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Growing Whole Bacterial Cellulose Garments with Membranes and Industrial Robotics

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Abstract

This research explores the aesthetic and environmental potentials of growing whole bacterial cellulose (BC) garments with membranes and robotics. The experiments were conducted with *Komagataeibacter Xylinus*,

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an aerobic microorganism metabolising oxygen and sugar to bacterial nanocellulose threads. On a visible hierarchy, these nanocellulose threads form a homogenous cellulose pellicle at the edge of nutrition liquid and oxygen. Using air-permeable membranes allows us to shape the nutrition liquid oxygen border and direct the cellulose pellicle growth three-dimensionally. In one of our small-scale experiments, we grew a trouser-shaped object within ten days of incubation. Based on these preliminary results, we started experimenting with robotic BC growth setups to program garment features as, for example, thickness, pattern, and buttonholes, locally and gradually. As of today, growing whole bacterial cellulose garments still bears limitations regarding costs, clean room standards and scalability. Nevertheless, mastering those challenges could offer fashion segments an option to cut down the fashion production chain, enable three-dimensional parametric garment designs and lead to more sustainable and individualised garment production.

Keywords: Growing whole garments; bacterial cellulose; three-dimensional fashion; fashion sustainability; robotics in fashion; biomaterials in fashion

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Figure 1: BC sample, photo by Jürgen Grünwald

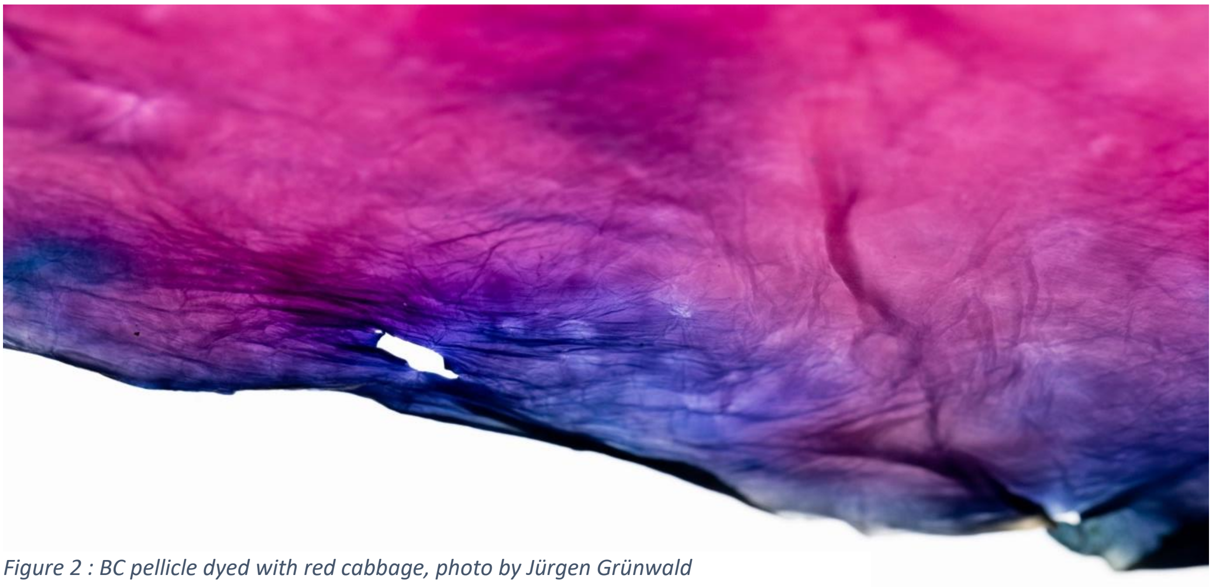


Figure 2 : BC pellicle dyed with red cabbage, photo by Jürgen Grünwald

1. Introduction

The fashion world is undergoing the most significant phase of upheaval since industrialisation. Fast fashion and similar practices lead to a highly negative impact on both society and the environment. There is an urgent need to shift towards more sustainable and biodegradable materials while at the same time reducing emissions of global logistics. Microorganisms may provide one pathway for the fashion industry toward creating sustainable, locally produced, high-quality garments. Zha et al. refer to "microbial" dark matter" as a term illustrating our still limited understanding of microbial biodiversity (Zha et al., 2022). This shortcoming might also offer great potential for a positive impact in various industries, such as fashion. Today, a new wave of designers and artists is exploring the potentials of biomaterials such as algae and bacteria. Biotechnology has been part of industrial

progress for more than a century. In the field of fashion, new enzyme technology creates stone-washed patterns on jeans (Fonds der Chemischen Industrie, 2009). Such can replace the chemical treatment that contaminates water and threatens sensitive ecological environments. The British fashion designer Suzann Lee pioneered the introduction of Kombucha Leather in the textile sector in 2004 (Wood, 2019). Her bio-fabrication research inspired us to investigate further the already well-known cellulose-producing model organism *Komagataeibacter Xylinus* (Singhsa et al., 2018), which could offer an alternative to cotton. Typically, cotton is cleaned, processed into threads, later woven into a fabric, bleached, coloured, chemically finished and then cut into a two-dimensional pattern pieces before it is finally sewn together into a three-dimensional garment. This process is labour intensive, demands lots of resources and generates fabric waste. In this research, we want to utilise biomaterials to eliminate production steps to create a more environmentally friendly alternative to cotton.

Therefore, our overarching goal is to bring fashion design from 2D into 3D in an interdisciplinary effort through digital tools and by experimenting with biochemical materials. Our practice considers robotic arms as an interface that can negotiate between analogue and digital, traditional and innovative, as well as living and non-living.

