Bacterial Cellulose: An investigation into living materials

Master thesis by Ane Dreyer Hensley

Oslo Metropolitan University, Product Design

Abstract

During the last decade designers have begun to fabricate new materials by using natural growth processes and reproducing living organisms such as bacteria, yeast, algae and fungi. This intersection of design and biology results in new materials provoked by humans but ultimately dependent on living nature to provide the foundational paradigms for production.

In this project I take it a step further, and include the material during the whole design process by growing it instead of simply sourcing it “off the shelf”. Using relevant methods and theory in order to discover bacterial cellulose’s properties and to evoke its aesthetic values in an attempt to promote its social acceptance, and, hopefully, result in meaningful and sustainable design applications. As a designer I aspire to be an active maker of materials, and to encourage others to think of material as a primary design element instead of a final problem to be solved. By manipulating living material, can a more sustainable, biodegradable and environmentally positive design industry take form?

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1.1 Introduction

During a vacation in Copenhagen I visited KEA´s (Copenhagen school of Design and Technology) material library. This material library contains seven thousand material samples. One section that caught my attention was devoted to natural material samples. During the last decade designers have begun to fabricate new materials by using natural growth processes and reproducing living organisms such as bacteria, yeast, algae and fungi. This intersection of design and biology results in new materials provoked by humans but ultimately dependent on living nature to provide the foundational paradigms for production. This visit inspired me to do more research, which resulted in my discovery of growing design and bacterial cellulose. In my education I have been conscious when choosing material, knowing that everything is made of something and the choice of materials is fundamentally tied to our planet´s present and future health. In my final project I want to take it a step further, and include the material during the whole design process by growing it instead of simply sourcing it "off the shelf". I used relevant methods and theory in order to discover bacterial cellulose's properties and to evoke its aesthetic values in an attempt to promote its social acceptance, and, hopefully, result in meaningful and sustainable design applications. As a designer I aspire to be an active maker of materials, and to encourage others to think of material as a primary design element instead of a final problem to be solved.

1.3 Method

The design process I present is divided into four steps: understanding bacterial cellulose, experiencing bacterial cellulose, discovering findings, and material application, including discussion and conclusion. The design process is inspired by The Material Driven Design method (MDD). The MDD methods aim is to encourage designers to gain knowledge through exploring, understanding, discovering and defining material properties, and encourage designers to enhance the material experiences by adding aesthetic (sensorial) and emotional values, as well as preformative values, for a wider and quicker acceptance in society.

In *understanding bacterial cellulose* I will use the tinkering approach presented in the MDD method, where the designer is expected to have a hands-on approach and work with the material to learn and discover its limitations and opportunities. They encourage cutting into the material, using different ingredients, burning the material etc . And to discover the materials experiential characterization (Karana et al, 2015). In this thesis I focus more on aesthetics because I believe that aesthetic experience plays an important role in societal acceptance. During *understanding bacterial* cellulose and *experiencing bacterial cellulose* I involve people in the process by introducing them to the material and surrounding the material with other materials, presented as material benchmarking in the MDD method. This will give insight on how the material is perceived/received and can lead to suggestions for material application. In the third step discovering findings I will discuss and reflect on my findings and identify the most substantial findings to then present applications in the last step, *material application*, where technical and experiential characterization of the material is represented in the designs proposals.

1.2 Research question

How can self-grown bacterial cellulose result in meaningful applications, and enhance the material experience of those applications by understanding and appreciating the technical, experiential, environmental and aesthetic value of the grown material?

2.1 Understanding bacterial cellulose

In this chapter I will create and work with bacterial cellulose using a hands-on approach. In the Material Driven Design method tinkering with the material is an essential part of the process. The aim here is to understand the material through direct manipulations. This is a crucial step towards understanding the material and how it can be further developed. Material tinkering aims to extract data, understand material properties, as well as their constraints and to recognize its potential source (Karana et al, 2015). Material tinkering will help me to gain knowledge about bacterial cellulose and to increase this knowledge through experiential learning. First I will introduce relevant literature that has been a part of my research, then apply that knowledge to making the material as well as working with it. At the end I present a user study where I introduced bacterial cellulose to people.

