# Embracing Bacterial Cellulose as a Catalyst for Sustainable Fashion

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# Abstract

Bacterial cellulose is a leather-like material produced during the production of Kombucha as a pellicle of bacterial cellulose (SCOBY) using Kombucha SCOBY, water, sugar, and green tea. Through an examination of the bacteria that produces the cellulose pellicle of the interface of the media and the air, currently named *Komagataeibacter xylinus*, an investigation of the growing process of bacterial cellulose and its uses, an analysis of bacterial cellulose's properties, and a discussion of its prospects, one can fully grasp bacterial cellulose's potential in becoming a catalyst for sustainable fashion. By laying the groundwork for further research to be conducted in bacterial cellulose's applications as a textile, further commercialization of bacterial cellulose may become a practical reality.

*Keywords*: *Acetobacter xylinum*, alternative textile, bacterial cellulose, fashion, *Komagateibacter xylinus*, sustainability

# Embracing Bacterial Cellulose as a Catalyst for Sustainable Fashion

## Introduction

One moment the fashionista is “in”, while the next day the fashionista is “out”. The fashion industry is typically known for its ever-changing trends, styles, and outfits. Furthermore, fast fashion offers the international market affordable clothing intended to entice the consumer with its inexpensive prices. On the other hand, the fashion industry is regarded as one of the main contributors to global pollution. Unbeknown to most consumers, the textile and apparel industry produces massive amounts of waste (chemical, textile, and environmental) that is constantly perpetuated.

According to the World Bank in 2011, solely the process of imparting color onto clothing caused twenty percent of the world’s global water pollution (Scott, 2015). Most alarming, this figure includes only one of the many components needed to create the final garment. Harvesting the raw material, spinning the fibers into yarns, weaving the yarns into fabric, cutting and sewing the garment, and adding the finishing chemicals onto the garment are also included within modern garment design, but were not included in the World Bank 2011 statistic of global water waste (Ng & Wang, 2016). With an increase in the production of apparel and an increase in the use of natural resources, sustainability is becoming a critical issue for current and future generations. Thus, seeking alternative sources of material that provide potential for creating less waste within the garment design process is crucial.

## Defining Sustainability

As sustainability becomes a catchphrase and a “megatrend” (Mittelstaedt, Schultz, Kilbourne, & Peterson 2014), fashion businesses are using the concept of sustainability as an incentive to promote value and gain a comparative advantage toward their respective consumers (Varadarajan, 2010). Furthermore, corporations and customers alike have been refining their focus on sustainability particularly to environmental and social effects. (Song & Ko, 2014a). Nevertheless, fashion consumers have not hampered or reduced their consumption of apparel. Although consumers tend to prefer sustainability in concept, they typically buy products that are not sustainable because of the limited number of sustainable, yet affordable products available in the market, and lack of diversity in regards to aesthetics and functionality. (Kim & Damhorst, 1998). Thus, promoting sustainability in an effective manner requires a combination of channels. Education, peer influence, and marketing campaigns are all necessary components to raise the consumer’s awareness of the importance of sustainability. However, fashion companies are not doing enough to impart amicable attitudes towards environmental causes and concerns. (Weller & Walter, 2008).

In addition to raising consumer’s awareness and providing sustainably affordable options, a sound definition that adequately defines sustainability for fashion is vital. In 1987, the United Nations through the World Commission on Environment and Development released the Brundtland Report, which defined sustainable development as, “development which meets the needs of current generations without compromising the ability of future generations to meet their own needs” (Brundtland et al., 1987, Ch. 2, para. 1). This spurred a plethora of conversations, and sustainable development became incorporated into the international community and agenda primarily on economic, social, and environmental standpoints. Furthermore, it also raised a variety of questions due to the lack of clarity surrounding the ambiguousness of sustainable development and relevant ways of measuring it.

Applying this meaning to the textiles and apparel industry, sustainable fashion is viewed as an oxymoron. How can an industry based on consumerism develop or provide sustainable fashion (Henninger, Alevizou, & Oates, 2016)? Fashion consumers not only believe that sustainable fashion exists due to their low awareness, but they also believe that it currently exists within the present state of fashion. Furthermore, fast fashion implies an industry of constant cyclic motions, whereas sustainability implies something that consists of long-term prospects and possibilities. Putting sustainable fashion into perspective, sustainable fashion is best defined as, “seeking to empower workers throughout the supply chain, utilize upcycling, recycling, and traditional production techniques, and incorporating renewable and organic raw materials” (Henninger et al, 2016, p. 401).

Incorporating the definition for sustainable fashion from Henninger et al. (2016), bacterial cellulose falls within the incorporation of, “renewable and organic raw materials” (p. 401). By attempting to incorporate bacterial cellulose within the fashion chain, one is potentially able to improve the lives of garment workers, shorten the garment development process, and impart less pollution upon our ecosystem. As a result, bacterial cellulose has been recently able to garner the attention and interest of fashion designers and researchers alike.

## What is Bacterial Cellulose?

In order to further investigate bacterial cellulose, a basic understanding of cellulose is necessary. Cellulose is the most abundant biopolymer on earth. (Araujo, Silva, & Gouveia 2015; El-Saied, Basta, & Gobran 2004). In addition to this, cellulose is not only inexhaustible and sustainable, but also a natural renewable resource (Gross & Kalra, 2002; Ng & Wang, 2016). Cellulose is ordinarily found either as a structural component within the primary cell walls of green plants and fungi, or secreted by some species of bacteria as a biofilm.

Otherwise known as microbial cellulose and biocellulose, bacterial cellulose is cellulose that is derived from bacteria able to produce cellulose. It is an organic compound with the formula $(C_6H_{10}O_5)n$ produced from certain types of bacteria. Figure 1 on the next page shows the cellulosic compound's chemical structure. Bacterial cellulose is an exopolysaccharide with unique structural and mechanical properties that is commonly compared to plant cellulose. There are only a few genera of bacteria capable of producing bacterial cellulose such as the following: *Acetobacter, Achromobacter*, *Aerobacter*, and *Agrobacterium*. Table 1 includes a chart of various microorganisms with their respective subspecies that have been recorded to grow bacterial cellulose.