Medical research shows that it is possible to grow blood vessels in silicone tubes. (Bodin et al., 2007). Thinking about human proportions, the scaling of silicone moulds bears several challenges regarding elasticity, mould fabricability and air-permeability. Other membranes, in contrast, provide a higher air permeability and less elasticity, making them better suited for our purposes. Our research investigates the use of textile membranes as spatial growing moulds. Such a garment-shaped membrane container enables the bacteria to grow cellulose pellicles with an even thickness, eliminating seams and, therefore, weak points. Clothing like highly functional sports apparel must fulfil a diverse range of functions. Those are usually non-evenly spread along the body surface. Finding ways to tweak nutrition, oxygen flow and temperature locally whilst the bacterial cellulose pellicle grows could allow interweaving functions gradually.

In 2D biomaterial experiments, we looked for perfect growing conditions for the model organism *Komagataeibacter Xylinus*. Our research partner from the biomedical department of JKU provided a finishing solution to obtain flexible and durable end products. Having done the basic research concerning the grown biodegradable material allowed us to tackle the next step. We present a method to produce whole bacterial cellulose (BC) garments three-dimensionally directly using air-permeable textile membranes. The membrane containers function as a bioreactor in which the bacteria metabolise sugar and oxygen into cellulose and CO2. The textile bioreactor is sewn together and subsequently sealed with waterproof tape. The production of the textile containers informed the generative pattern design, resulting in organic patterns. Though the membrane slows down pellicle growth, it adds the possibility of seamlessly growing cellulose to the membrane's surface into three-dimensional objects.

The first 3D small-scale experiment was conducted in February this year, showing the potential of bespoken textile bioreactors. The simple shaped trousers grew in ten days. It was necessary to cut it open at the waist and legs. The membrane technique and previous successful experiments, such as plant-based dyeing and the finishing treatment mentioned above, build the foundation for including an industrial robotic arm to assist alongside that process. The capability of multi-tool use on a single robot creates flexibility in our upcoming experiments, which involve controlling temperature with infrared light and increasing oxygen flow by the micro punctuation of the textile bioreactors. Coupling a programmable growing process with parametric robotics would help to enable individualised and more sustainable garment manufacturing.

Figure 4: small scale textile bioreactor

Figure 3: whole BC trousers grown in textile membrane

This process offers new possibilities for regional production and reduces the amount of arable land used due to the ability to stack the containers vertically. The logistic effort will decrease by decentralising production.

We propose mastering this technology could change the way we manufacture fashion in the future. The mentioned method allows us to skip certain steps in production and create new aesthetics. However, the main goal of this research is to produce already-finished garments with the help of bacteria.

2. Theoretical Background

2.1. Environmental Impact of the Fashion Industry

Years ago, the phrase "fast fashion democratises access to fashion" was trendy amongst many people from the textile industry. Considering the environmental impact caused by globalising and industrialising the fashion industry, this argument has been proven short-sighted. Estimably more than half of the fabrics used in the textile industry today are made from petrol-based polymers (Henry et al., 2019). After a short life cycle, most of those end up in landfills or the sea. Digested by fish, some re-enter our life as microplastic in our food chain (Carbery et al., 2018). But not only does the overuse of petroleum fibres causes the fashion industry environmental issues, but the mass production of natural fibres also has its downsides.

The drying up of the Aral Sea is just one devastating example of how much impact cotton plantations can have on the environment. There, the installed irrigation system for the cotton plantation back in the 1950s turned the once fourth largest lake in the world into a desert (Whish-Wilson, 2002). Pesticides and salt cumulating on the ground of the former lake have been exposed and brought by the wind into the surrounding environment, causing cancer and respiratory diseases in the region.

2.2. Cradle-to-Cradle (C2C)

The fashion industry has to change. Part of a solution could be the cradle-to-cradle (C2C) principle, which aims for a closed-loop production, considering economics and environmental and social factors (Henninger et al., 2020). In parallel to changing the production principle, a search of materials of circularity is necessary. Acknowledging bacterial cellulose material properties as a polymer in plant-based fibres (Lee et al., 2012; Qiu and Netravali, 2014), we would like to think about bacterial cellulose as a future alternative to cotton.

2.3. Environmental Impact of Cotton Production

In the example of cotton, 25 million tons of cotton are being produced annually on 2,5% of the world's arable land (Khan et al., 2020). A cotton tee needs 2700 litres of water throughout the whole production process (Hoekstra and Chapagain, 2006). Let's useLet'sexample of taking a shower to put that number in relation. As taking a shower for 5 minutes demands about 67 litres of water, the amount of water used to produce one T-shirt can be compared to showering 5 minutes daily for forty days. Besides excessive water usage, pesticides also negatively impact arable land and the people in contact with the pesticides. It is important to note here that to farmers, pesticides are one of the few guarantees of income in today's fashion supply chain. In the further cotton processing into threads and textiles, besides the already mentioned water resources, many chemicals are used to clean, pre-treat, dye and finish the fabric.

2.4. 3D Garment Fabrication Techniques

Traditionally, to dress the complex shape of the three-dimensional body, 2D pattern-making methods have been developed. The predominantly used material in fashion is textiles, for which 2D patterns can be easily applied. Nowadays, digital design tools allow us to design complex 3D shapes for fashion. New additive manufacturing processes such as 3D printing seem to enable the development of new strategies for thinking fashion. However, while 3D printing technology has advanced, fashion examples are still reduced to a few artistic and conceptual projects. In parallel, traditional three-dimensional garment fabrication techniques like knitting are also evolving with technology.

