the more porous parts of the Bacterial cellulose membrane. This new tissue, combined with the cellulose, had fibroblasts and fresh collagen.

Further, these nanocomposites have been used to build flexible electronic devices, filtration systems, and to make desirable parts that are components in high performance materials for the aerospace and automotive industries.

4. Applications of bacterial cellulose

Bacterial cellulose applications Biomedicine is one of the most effective areas for BC. The ability of Bacterial Cellulose to act as a good wound dressing material, that is, creating an environment of a moist wound that will promote healing, while preventing infection from bacteria makes it one of the best materials as a wound dressing. BC is also a scaffold for tissue engineering due to its high porosity and biocompatibility. BC scaffolds have recently been shown to aid in skin, bone, and cartilage tissue regeneration, thus making them a potential organ repair and artificial tissue candidate. Additionally, BC’s long, sustainable, and biodegradable state makes it a viable cheap option for plastic polymers.

Because plastic is expensive and petroleum limited, BC can be used in packaging, particularly as a replacement for petroleum-based plastics. BCs physical strength and sustainability meet the growing demand for sustainable materials in the food packaging industry, where BC can function as a biodegradable film. Furthermore, BC is also used as a filter membrane material due to nanostructured pores in BC which enables the capture of particles while allowing liquids to pass. They could be used for water purification, and air filtration, as important components of wearable sensors that monitor environmental pollutants and much more. Nanotechnology is another area of BC that has progressed quite a bit. The preparation of BC-based nanocomposite has been developed for new applications in electronics, biosensors, and energy storage devices. This has the potential to influence the design of wearable electronic devices and renewable energy energy storage systems.

Healing a wound isn't just about slapping on a bandage and hoping for the best. It's a whole team effort involving different types of cells and what they produce, like the stuff that holds our tissues together and little helper molecules that tell cells to multiply (growth factors). Nowadays, we want our wound treatments to do more than just keep things moist and protected. We're looking for materials that can do all sorts of fancy stuff, like soaking up extra goo, letting the right amount of air through, keeping the wound at a comfy temperature and pH, coming off without hurting, stopping infections, and all without breaking the bank. And guess what? Bacterial cellulose (BC) and its buddies (BC composites) can do all that.

In recent years, there's been a lot of work to make BC even better at helping wounds heal. For example, Lamboni and the team came up with a mix of silk sericin and BC. This combo made the skin cells that help repair wounds (fibroblasts) work faster and made more of that good stuff that holds everything together, which meant wounds healed quicker. And it didn't stop there. They also added a germ-fighting ingredient called polyhexamethylene to BC. This not only helped cells move around and make more collagen but also showed that it didn't irritate the skin, stopped infections, and made wounds get smaller, faster.

5. Future directions and challenges

New applications based on research on BC continue to emerge, especially in advanced applications including 3D bioprinting and regenerative medicine. BC is a biocompatible and structurally stable material that makes it desirable for bioprinting tissues and organs that will change the field of tissue engineering. They are also at work trying to genetically modify the bacteria that produce BC to purposefully change the properties of cellulose for a broader range of uses. The synthesis process at the genetic level can be manipulated to yield BC with enhanced mechanical, chemical, or biological properties, which opens up new applications possibilities for these fancy materials in a diverse number of industry areas. But those are still some things that have to be addressed. The high cost of production is one of the main factors that stifles the acceptance of BC. Particularly expensive is the fermentation process, in terms of controlling the conditions such that the bacteria will continue to grow. Additionally, for industrial applications to be strengthened, demanding properties of cellulose would remain a challenge since the cellulose properties are highly specific. On the production side, there are researchers looking into using low-cost feedstocks, working to improve the efficiency of the overall bioreactor process to create BC that is cheaper and more stable.

Bacterial cellulose is showing up to be a real jack-of-all-trades in the biomedical field. It can also serve as the strong framework needed for growing tissues in the lab. While many researchers are working on creating new synthetic materials for medical use, these often fall short. They might not be strong enough or might not get along well with our body's tissues. Early studies are suggesting that Bacterial cellulose could be a superior choice for building tissues in the lab because it's both tough and safe to use inside our bodies. It's a material that has a lot of potential for making all sorts of medical devices. In fact, there have been some clinical trials that show it works well for healing wounds and replacing organs. But to really make the most of Bacterial cellulose, we need more research from different fields. We need to test how different types of animal cells grow on these membranes to see if they thrive. More studies in real-world settings will be needed to prove its worth. If Bacterial cellulose can prove its mettle in healing wounds and building tissues, then we'll need to figure out how to make a lot of it. Luckily, because it's made through a simple fermentation process, scaling up production seems doable. But we'll work out the engineering details to fully understand and optimize how Acetobacter bacteria make this cellulose.

In addition, BC is really good at supporting cells from mammals when they're grown in a lab. Lately, BC has been used as a kind of base or scaffold for all sorts of cells to grow on. The fact that BC has lots of little holes (porosity) is great for making cartilage, which is the stuff that's in our ears and nose. Feldman and the team came up with a clever way to mix BC with tiny wax beads to make a scaffold. Human cells that make cartilage (chondrocytes) could move around on this, change into the right kind of cells, and make the stuff that cartilage is made of. If we tweak BC a bit more, it could get even better at this. They also used lasers to poke little 3D channels in BC, which helped get the chondrocytes to stick to it better. Some studies with mice looked at how well a mix of BC and another material called alginate, with some human cells from the nose and immune system cells, worked. After about two months, the mix was really stable and a good place for the chondrocytes to grow.

BC has also been used to grow other types of tissues. For example, when they grew a certain type of human stem cell on BC with some bone-like minerals, the stem cells turned into bone-making cells after three weeks. Similarly, when they mixed BC with collagen, a bone-like material, and a special growth peptide, it helped turn cells into bone-making cells. Lastly, BC has been used to help stem cells grow and change into different types of cells. Krontiras and the team found that using BC as a 3D scaffold was a better way to grow mouse stem cells into fat cells in the lab than the methods they had before. More recently, they used BC with a special peptide to mimic how blood vessels form in a type of skin cancer called melanoma. This helped the cancer cells stick and organize better, making it a good model for testing drugs against melanoma.

6. Conclusion

Bacterial cellulose is a versatile biopolymer for predominant utilization. As a material with unique mechanical strengths, biocompatibility, and environmental sustainability, it is a valuable material for the future. However, continued work in biotechnology and materials science to advances in biotechnology will continue to see us use bacterial cellulose in new ways. Bacterial cellulose will be an important material for sustainable technology, in wound care, as packaging, or in advanced electronics.

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