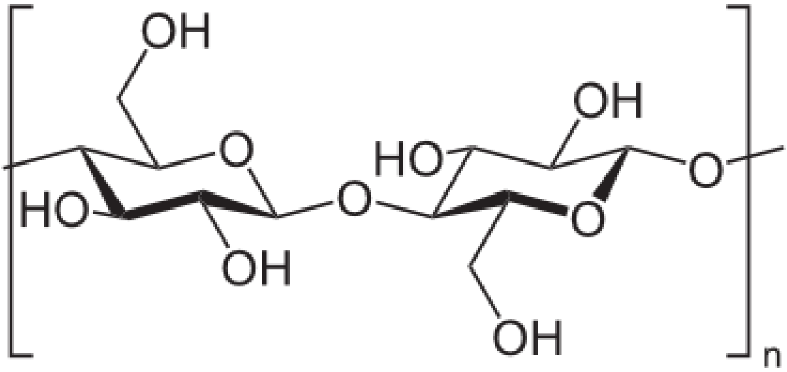


*Figure 1*. Chemical Structure of Cellulose

Table 1

*Producers of bacterial cellulose*.

| ***Genus*** | **Cellulose Structure** |
|---|---|
| *Acetobacter* | Extracellular pellicle |
| *Achromobacter* | Fibrils |
| *Aerobacter* | Fibrils |
| *Agrobacterium* | Short Fibrils |
| *Alcaligens* | No distinct fibrils |
| *Pseudomonas* | Short fibrils |
| *Rhibozium* | Amorphous Cellulose |
| *Zoogloea* | Not well defined |

*Note*. This table lists genera that can produce bacterial cellulose, and their cellulose structures. Adapted from “Production and Application of Microbial Cellulose,” by R. Jonas and L. F. Farah, 1998, *Polymer Degradation and Stability*, *59,* pp. 101-106. Copyright 1998 by Elsevier. Reprinted with permission.

Within the genera *Acetobacter*, *Acetobacter's* species *xylinum* has been the most studied microorganism for the production of bacterial cellulose due to its ability to polymerize glucose at a rapid rate, "up to 200,000 glucose molecules per second" (Eryilmaz et. al, 2013, p. 2). This makes *Acetobacter xylinum*, nature's most prolific cellulose producing microorganism.

## Background information on genus *Acetobacter*

The genus *Acetobacter* is composed of acetic acid bacteria. Acetic acid bacteria are able to convert ethanol to acetic acid aerobically (in the presence of oxygen). There are currently 14 genera that consist of acetic acid bacteria. Furthermore, bacteria within the genus *Acetobacter* have the capacity to oxidize acetate and lactate into carbon dioxide and water. The genera *Acetobacter* is also gram-negative. Being gram-negative bacteria, this means that *Acetobacter* has a thin peptidoglycan layer in between the cell's walls and the membrane.

In addition to the ability to produce fibrils from cellulose, "A remarkable feature of these strains is their ability to survive under extreme environments, such as high sugar concentrations and low pH values, which makes AAB [Acetic acid bacteria] suitable for various industrial applications" (Zhang et al., 2017, p. 1). Unlike other bacteria, acetic acid bacteria thrive off high sugar content and use the sugars to create bacterial cellulose.

Out of the genus *Acetobacter*, *Acetobacter xylinum* is the ideal model microorganism to study the process of growing bacterial cellulose as an alternative textile for the fashion industry because of its speedy production of cellulose in comparison to other bacteria. As a result, it attracts various researchers interested in studying the biosynthesis of cellulose and using bacterial cellulose for industrial applications. Besides this, many of the other bacteria that are able to create bacterial cellulose are potentially pathogenic. This limits the amount of commercial capabilities that can be explored with the other biopolymers.

Being the paramount organism to create bacterial cellulose, *A. xylinum* is found in a variety of locations. *A. xylinum* is either found in nature on soil or found on rotting fruits. It can also be located in symbiosis with plants such as sugarcane or coffee. Finally, *A. xylinum* is involved in the process of making kombucha tea. The process of using *A. xylinum* from kombucha tea to grow bacterial cellulose is the most promising method of creating bacterial cellulose.

## Historical Origins

*Acetobacter xylinum* was first studied in Europe by Brown in 1886. Brown was a British professor of malting and brewing, and pioneered the studies in enzyme kinetics. He wrote the first scientific paper about bacterial cellulose, describing a fermentative substance that was referred to as the vinegar plant (Brown, 1886). He then described the production of cellulose by resting cells of *Acetobacter* in the presence of oxygen and glucose. Furthermore, he noticed the entire surface of the liquid became covered with a gelatinous pellicle.

In 1864, French physician Louis Pasteur showed that *Acetobacter* bacteria was the cause of the conversion of alcohol into acetic acid. The *Acetobacter* bacteria worked symbiotically, producing enough acetic acid as to disrupt and lower the pH to inhibit the growth of contaminating organisms. Though it was Brown who first reported the synthesis of a gelatinous pellicle in 1886, cellulose synthesis of *K. xylinus* began to be analyzed in-depth by Hestrin and Schramm (1954). Hestrin and Schramm discovered that the resting and lyophilized cells in *Acetobacter* bacteria synthesized cellulose in the presence of glucose and oxygen.

## Reclassification of *Acetobacter Xylinum*

*Acetobacter xylinum* has gone through the course of several reclassifications, making the process of finding articles rather challenging. Originally, labelled as *A. xylinum*, *A. xylinum* was listed on the Approved List of Bacterial Names in 1980 as a subspecies of *Acetobacter aceti* subsp. *xylinum* (Skerman, McGowan & Sneath, 1980). Since then, *A. xylinum* relocated into the genus *Gluconacetobacter* as *Gluconacetobacter xylinus* (Validation List no. 64, 1998). Then, *G. xylinus* was last re-classified as *Komagataeibacter xylinus* in 2012 (Yamada, Hoshino, & Ishikawa, 1998; Ross, Meyer, Benziman, 1991).

Even though *K. xylinus* is the most recent name for the microorganism, most literature that addresses *K. xylinus* addresses the bacterium as either *A. xylinum* or *G. xylinus*. As a result, it is important to know all three of the scientific names that this microorganism has been named when locating articles about this particular bacterium. For the remainder of this thesis, only *K. xylinus* will be used as to prevent confusion with its other scientific names.

## Bacterial Information about *Komagataeibacter xylinus*

*Komagateibacter xylinus* is a particular species within the *Komagateibacter* genus, and *Acetobacteraceae* family. *K. xylinus* is a rod-shaped bacteria, measuring 2 microns long and 0.6 microns wide (Mohammad, Rahman, Khalil, & Abdullah, 2014). In addition to this, *K. xylinus* has 3 subspecies consisting of the following: K. xylinus E25, K. xylinus NBRC 13693, K. xylinus NBRC 15237. Besides this, *K. xylinus* is an obligately aerobic organism. Obligately aerobic means that *K. xylinus* needs oxygen because it cannot metabolize anaerobically. Currently, 66 genomes for the family *Acetobacteraceae* have been completed and published within the NCBI databases. Out of these genomes, one exists for *K. xylinus* E25. What makes *K. xylinus* unique is that it synthesizes massive amounts of extracellular cellulose in the form of a pellicle. This pellicle is then dried to create a bacterial cellulose sheet, and used as an alternative textile.