2.5. Dependency between Design and Technology

In general, technologies in the classical garment assembly process did not change for corporate social responsibility. However, knitting technology has the potential to shift the paradigm. As Tracy Cassidy writes, the evolution of knitwear made from the early hand-knitted pieces to now whole garment knitting solutions draws the perfect image of the dependency between design and technology (Cassidy, 2017). Historically the production of jersey fabric was low and, therefore, affordable. In the 70s, technology got pushed by Missoni's colourful designs. Introducing technical yarns in the early 2000s opened the sportswear apparel sector for knitwear.

2.6. Kombucha and Bacterial Cellulose in Fashion

With our research, we want to build on the success of this technology-driven design approach to change the way we produce fashion in the future. As mentioned above, Suzanne Lee established the experimental use of kombucha as a leather substitute in 2004 (Wood, 2019). Exemplified through a leather and a bomber jacket, those easily readable kombucha garments influenced and still has a significant impact on young fashion creators, who do not want to unsee climate change and aim for a more sustainable fashion future. Kombucha is a fermented drink produced by a Symbiotic Culture of Bacteria and Yeast. Therefore, the pellicle forming on the surface area is called SCOBY. In contrast, BC is free from yeast and has very high purity.

Jen Keane was awarded the 2019 STARTS Prize for her outstanding work "This is grown". In her work, a thread-weaving robotic arm creates a 2D woven structure for the bacterial cellulose to grow around (Melton, 2022). Keane´s work and Chan´s research showed that it is possible to grow BC into 2D pattern pieces directly and reduce the waste material to a minimum (Chan et al., 2018). Together with Ben Reeve, she founded the Start-up Modern Synthesis. Modern Synthesis uses the bacteria strain *Komagataeibacter rheaticus*. Compared to *Glucanobacter Xylinus* it produces 50% more yield and is less porous in its three-dimensional structure (Machado et al., 2016).

2.7. Bacterial Cellulose (BC)

Bacterial Cellulose (BC) is produced by acetic acid bacteria. *Komagataeibacter Xylinum*, formerly known as *Glucanobacter Xylinus* and *Acetobacter Xylinus*, produces cellulose nanofibrils in an aerobic environment. It is cultivated in static or agitated liquid media. The bacterial nutrition source is mainly glucose, which enables metabolites in the transcription phase to activate the bacterial cellulose synthase process in the cytoplasmic membrane (Singhania et al., 2021). The production of a cellulose pellicle on the surface area, where the microorganism is in contact with air, is mainly a bacterial safety mechanism, protecting them from drying out. The pure cellulose yield is primarily consisting of water. Without adding additives in the drying and finishing process it would develop paper like characteristics (Pieger, 2019).

2.8. BC in Medicine

With the right postprocessing, bacterial cellulose (BC) is a versatile material with good mechanical qualities for applications ranging from the food industry and cosmetics to sophisticated medical solutions. In the medical sector, the usage of bacterial cellulose ranges from industrialised applications to laboratory research. For example, market-ready are wound healing scaffolds (Picheth et al., 2017). Further research investigates BC wet wound healing abilities and drug delivery systems (Freire et al., 2022). Due to BCs purity and high body compatibility, much research is also happening in the field of artificial blood vessels (Pieger, 2019). Pieger for example, studied the three-dimensional growth of aortic valves on silicone moulds sequentially dipped in nutrition liquid.

2.9. BC in Food Industry

When it comes to BC in the food industry, Nata de Coco is one of the most well-known examples of bacterial cellulose production. It is a widespread dessert that originated in the Philippines, in which coconut water gets fermented by bacteria resulting in a gelatine-like substance. Even though the traditional and family-derived practice ranges from small to middle-scale production facilities, it shows that BC sheet production in higher quantities is possible. For example, only in the Ben Tre, province of Vietnam, 15.000 tons of Nata de Coco are grown annually (Phisalaphong et al., 2016).

2.10. Fashion and Robotics

In recent decades the regional textile industries could not keep up with the industry globalisation. Looking at the fashion supply chain nowadays, even small companies outsource their garment production and only keep the design, marketing and branding in-house. Compared to agile sourcing, a classical vertical supply chain is not as adaptive to trends, and responsiveness often results in higher margins, as exemplified by Zara (Perry and Wood, 2018). Here, robotics and especially universally applicable robotic arms could provide the potential to re-enable a more agile local fashion production.

Robotics is a vast field (Siciliano et al., 2008), ranging from autonomous cars to bipedal machines. Within the scope of our research, we focus on robotic arms. Robotic arms have been used in industry for many decades and can still mostly be found in high-volume mass production, e.g., for the fabrication of cars. Automotive companies rely on robotic arms because they are not specialised machines. Instead - just like a human hand - they can be equipped with various tools to perform a similarly wide range of applications. Therefore, automotive companies do not have to build entirely new machines for every new car model. Instead, they can take a robot, equip it with the right tools and then, through code, embed their knowledge in areas such as welding or coating. Due to this flexibility, there has been rising interest from the creative industry in robotic arms, particularly architecture: "... robotics announces the possibility to radically overcome the constraint of large series that had hampered so many former attempts to industrialise. In this world, prototyping and small-scale production of sophisticated components would advantageously compete with repetition and mass production..." (Gramaz"o et al., 2014). However, the challenge is that the software for programming robotic arms was targeted at mass production, expecting the programmer to spend much time fine-tuning a motion sequence. Unlike the automotive industry, the creative sector sought solutions for mass customisation, e.g., creating parametric families of objects where every individual thing might have a different shape. This changed when the creative industry started developing its own toolsets, among them HAL, Robot DK and KUKA|prc (Braumann and Brell-Cokcan, 2011). The idea is not to create dedicated robotic software but to implement robot simulation and programming in environments already actively used in the creative fields, such as the visual programming environment Grasshopper or, more recently, Unity Visual Scripting (Braumann et al., 2022). The advantage of visual programming is that the user can program graphically by connecting nodes with each other and immediately see the result. Especially with robotics, the user can create a custom process and connect it to the robotic arm as the last step. Whenever the process data changes, the robot simulation immediately updates. This feedback loop allows a direct link between action and reaction, enabling the user to learn quickly and efficiently. It is essential to note that just as robots are "generic machines", Grasshopper and Unity are "generic programming environments". Unlike, e.g., specialised milling software limited to a few parameterisable processes, Grasshopper and Unity allow the designer to freely create their logic, such as welding fabrics or depositing biomaterials. Combining these generic environments with deep craft knowledge and material expertise makes it possible to create entirely new, specialised processes custom-tailored to the fashion requirements.