2.2 Biodesign

Biodesign is the use of living organisms in design. Biodesign incorporates the use of living organisms such as fungi, bacteria, algae, yeast and cultured tissues. These materials can be part of standard crafting methods or the more complex fields of biomimicry and synthetic biology. The idea is to create a product whose properties are enhanced as a result of the use of living materials. One of the aims of bio design is to use natural resources, and taking no more than can be returned to nature (Myers & Antonelli, 2018). Bio-design is a rising design movement that involves scientists, artists, and designers integrating organic processes as material sources. The integration of design with biological systems incorporates or imitates living organisms into design as a material source, in a sense the scientist becomes a designer and vice versa. Unlike biomimicry, cradle-to-cradle, and the vague word green design, bio-design refers specifically to the incorporating of living organisms or ecosystems as essential components, enhancing the function of the finished work (Myers & Antonelli, 2018).

An example of this living textile project by Roya Aghighi (see figur x). Their research has resulted in developing photosynthetic living textiles with microalgae. The user can observe the growth and the way the algae change or make patterns through time as an indicator of their livingness and eventually end of life. This life cycle depends on how it´s cared for, like a plant you have to water your textile in order to keep it alive (TUdelft, u.å).

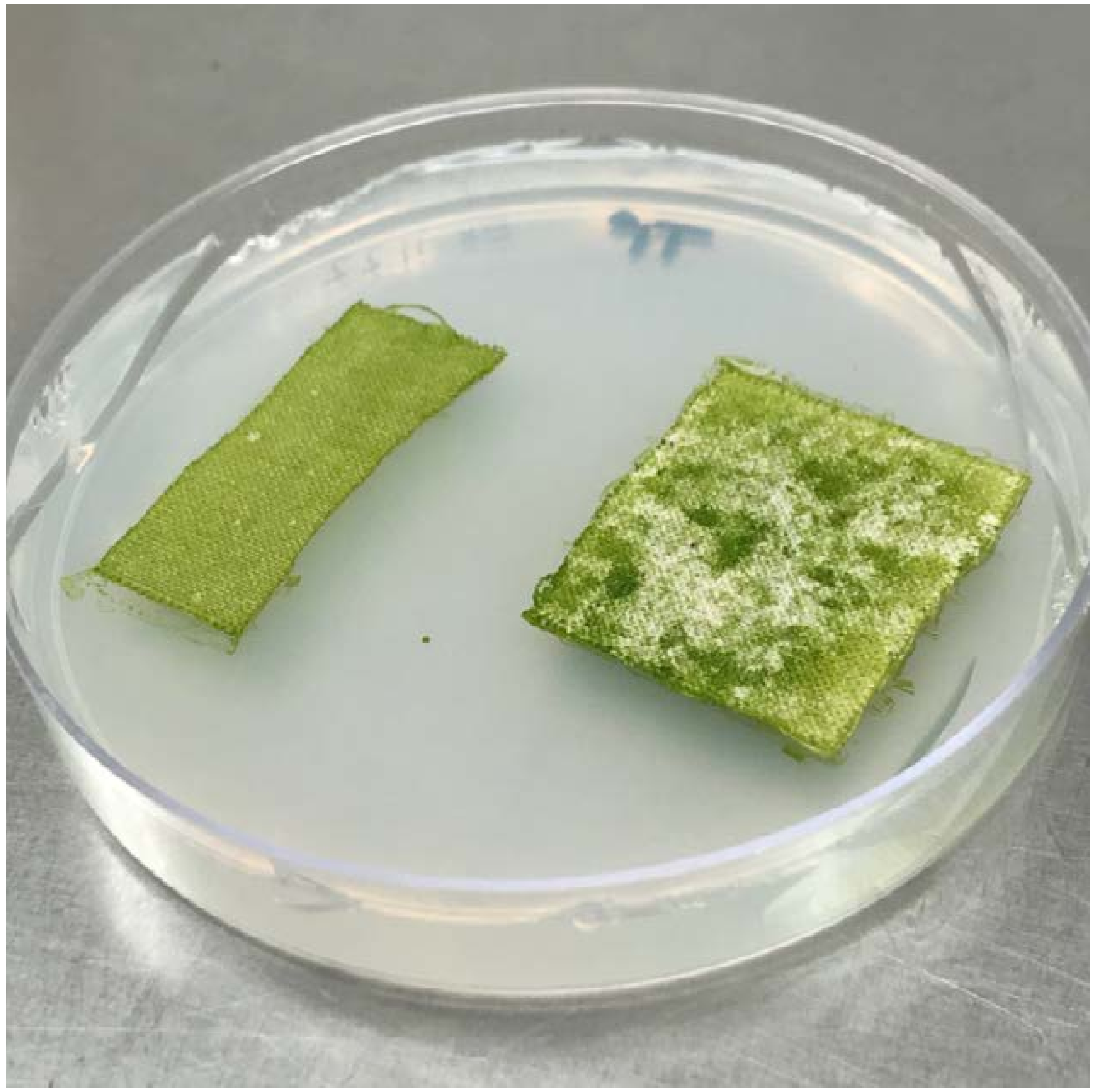


Figure 1: living textile project by Roya Aghighi, (TUdelft, u.å).

2.3 DIY materials and growing design

DIY has alway been a practice involving knowledge and experience from different sectors. The DIY world is expanding beyond crafted artifacts to include materials. Hence the DIY ethos is no longer just about the thing itself, but also what the thing is made from. In the article Defining the DIY-Materials Approach, Rognoli & Ayala-Garcia, (2021) the authors describe the approach as materials self-produced by designers, who follow their own design inspiration, looking for original and unusual sources and adopting a low-cost approach and technique. When the designer has the opportunity to self-produce material it provides them with unique tools to innovate design solutions with authentic and meaningful material experiences (Rognoli & Ayana-Garcia, 2021).