## Cellulose Synthesis of *K. xylinus*

The synthesis of cellulose by *K. xylinus* comprises a variety of steps, “involving a large number of both individual enyzmes and complexes of catalytic and regulatory proteins, whose supramolecular structures ha[ve] not yet been well-defined” (Bielecki, Krystynowicz, Turkiewicz, Kalinowska, 2005, p. 45). Figure 2 shows an in-depth schematic involving the process of converting glucose into cellulose. Cellulose synthesis occurs within a four-step process consisting of the following:

1. Phosphorylation of glucose to glucokinase
2. Conversion of glucose-6-phosphate (G6P) to glucose-1-phosphate (G1P) by phosphoglucomutase
3. The synthesis of uridine diphosphate glucose (UDP-glucos from glucose-1-phosphate by UDP-glucose pyrophosphorylase

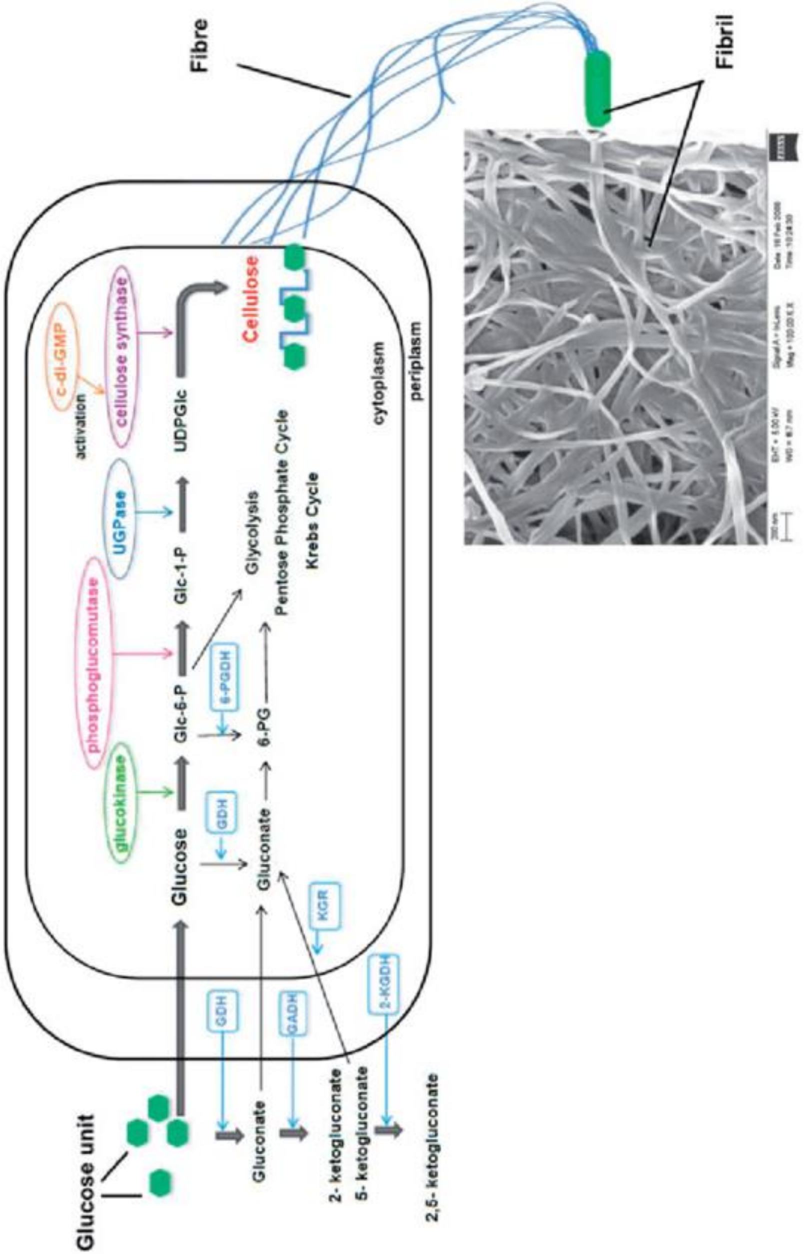


*Figure 2*. Schematic showing glucose metabolic pathway of K. xylinum. Adapted from "More than meets the eye in bacterial cellulose: biosynthesis, bio-processing, and applications in advanced fiber composites," by K-Y. Lee, G. Buldum, and A. Mantalaris, 2012, *Macromolecular Bioscience*, *14,* pp. 10-32. Copyright 2013 by John Wiley and Sons. Reprinted with permission.

4. The synthesis of cellulose from UDP-glucose by cellulose synthase that essentially converts glucose into cellulose (Reddy & Yang, 2015, p. 308).

*K. xylinus* secretes cellulose as microfibrils form a row of pores along the longitudinal axis of the cell. The microfibrils emerging from the pores intertwine to form ribbons of cellulose, making a cellulosic mat on the surface of the medium. According to Cannon and Anderson (1991), each cell that is actively producing cellulose produces ribbons between widths of 40 to 60 nm. Figure 3 shows how the microfibrils are created on the longitudinal axis, and how the ribbons of cellulose are formed.

## Growing Process of Bacterial Cellulose

There are a variety of ways to use *K. xylinus* for growing bacterial cellulose. The two typical approaches that are used in producing bacterial cellulose are static culture and agitated culture (Watanbe, Tabuchi, Morinaga, & Yoshinaga, 1998; Watanbe et. al, 1998). The static and agitated cultures both provide slightly differing results. Furthermore, bacterial cellulose can be created in three different forms, each having a different outcome and creating the following: pellicles, fibrils, and sphere-like particles.

The agitated culture's bacterial cellulose is more suitable for biomedical and engineering purposes. On the other hand, static culture's bacterial cellulose is most suitable for analyzing bacterial cellulose's potential in the fashion industry. If the culture undergoes shaking, bacteria will grow faster but produce less cellulose.