In research in fashion design, companies today mainly focus on how digitisation and automation could bring production back into the EU. At this, machines merely duplicate manual labour, promoting the fact that they can replace several human workers. We believe it is crucial to go another way and open up new avenues. Rather than streamlining what has been done by hand, we should aspire to find new, innovative and sustainable methods and forms that advance the discipline by looking at new digital and nature-inspired processes that have not been explored in the field of fashion so far. These developments should not be simply technological advancements but catalysts for new design strategies incorporating entirely new materials, forms, and craftsmanship with minimal waste and emissions.

3. Method

3.1. Bacteria Species

All experiments presented in this paper were conducted with *Komagataeibacter Xylinus*, a nano cellulose-producing microorganism. It belongs to the family of acidic bacteria and is aerobic, which means it needs a carbon source and oxygen to be able to produce its threads.

3.2. Nutrient Medium

	Medium HS adapted	**Medium 105**
Distilled water	500 ml	500 ml
Peptone	2.5 g	
Yeast extract	2.5 g	5 g
Glucose	50 g	50 g
Disodium phosphate	3.4 g	
Citric acid	0.58 g	
Calcium carbonate		10 g

Figure 5: nutrient medium recipes

We use two different nutrient solutions to grow the bacteria. The 105 medium for preliminary small-scale experiments at the biomedical institute of the Johannes Kepler University and an adapted version of the HS medium for large-scale experiments at the fashion department of the University of Arts (Figure 5). To assure consistency routinely stem care is carried out weekly at the two separate facilities.

3.3. Lab Conditions

At the biomedical institute, small-scale experiments are being conducted, including testing the tensile strength and developing a sustainable finishing treatment. In contrast, at the fashion department, the aim is to scale those experiments up. Due to the increased size and unstable cultivation conditions outside of the incubator, the cultures suffer from time to time, resulting in reduced growth. In a not sterile environment like the lab at the fashion department, the BC cultures are exposed to other microorganisms, which leads to seldom contamination. The freeze-dried culture kept at the biomedical institute functions as a backup. For the project's first two years, we mainly worked on the growth of two-dimensional BC fabric. Those experiments allowed us to gain insights on ideal growth conditions for our culture and setup. When scaling up, we built on this knowledge but also had to simplify our infrastructure and resource demand.

Figure 6: lab collage: K.Xylinus cultures in the incubator, grown BC pellicle in glass broth, BC fabric quality samples an post processing (left to right, up to down)

3.4. Growth Conditions

The optimum growth temperature for *Komagataeibacter Xylinus* is 28°C. An imbalance in nutrition and population results in interrupted growth. The grown BC can be harvested every ten days when using an incubator. In comparison, on average, experiments with no incubator system took 40 days due to temperature fluctuations.

3.5. BC Postprocessing

The postprocessing of the material includes cleaning, dyeing and the finishing treatment to conserve the material's flexibility. After harvesting the pellicle, it has to be autoclaved for 23 minutes at 120°C. This step is necessary to prevent the material from growing any further. In medical applications, the harvested pellicle is also washed in natrium hydroxide to clean the cellulose from bacterial residues. Higher porosity is obtained by a mild alkali treatment, compared to the common denaturation process with natrium hydroxyl (Tang et al, 2010).

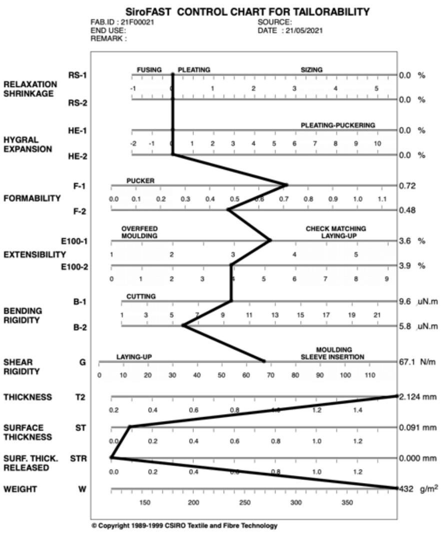
The chemical washing process can be neglected for the use as a textile alternative on the body. Instead, we leave the pellicle for 24 hours in distilled water to reduce the yellow tinge as much as possible. To create textile-like haptics, the pellicle baths in a saturated magnesium chloride solution at 80°C for 60 minutes (Zhang et al., 2020). Chemically speaking, MgCl2 attracts water molecules from the surrounding environment, which conserves textile-like haptics. BC is known for its very strong mechanical properties in its wet state, compared to untreated dried BC sheets. The in-