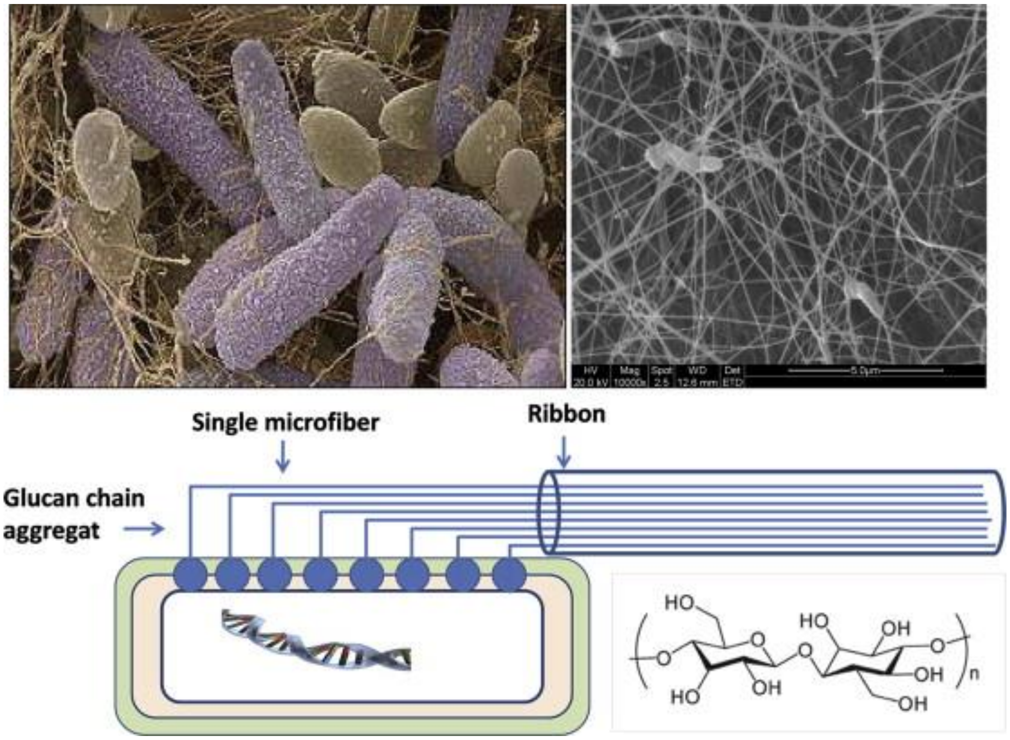


*Figure 3*. SEM images of Acetobacter xylinus and formation of Bacterial cellulose. Adapted from “Utilization of bacterial cellulose in food,” by Z. Shi, Y. Zhang, G. O. Phillips, and G. Yang, 2014, *Food Hydrocollids*, *35*, pp. 539-545. Copyright 2014 by Elsevier. Reprinted with permission.

## Growing Bacterial Cellulose with Kombucha Tea (home-grown process)

Bacterial cellulose is commonly grown using tea at room temperature, making it more accessible for the public to grow bacterial cellulose within their own homes. Kombucha tea is a relatively inexpensive medium that has been most explored in the process of creating bacterial cellulose. Utilizing the home-growing process of kombucha tea to create bacterial cellulose, one needs to use the following ingredients or variations of the following ingredients: kombucha tea, water, sugar, and green tea.

## Kombucha Tea

Kombucha tea is a fermented, probiotic drink sold internationally and acclaimed for its potential health benefits. Originating in Manchuria, China, kombucha has been consumed for thousands of years. Prized for its detoxifying and energizing properties, kombucha spread throughout Japan, Russia, and eventually in Europe by the beginning of the 20th century. Kombucha has become such a prominent beverage that there is, “a kombucha journal that is electronically published . . . available worldwide in 30 languages” (Jayabalan, Malbasa, Loncar, Vitas, & Sathishkumar, 2014, p. 539). Kombucha tea consists of the fermented tea broth, and the kombucha SCOBY (symbiotic colony of bacteria and yeast) on the surface. Figure 4 depicts the two components found within kombucha. The kombucha SCOBY culture consists of a mixture of bacteria (*K. xylinus*) and yeast. Furthermore, the microbial composition of kombucha is not exact; variations may occur as there are different sources that are used to inoculate the tea fermentation process.

## Water

The water source used to grow bacterial cellulose must be purified or boiled as to remove the ions and chemicals that would otherwise kill the *K. xylinum*. Once the process of water has been boiled or purified, one is then able to add the sugar, tea, and bacteria into the medium.

## Sugar

As there are a variety of sugar brands and types, it is important to know which sugars are most convenient to use. When buying the sugar to use in creating bacterial

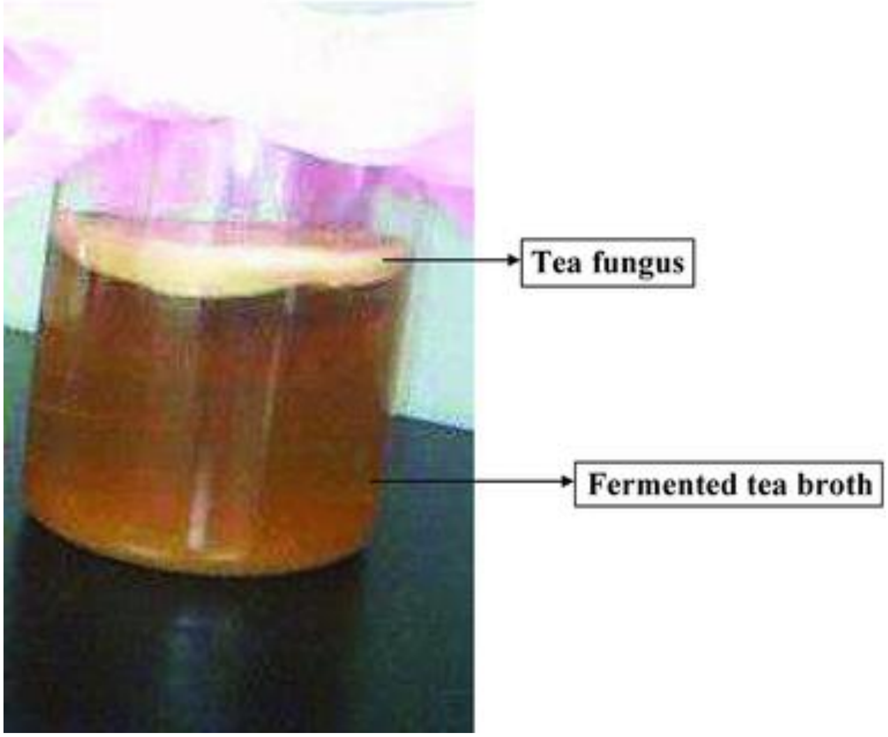


*Figure 4*. Components of Kombucha tea. Adapted from, "A Review on Kombucha tea—Microbiology, Composition, Fermentation, Beneficial Effects, Toxicity, and Tea Fungus," by R. Jayabalan, R. V. Malbaša, E. S. Lončar, J. S. Vitas, and M. Sathishkumar, 2014, *Comprehensive Reviews in Food Science and Food Safety*, *13*, pp. 538-550. Copyright 2014 by John Wiley and Sons. Reprinted with permission.

cellulose, steer away from the alternative substrates such as potato starch and lentil flour. It is easiest to buy and utilize white sugar for home-growing purposes.

## Green Tea

Because bacterial cellulose is also grown using a nitrogen source, green tea can be used to provide nitrogen in the creating process. There are two ways of utilizing tea to make bacterial cellulose. First, one can buy the green tea already distributed within the tea bags. This is the most convenient method; however, it can also create problems in distributing the tea proportionally. Second, one can also buy the green tea loose-leaf, and create a tea bag to put the grams of tea needed into the bigger tea bag.

## Contamination

With the home-growing process of bacterial cellulose, contamination is more likely to occur. If the bacterial cellulose starts getting green or brown circular formations on top of the surface, it is most likely that mold contamination has occurred. To remove the mold, use a solution of half-water and half-vinegar. Put the solution into a bottle, and spray the solution onto the affected areas. Within a few days the mold should disappear, allowing the bacterial cellulose to grow again.

## Components of the Growing Process

**Carbon and nitrogen.** The most commonly used source of carbon is glucose because it yields the greatest amount of extracellular cellulose from *K. xylinum*. A plethora of sources have been explored as alternative carbon sources in addition to glucose such as galactose, xylose, sucrose, molasses, fructose, Mannitol, glycerol, coconut water, fruit juice, and beet molasses (Prashant, Ishwar, Shrikant & Rekha, 2008; Romano, Franzosi, Seves, & Soras, 1989; El-Saied et al., 2004; Kamarudin et. al, 2013; Kurosomi, Sasaki, Yamashita, & Nakamura, 2009; Keshk, Razek, & Sameshima, 2006). Some of these have proved to yield bacterial cellulose successfully, while other attempts have resulted in slower growth rates. Bacterial cellulose is able to grow best with ample carbon, and slight nitrogen. As researchers look for cost-effective sources of carbon and nitrogen, kombucha tea for carbon and green tea for nitrogen have worked respectively as promising sources. Table 2 on the next page contains further carbon sources that have been tested using *K. xylinus*.

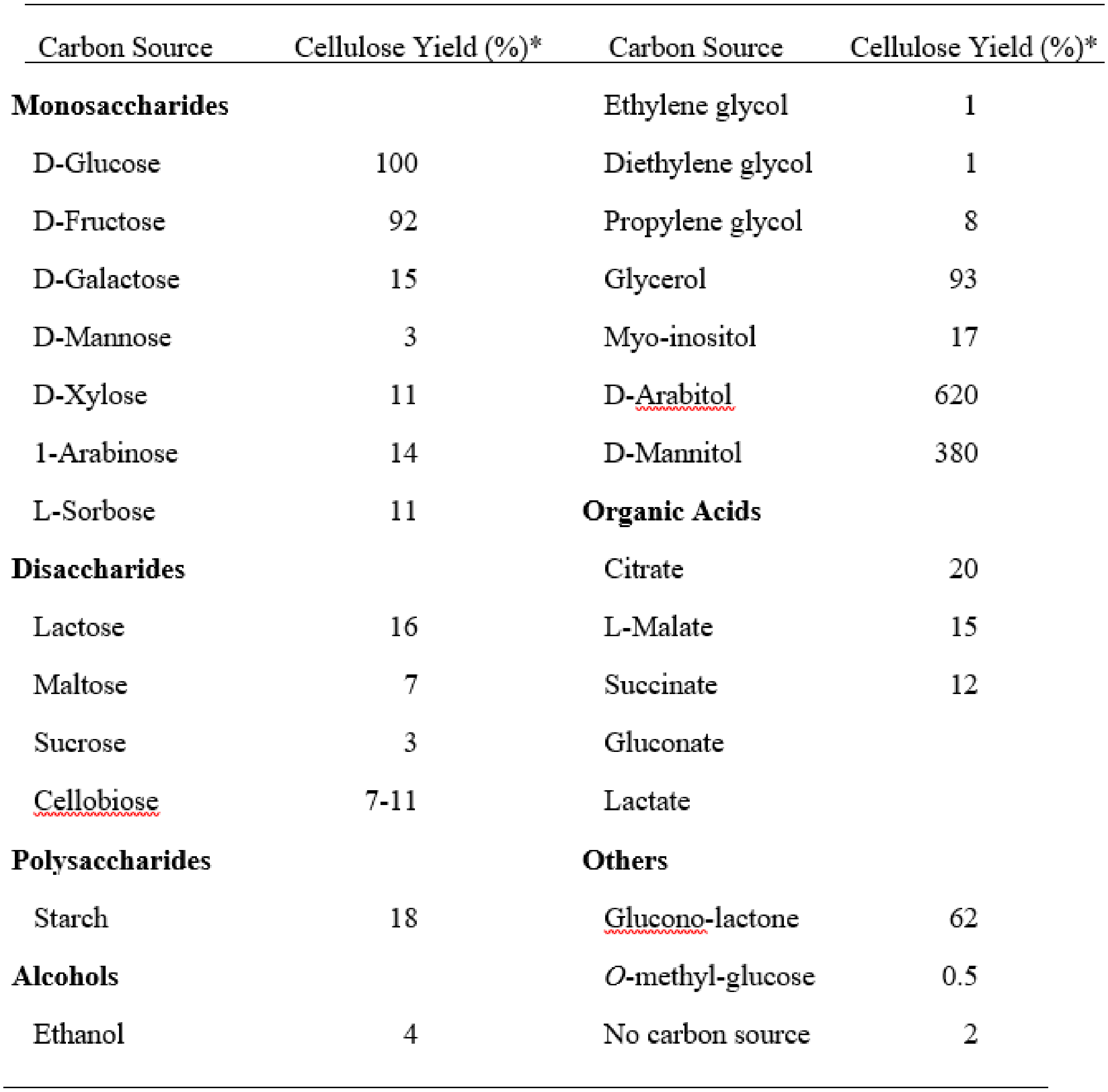
**Duration of growth.** Duration of growth depends on the manner in which bacterial cellulose is grown. For the growing of bacterial cellulose from kombucha tea, the pellicle grows thickest in two to three weeks. For biomedical or bioengineering purposes, researchers have typically grown the bacterial cellulose between four to ten days (Jonas & Farah, 1998). Harvesting a pellicle before two to three weeks will result in a very thin pellicle that would not be suitable for the process of garment design.