Figure 7: BC samples with different material qualities

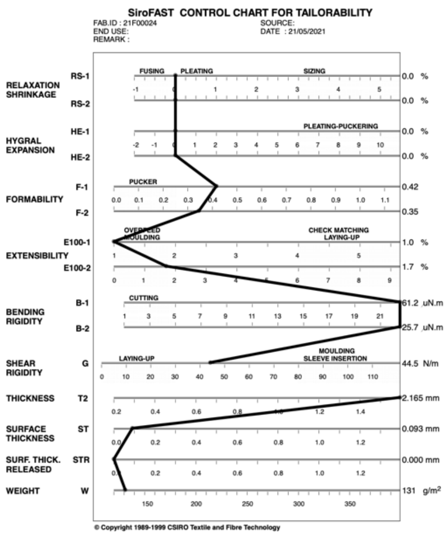
between state achieved with MgCl2 allows the material to still be considered as a textile alternative. The MgCl2-treated sheets get their final touch through heat pressing. The grown BC pellicle does not dissolve in water and therefore is washable in two steps. Cleaning would happen with NaCO, which would then require another MgCl treatment to ensure its flexibility.

3.6. FAST Measurements

The table in Figure 8 shows our post-processed BC samples' tailoring ability compared to Molino. Sandra Kuijpers conducted these preliminary FAST measurements at AMFI. The Molino and the bacterial fabric samples had the same thickness. Still, the non-woven BC samples weighed twice as much as the woven fabric. Furthermore, the BC fabric achieved higher extensibility and a much lower bending rigidity. This performs in a very nice heavy fabric fall, and it is easier to work with overfeeding and extra width.



Bacterial cellulose



Molino

Figure 8: FAST measurements by Sandra Kuijpers

4. Experiments

4.1. Dyeing BC

Especially in textile dyeing, one wants to achieve a long-lasting bright colour that will sustain a high number of washings. Colour and light fastness are decisive for the quality of the product. Our earlier experiments with the *Komagataeibacter xylinus* culture already achieved a broad colour spectrum with kitchen waste materials, like onion, beetroots and avocado pale. In the setup shown in the images below, we added Ethanol and Acetic acid to the colour broth, trying to achieve different hues. The substances had the most effect on the red cabbage, also known as a natural pH indicator. Unfortunately, these samples also lost colour after two weeks. Thus, the dyed BC samples were

Figure 10: ex-situ dyeing of BC samples

Figure 9: ex-situ dyeing results

not lightfast. However, the research revealed that crucial processes were missing in the previous experiments, especially preparing the material before it gets coloured. That includes desizing and mordanting. Metals are used in the mordanting process to create a stable chemical bond between fabric and colour particles. The problem with metallic mordants is their environmental incompatibility. The state of the art is aluminium mordant forms a weak bond but is the least dangerous to the environment (Vankar and Shukla,2019).

Besides the ex-situ dying methods, we tested in-situ dying, where the colour is directly added to the nutrition liquid. Hypothetically the colour pigments would grow into the pellicle. Unfortunately, the results were very pale, and the colour hinge did not sustain the post-treatment process.

Figure 11: in-situ colouring method

4.2. Growing Perforated BC

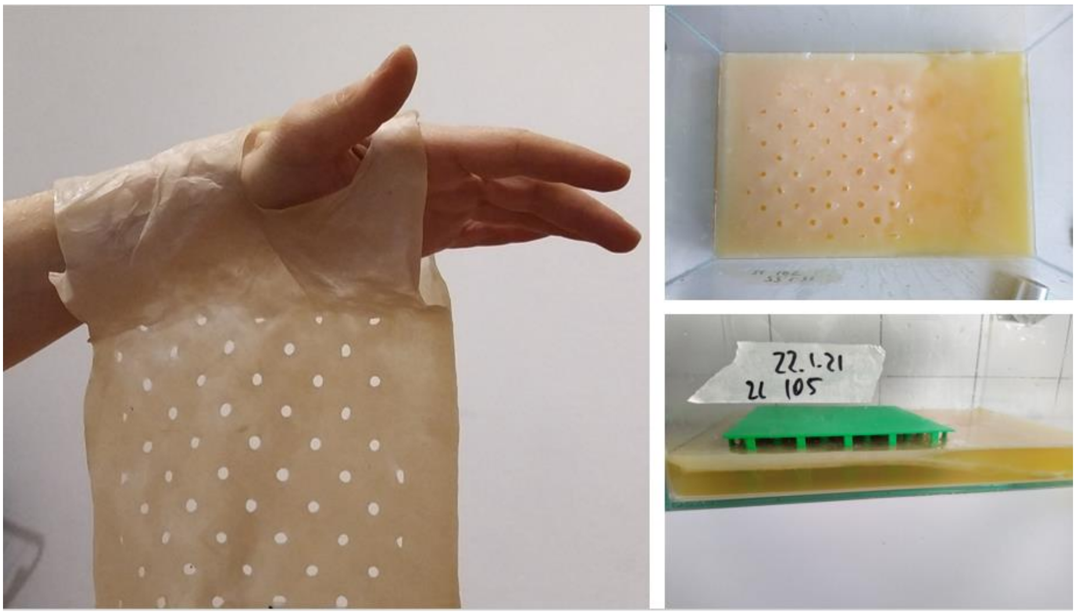


Figure 12: performated BC experiment

Unmanipulated BC is hardly breathable. Therefore, our goal for this experiment was to grow perforated BC by adding a 3D-printed negative in the growing broth. The hypothesis for this experiment was that ingrown holes are more resilient to crane impact, as cutting or stitching of harvested BC can lead to ripping the fabric. The result is documented in the image below. Besides adding an air-passing structure to the fabric, the structural elements could also serve as a method to parametrically add aesthetics to the design.

This experiment also led to another unexpected finding. During the growth process, the mould was once accidentally pushed down. This flooded a part of the BC layer with nutrition solution and the second layer of BC grew on the flooded surface area. The two layers grew together at the edges of the flooded area, resulting in a very strong binding. A similar technique could potentially be used for growing the front and back of a garment with microbial seams in a single growth process.