**pH.** The pH-value and temperature both have significant factors in creating the most efficient cell growth and cellulosic production. The optimum pH value for the best growth varies within the literature. Mohammad et. al (2014) states that *K. xylinum* can grow at a pH between 3.5-7.5, 4.3 being the most efficient. Moreover, Fontana, Franc, Souza, Lyra, & Souza (1991) narrows this value down and says the optimal range is pH 4-6, whereas Galas, Krystynowicz, Tarabasz-Szymanska, Pankiewicz, & Rzyska (1999) proved pH 4-7 to be best. Most researchers use either pH 5 or 6. Qiu & Netravali (2014) mention that fermentation ranges are most suitable at pH 4-6 as well.

**Temperature.** Most studies have noticed optimal temperatures for cellulosic production at 25-30C. For home-growing processes, room temperature is the best medium. AL-Kalifawi and Hassan (2013) reported that bacterial cellulose gel pellicles were able to grow from a range of 20-50C using Kombucha tea and black tea as its nitrogen source. However, 60-80C did not create a pellicle formation on the surface of

Table 2

*List of carbon sources that have been used to create bacterial cellulose.*



| Carbon Source | Cellulose Yield (%)* | Carbon Source | Cellulose Yield (%)* |
|---|---|---|---|
| **Monosaccharides** | | Ethylene glycol | 1 |
| D-Glucose | 100 | Diethylene glycol | 1 |
| D-Fructose | 92 | Propylene glycol | 8 |
| D-Galactose | 15 | Glycerol | 93 |
| D-Mannose | 3 | Myo-inositol | 17 |
| D-Xylose | 11 | D-Arabitol | 620 |
| 1-Arabinose | 14 | D-Mannitol | 380 |
| L-Sorbose | 11 | **Organic Acids** | |
| **Disaccharides** | | Citrate | 20 |
| Lactose | 16 | L-Malate | 15 |
| Maltose | 7 | Succinate | 12 |
| Sucrose | 3 | Gluconate | |
| Cellobiose | 7-11 | Lactate | |
| **Polysaccharides** | | **Others** | |
| Starch | 18 | Glucono-lactone | 62 |
| **Alcohols** | | *O*-methyl-glucose | 0.5 |
| Ethanol | 4 | No carbon source | 2 |

*Note*. *Glucose was set as 100% yield. Production and Application of Microbial Cellulose,” by R. Jonas and L. F. Farah, 1998, *Polymer Degradation and Stability, 59*, pp. 101-106. Copyright 1998 by Elsevier. Reprinted with permission.

their containers. Although bacterial cellulose can be grown at a variety of temperatures other than 25-30C, those outlier temperature ranges will not be as effective in the formation of cellulose.

**Drying process.** Once the bacterial cellulose has achieved a desirable thickness, the bacterial cellulose needs to dry so that it can be used as an alternative textile. The pellicles of bacterial cellulose can be placed onto a wooden board and left to dry. However, before one places the mats on a surface, petroleum jelly should be rubbed onto the board. Thus, when the pieces of bacterial cellulose are dried, it is easier to remove them off the board.

In addition to this, bacterial cellulose can dry in a variety of ways. Sunlight dries the mats the fastest, although leaving them indoors is possible as well. The drying process typically takes a few days for the bacterial cellulose to be dried and utilized within the fashion design process.

## Current Uses of Bacterial Cellulose

### Medical Uses

**Blood vessels.** In circumstances that involved clogged or hardened arteries, bypass operations are commonly needed. The synthetic materials used within the operations often contain risks of blood clots being created. Keshk (2014), states that bacterial cellulose contains a lower risk than synthetic materials in producing blood clots. Furthermore, the cellulose works well in contact with the blood, which makes bacterial cellulose a promising source of artificial blood vessels.

**Wound-healing.** Bacterial cellulose has been commonly used as wound dressing material due to its capacity for water intake and high porosity. Furthermore, it has been explored as an advanced clothing textile to be used for patients suffering from burn wounds. (Ashjaran, Yazdanshenas, Rashidi, Khajavi & Rezaee, 2013). One company, BioFill Industries, has developed a product named Biofill that markets bacterial cellulose within the wound care market. The gelatinous membrane of extracellular cellulose synthesized by *K. xylinus* was converted into a wound dressing resembling artificial skin (Fontana et al., 1990). For example, in the case of second or third degrees burns, BioFill is to be used in substitution of human skin. Because of bacterial cellulose's high mechanical strength in its wet phase and overall permeability, Fontana et al. (1991) observed that it was more effective in covering off temporary wounds if used as an artificial skin gauze.

### Paper-thickening agent

Bacterial cellulose has been explored as a binding solution for paper, due to its small clusters of microfibrils (Keshk, 2014). This characteristic of bacterial cellulose allows the paper to contain enhanced strength and increased durability. Currently, Mitsubishi Paper Mills and Ajinomoto Co. are engaging in the process of developing bacterial cellulose to be incorporated within paper products (Keshk, 2014). Finally, Basta and El-Saied (2009) observed that, "incorporating 5% of BC with wood pulp during paper sheet formation was found to significantly improve kaolin retention, strength, and fire resistance properties as compared to paper sheets produced from incorporating BC" (Keshk, 2014, p. 7; Basta & El-Saied, 2009; Kai & Keshk, 1999).

## Sony Headphones

Sony, in collaboration with Ajinomoto, and the Research Institute for Polymers and Textiles have been working to develop applications for bacterial cellulose sheets. “Sony has employed these sheets for loudspeaker diaphragms, in order to capitalize on their high specific modulus and high internal loss” (Hongu & Phillips, 1997, p. 110). The results from these experiments demonstrated outstanding quality, so Sony decided to commercialize its brand that uses bacterial cellulose sheets.

## Nata de Coco

Nata de coco is a dessert originating from the Philippines and created by the use and fermentation of *K. xylinus* and coconut water as its medium. Otherwise known as “coconut jelly” it is a chewy, translucent jelly-like dessert. (Sanchez, 2008). In essence, the “coconut jelly” is the wet pellicle reaching a desirable thickness that is instilled with flavor through its medium of coconut water. The consumption of nata de coco has grown in popularity, as it has been shown to have benefits such as lowering plasma cholesterol. (David, 1996). Commercially grown nata de coco farms can be found primarily in the Philippines, but also in Malaysia, Indonesia, and Thailand (Grimwood & Ashman, 1975).

# Bacterial Cellulose’s Properties

## Free of Impurities

Bacterial cellulose contains a lot of excellent and promising properties. First, bacterial cellulose contains high-purity cellulose that is free of impurities commonly found in plant cellulose such as lignin, pectin, hemicellulose, or wax. (Yim, Song, & Kim 2016). This reduces the cost needed in purifying the cellulose for prospective manufacturing applications. In addition to this, the cellulose within bacterial cellulose is close to 100% cellulosic content. On the other hand, plant cellulose contains approximately 60-70% cellulosic content (Klemm, Schumann, Udhardt & Marsch, 2001).

## Degree of Polymerization

Next, bacterial cellulose contains a higher degree of polymerization than plant cellulose. A high degree of polymerization co-relates with higher mechanical strength. Qiu & Netravali et al. (2001) state that the degree of polymerization can reach a maximum of 20,000, and Klemm et al. (2001) mentions that the degree of polymerization can reach 16,000-20,000 whereas plant cellulose only reaches between 13,000-14,000 degrees of polymerization.

## Water Retention Capacity & Tensile Strength

Bacterial cellulose is able to absorb enormous amounts of water in its wet pellicle phase. As a result, it has enormous potential within the biomedical field. Bacterial cellulose during its wet stage resembles a hydrogel. According to Qiu & Netravali (2016), water content accounts for up to 98% of a pellicle’s wet weight. Furthermore, the high degree of polymerization found within bacterial cellulose gives bacterial cellulose a high tensile strength. Qui & Netravali (2016) also stated, “the Young’s modulus of [a] single [bacterial cellulose] nanofiber is estimated to be up to 114 GPa, close to many high strength synthetic fibers” (p. 601).

## Biodegradability

Because bacterial cellulose is biodegradable, it is a promising, sustainable, green material in a variety of industries. Pertaining to fashion, a lot of textile waste is created as consumers discard the clothing that is no longer worn. Often times, the textiles that were incorporated in the garments can be hard to break down due to the blending of fibers. Having bacterial cellulose as an alternative textile in the fashion industry provides an eco-friendly solution to the post-life of a garment once the consumer is finished wearing it. Table 3 on the next page displays a list of the unique features of bacterial cellulose that distinguish its potential from other alternative textiles.

## What needs to be done in Terms of Future Research?

Although bacterial cellulose exhibits enormous potential, the production of bacterial cellulose is currently restricted due to certain limitations. In order for bacterial Cellulose to shift from conceptual novelty to commercial practicality, research must be done on the following: textile developmental features, cost-effective sources of growth media, shortening and improving the growth cycle, creating an industrial mechanism to mass-produce bacterial cellulose, and establishing an alternative design paradigm with bacterial cellulose.

### Textile Developmental Features

**Waterproofing.** While the wet pellicle of bacterial cellulose is composed primarily of water, bacterial cellulose in its dry state is not waterproof. Moreover, a pellicle does not react well to water after it is dried. As a result, garments made from bacterial cellulose are not able to handle moisture or water, and if worn would eventually fall apart. This means that methods in increasing bacterial cellulose’s effectiveness against water will be necessary.

Table 3

*Unique features of bacterial cellulose*

| **Property** | **Description** |
|---|---|
| Purity | - Cellulose is the only biopolymer synthesized.<br>- Absence of lignin or hemicelluloses<br>- Completely biodegradable and recyclable, a renewable resource |
| Great Mechanical Strength | - High strength crystalline cellulose I<br>- Consistent dimensional stability<br>- High tensile strength<br>- Light weight<br>- Remarkable durability |
| Extraordinary absorbency in the hydrated state | - Remarkable capacity to hold water<br>- Selective porosity<br>- High wet strength<br>- High surface-to-volume carrier capacity |
| Direct membrane assembly during biosynthesis | - Intermediate steps of paper formation from pulp unnecessary<br>- Intermediate steps of textile assembly from yarn unnecessary<br>- Extremely thin, submicron, optical clear membranes can be assembled |
| Cellulose orientation during synthesis | - Dynamic fiber-forming capabilities<br>- Uniaxially strengthened membranes |
| Direct modification of cellulose during assembly | - Delayed crystallization by introduction of dyes into culture medium<br>- Control of physical properties of cellulose during assembly (molecular weight and crystallinity) |
| Genetic modification of cellulose product | - Direct synthesis of cellulose derivatives (such as cellulose acetate, carboxymethyl cellulose, methyl cellulose, etc.)<br>- Control of cellulose crystalline allomorph (cellulose I or cellulose II)<br>- Control of molecular weight of cellulose |

Adapted from, “Research Progress in Friendly Environmental Technology for the Production of Cellulose Products (Bacterial Cellulose and Its Application),” by H. El-Saied, A. H. Basta, and R. H. Gobran, 2004, *Polymer-Plastics Technology and Engineering*, *43*(3), pp. 797-820. Copyright 2004 by Taylor & Francis. Reprinted with permission.

Further studies on modifying *K. xylinus*' process of cellulose synthesis, genetically modifying or altering its properties to explore waterproofing, adding enzymes that the bacteria can use in the process of growing bacterial cellulose for waterproofing, or adding finishes to the dried bacterial cellulose pellicle are all possibilities that should be explored. This is bacterial cellulose's main restriction in becoming an alternative textile that can be used for sustainable fashion. Furthermore bacterial cellulose does not bode well with humidity or moisture. Figuring out effective solutions in response to the effects of consumer's moisture and the weather's humidity on bacterial cellulose are necessary.

**Increasing thickness.** Once bacterial cellulose becomes dry, it loses a significant amount of its thickness. In a study conducted by Yim, Song, and Kim (2016), they analyzed bacterial cellulose dried sheets with top-grain leather. Comparing top-grain leather and bacterial cellulose fabric, they concluded that bacterial cellulose was stronger than top-grain leather of similar thickness due to its cellulosic structure and high crystallinity. At the current state, one is able to place two wet pellicles on top of each other, and have them fuse together. This could possibly be a temporary solution to solving bacterial cellulose's thickness. However, future studies should be conducted to harness and regulate bacterial cellulose's mechanical properties.

## Cost-Effective Sources of Growth Medium

Presently, bacterial cellulose is more expensive than plant cellulose due to its limited yield and high-cost of carbon source. In addition to this, bacterial cellulose's lack of being able to grow on a production scale increases the cost. Based on earlier information, there are a lot of alternative carbon sources other than white sugar that are being looked upon. Increasing the research conducted on other carbon sources, and even analyzing waste sugars as an alternative source should be considered. Some carbon waste sources that have been examined are the following: Wastewater of candied jujube processing (Li et. al, 2015), saccharified food wastes (Moon, Park, Chun, & Kim, 2006), acetone-buthanol-ethanol fermentation wastewater (Huang et. al, 2015), and pineapple waste (Alga et. al, 2015).