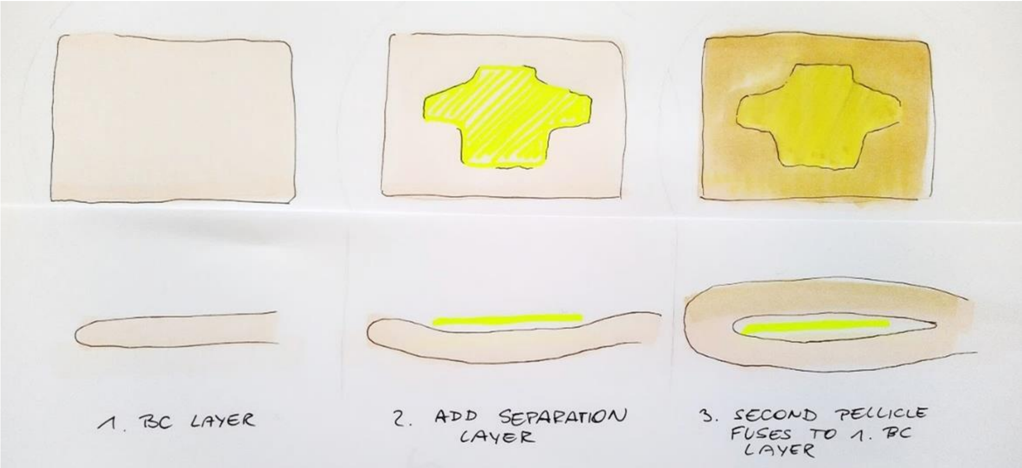


Figure 13: sketch of BC ayer technique

We assume that these two techniques could be used in buttonhole manufacturing and pocket fabrication. Further experiments need to be conducted to fathom the potential of this method.

4.3. Thermoforming BC three-dimensional

The goal of this experiment was to generate a 3D shape out of basic BC surface growth. After five days, the bacteria were accompanied by a parametric structure, 3D printed with biodegradable filament. The bacteria grew around the 3D print in a couple of days. The hybrid material was autoclaved. The temperature of the autoclave process made the 3d print temporary formable, so it could be pressed over a shoe last and left to dry.

Figure 14: thermoformed BC composite

This approach could be used as a structural element to shape a garment, for example, shoulder pads, boots and other more architectural-inspired designs. In manufacturing, the pressing in shape could be realised with a robotic arm and a soft end-effector that adapts to various forms.

4.4. Growing Whole BC Garments in Silicone Membranes

Figure 15: growing whole BC garments installation at Ars Electronica Center, June 2021

Inspired by the growth of BC blood vessels in and around silicone moulds in the medical context, scaling such process up to a 25% human scale was our first approach to growing whole garments directly. Silicone is air permeable and, therefore, can provide the necessary oxygen flow as, e.g., proven in the growth of mentioned blood vessels. We fabricated a trouser-shaped silicone mould using an injection moulding process for a 3D-printed negative shape. Unfilled, the trouser had a size of 15 x 20 x 8 cm, a volume of 1 litre, and a wall thickness of about 2mm. The expanding material contained double the amount of nutrition liquid than estimated. The shape of the trousers got deformed by the liquid's weight due to silicone's elastic characteristics. A reverse engineering process or a supporting structure would have been necessary to achieve the designed shape of the trousers. Considering these preliminary results on a 1:4 scale of an actual garment, we decided against further experiments on a more suitable method using silicone.

Still, we want to point out some ways how a scaling up of this approach might work. For example, a double-layer silicone growing mould with a supporting structure out and inside and the in-between space filled with nutrition liquid could be promising and also allow to program textile patterns. Additionally, as the growth in our DIY silicone mould was relatively low, we suspect too less oxygen has passed through the silicone membrane. Here a chamber with increased oxygen pressure could improve the result. The 3D print surface structure transferred to the silicone mould led to a high BC attachment to the silicone. Experimenting with different silicone surface structures could further improve the results.

4.5. Growing Whole BC Garments in Textile Membranes

The difficulties in scaling up three-dimensional BC growth in silicone drew our attention to waterproof and air-permeable textiles. For example, a composite of woven textile and a nanolayer of PTFE results in a waterproof membrane with lower elasticity and a higher air permeability than silicone. Due to availability and our limited access to alternative membrane technologies, we agreed to realise these experiments preliminary with PTFE composite textiles but have to mention that we

Figure 16: proof of concet experiment, growing whole garments in a textile bioreactor

would have preferred to use a more sustainable alternative.

The pattern of the 20 x 20 cm proof of concept growing mould was fused via heat pressing for 30 seconds at 220°C. First, small-scale tests revealed its BC growth potential. After just ten days of growing, the harvested trousers were grown into shape with a hollow inside. Compared to the preceding flat surface growth, the achieved thickness through three-dimensional growth in textile membranes was one quarter.

Figure 17 : CLO3D visualisation of whole garments grown in the textile bioreactor

These results pushed the first real scale tryouts. In real scale, heat-pressed membrane connections did not withstand the nutrition liquid pressure inside. Therefore, we decided to stitch the seams together and seal them with waterproof tape from the inside. Additionally, we oriented our design towards organically shaped growing moulds to distribute the liquid pressure. This described technique is still prone to leaking but working. For further improvements, another method to fuse the textile membranes must still be found.