## Alternative Design Paradigm with Bacterial Cellulose

If bacterial cellulose were to be utilized as a mass-market textile within the fashion industry, it would require creating industrial mechanisms capable of mass-producing bacterial cellulose, and establishing an alternative design paradigm with bacterial cellulose. Figure 5 depicts the steps in traditional textile processes that are skipped when bacterial cellulose is used. One can see how almost every step on the conventional processes of fashion making is circumnavigated by the transformation of the bacterial cellulose’s cultivating solution to a 2D sheet or a 3D garment.

## Improving the Growth Cycle

**Shortening the growth cycle.** Because bacterial cellulose takes weeks to grow, shortening the growth cycle of bacterial cellulose is required to increase its potential for industrial applications. From two to three weeks, it would be desirable to reduce the cellulose synthesis to two to three days. This would most likely also involve research within the fermentation processes of *K. xylinus*, and use of enzymes and catalysts, and genetically modifying the bacterium to speed up the cellulose synthesis.

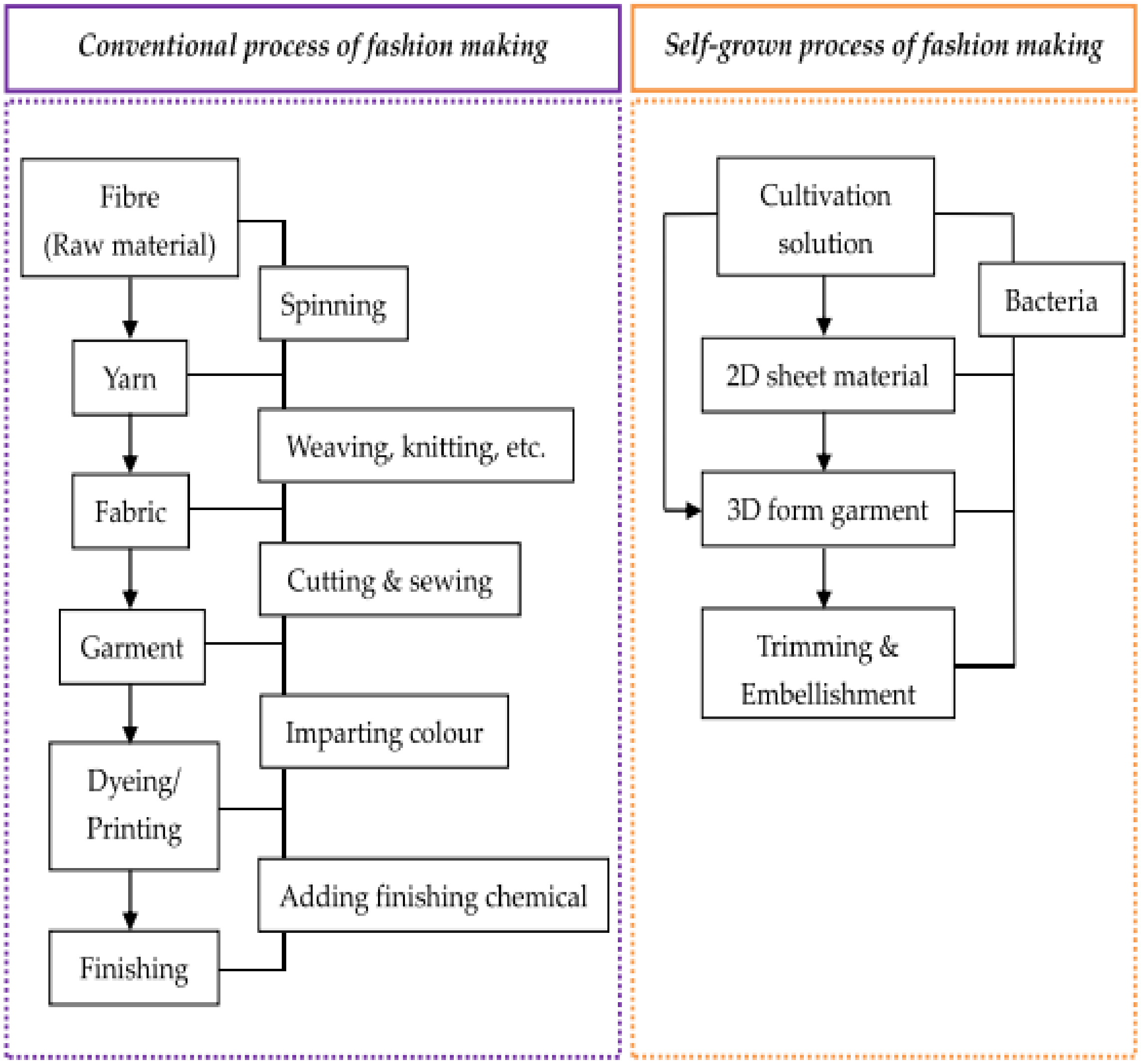


*Figure 5*. Comparing traditional garment design with bacterial cellulose garment design. Adapted from, “Natural Self-grown Fashion From Bacterial Cellulose: A Paradigm Shift Design Approach In Fashion Creation,” by F. Ng and P. W. Wang, 2016, *The Design Journal*, *19*(6), pp. 837-855. Copyright 2016 by Taylor & Francis. Reprinted with permission.

**Depth of total volume.** Not enough research has been conducted in regards to how the depth of the materials used to synthesis the cellulose, specifically water, play a role in the bacterial cellulose’s thickness. That being said, further research in the proportions used in the growing process of bacterial cellulose, and how the volume plays a role would be useful.

### Color Receptivity

Although it is known that bacterial cellulose is very receptive to color, an analysis on how different dyestuffs react to the fabric and impart their colors has not been conducted. It would be of use to the fashion industry to see whether there is a difference between natural and synthetic dyes. In addition to this, discovering the most cost-effective ways to impart color onto bacterial cellulose would be crucial. For instance, would it be easier to impart color as the leather is growing, or once it is dried?

## Conclusion

Bacterial cellulose is one of the fastest emerging by-products of fermentation that is being studied for a plethora of reasons. Due to its unique properties, the possibilities that can be found with bacterial cellulose are limitless. As interdisciplinary collaborations analyzing bacterial cellulose increases, its textile features will only improve allowing bacterial cellulose to become an eco-friendly, sustainable, yet affordable alternative. With the fashion industry perpetuating enormous amounts of textile waste, the need for sustainable textiles has never been more opportune. Thus, bacterial cellulose’s potential to radicalize the fashion industry is becoming an increasing reality.

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# Appendix

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