4.6. Programming BC Growth with Robotics

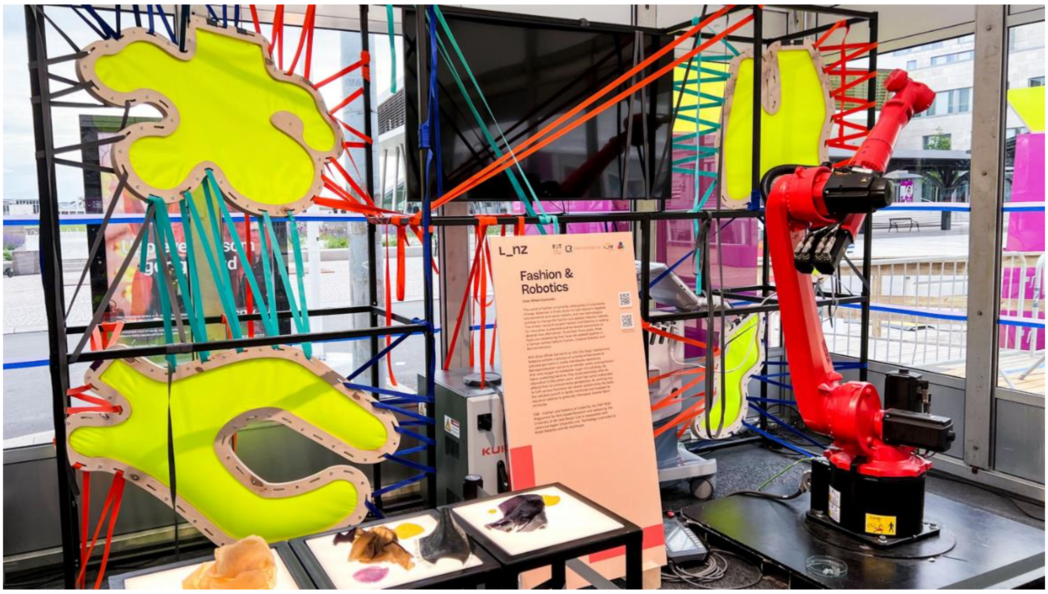


Figure 18: Fashion & Robotics installation at H22 City Expo in Helsingborg

Robotic arms provide the potential of a parametrically programmable machine, which could be equipped with multiple tools. The setting of the grown trousers in the textile membrane was recreated, adding a robotic arm. The robotic tool tip was equipped with an acupuncture needle 0.14mm in diameter. This experiment hypothesised that punching tiny holes into the textile bioreactor might locally enhance bacterial growth by increasing air permeability. Through execution with an industrial robotic arm, this can be realised gradually across the three-dimensional surface and sequentially throughout the growth period. In our test setup, the textile membrane is punched in a linear array every 3 hours in the same position. Against our hypothesis, the results show that the needle punches led to tiny holes and thicker edges instead of equally increased BC thickness. This could be due to the materiality of the needle, certain metal blocks BC growth, and/or due to the punching force itself.

5. Results

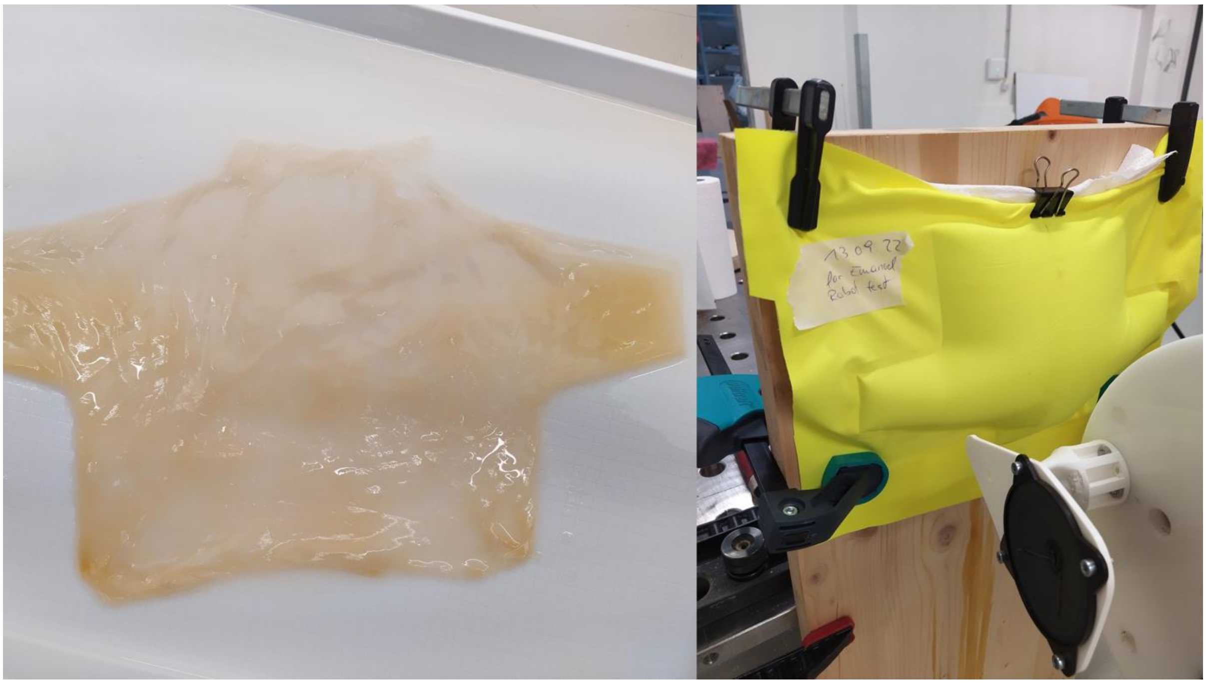


Figure 19: whole grown BC shirt, industrial robotic arm interfering with the membrane containing nutrients and a bacteria suspension

The ongoing experimentation shows that growing whole BC garments is generally possible but demands further investigation. After ten days, the bacteria show a reduced growing activity in membrane bioreactors. Therefore, we stopped all textile bioreactor growth tests after ten days to evaluate. Future experiments with improved growing conditions still have to be carried out. The bacterial growth is directly linked to the oxygen supply. A more concentrated oxygen supply, artificially created in an oxygen chamber, could be helpful to optimise the growth. Also, the BC garments grown in textile membranes imprinted the seams of the mould and therefore reproduced weak seam points.

On the robotic side, additional research is required to monitor and program the bacterial growth during the most viable phase of the bacteria. Punctuation of the membrane also causes holes in the BC garment. This finding could be used as a functional design element of breathable pores. As carried out in this project, the parametric programming of robotics interaction could also be used as a pathway to customise. Once programmed, the generic definition allows individualising garments depending on defined inputs. The assumption is that the cellulose nano-fibrils grow directly on the inner surface of the membrane, blocking oxygen from entering. Another idea is to use speakers mounted to the robot, which create vibrations strong enough to cause the bacteria to lose grip on the inner membrane, forming a tiny gap between the BC layer and membrane and perhaps enhancing the growth at those spots.

6. Discussion

Let us retake the example of a T-Shirt to discuss the water consumption of a BC T-Shirt. Starting with the flat BC layer method fermented in 70 x 50 cm containers, we would need four containers with five litres of nutrition solution to obtain a nice wide-fitted BC shirt. The water amount can be reduced by pressing the BC and removing 90% of the water. The harvested pellicle is very vulnerable to folding, whereas a uniform pressing of the pellicle results in a more homogenous look. By pressing the pellicle directly after harvesting, it is possible to compromise the grown structure and enclose the bacterial residues, colour particles and smell from the nutrition media. The water usage for the post-processing is generously estimated at 20 litres per treatment.

Processing Steps	**Option 1**	**Option 2**	**Option 3**
Growing	5L	5 L	5 L
Pressing			X
Autoclaving	20 L	20 L	0,3 L
Cleaning	20 L	20 L	2 L
Soaking in distilled water for 24 hours	20 L	20 L	2 L
Pressing		X	
Mordanting	20 L	2 L	2 L
Colouring	20 L	2 L	2 L
Finishing treatment	20 L	2 L	2 L
¼ T-shirt	**125 L**	**71 L**	**15,3 L**
T-shirt	**500 L**	**284 L**	**61,2 L**

Figure 20: Water usage in the BC fabrication cycle

These three treatment variations are just showing the water usage that we monitored. The lowest water consumption can be reached by pressing, and therefore compromising on the structural benefits that BC could have, like scent encapsulation methods inside of the pellicle. At this point, we are not able to take into account the water consumption being used in the production of the nutrition sources NaOH and MgCl2. It needs more thorough research to investigate this issue in more detail. Besides that, the three options will affect the quality of the end product differently. Option 1 would require an industrial scale to purify the material without hurting by folding it into a small cooking pot. We advise pressing gently not to lose the integrity of the material. A moderate option to lose the amount of water is using botanical heating plates, the pellicle covered in Molino and a heat press from time to time over 48 hours. That accelerates the drying process without risking ripping the inner layer of the pellicle. Facing the workshop-lab conditions at the fashion department, we recommend using option 3 for a larger number of fabrics to process. The weight of the fabrics is much easier to handle and also doesn’t consume much water in the processes later on. Another benefit of that method is the control over uniformity from the beginning on. On the downside, you are stuck with a darker and smellier fabric. In ongoing research, we further investigate the methods mentioned to gain more control over fabric quality.

Staying with the example of the t-shirt, we also want to share the material costs for option 3. When buying small quantities of all the ingredients, it costs us around 105 € per t-shirt. Through streamlining the process, the costs will drop. Also, some recent experiments showed that the use of yeast extract is not necessary for the bacterial growth.

Components	**Amount**	**Costs**
Peptone	25 g	3,05 €
Yeast extract	25 g	3,2 €
Glucose	500 g	2,5 €
Citric acid	3 g	kA
di-Sodium hydrogen phosphate dihydrate	17 g	0,51 €
Magnesium chloride	352 g	1,76 €
Distilled water	15,3 L	15 €
¼ T-Shirt		26,02 €
T-Shirt		**104,08€**

Figure 21: average material cost under lab conditions of a BC shirt

As mentioned earlier, using a robotic arm directly enables the individualisation of each garment piece. It could allow embedding patterns, text and function in the growing process. Growing whole garments might seem to leave out the labour-intensive work of sewing, but since this is no industrialised process yet, it is hard to say how much human-required labour will be needed. The growing process can be monitored by machines sensing pH value, temperature and oxygen concentration and changing those parameters accordingly to the best growth conditions using an algorithm responding to environmental changes immediately.

7. Outlook

In our future research, we want to research sustainable enzyme-based mordants, to lower the environmental impact of dyeing. Furthermore, we will look into possibilities of programming bacteria cellulose already within the growing process as well

Figure 22: BC grown into knitted substrate

as investigate possibilities of diversifying such features locally. Additionally, we are interested in researching BC growth on a knitted substrate structure in a robotic dipping process. The dipping process could allow the substrate to be wet and filled with nutrients and optimise the oxygen supply for BC growth. Previous experiments showed a possible growth on knitted structures. Depending on the density of the knitted material, the bacteria either grow around the threads creating holes, grow through the material, create a composite, or coat the material with a BC layer. The latter option would be the preferred one to ensure the garment-shaped substrate can be reused multiple times.

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