Growing design is defined as the fabrication of materials and products from living organisms, and it›s considered as a type of "DIY material practice". In growing design you are able to control the molecular matter on an atomic level and achieve variants of natural materials, this can change the way we relate to nature. Designers who grow materials start the fabrication process and then let the living organisms take control as the maker (Camere & Karana, 2017).

I personally found the material experimentation to be both challenging and inspiring. By developing my own living materials instead of taking something "off the shelf" the whole product design process was infected with a sense of adventure.

2.4 Bacterial cellulose (BC)

Cellulose is the most common polymer found in nature. It is the cell wall of plants, fungi, and some algae. Instead of creating cellulose from photosynthesis like plants, the bacterium acetobacter xylinum can produce glucose, sugar. glycerol, or other organic substrates and convert them into pure cellulose (Wang & Tang, 2019). Bacterial cellulose has different properties from plant cellulose, it is characterized by high purity, strength, moldability and increased water holding ability. Bacterial cellulose is naturally produced in nature, but it can also be produced outside of nature. By controlling synthetic methods, bacterial cellulose can be tailored to have specific desirable properties (Wang & Tang, 2019).

Material cellulose was discovered by Anselman Payen in 1838, but the cellulose produced by bacteria was discovered by A.J Brown in 1886. Brown used Acetobacter xylinum to synthesize an extracellular gelatinous mat. It was not until the 20th century that more studies on bacterial cellulose were conducted. In 1931, Tarr and Hibbert published the first detailed study of the formation of bacterial cellulose. Later on in the mid 1900s the necessity of glucose and oxygen in the synthesis of bacterial cellulose was proven. These studies have led to new uses and applications for the material (Wang & Tang, 2019).

Based on distinctive structural properties, the material is being used for a wide variety of commercial applications including cosmetics, food products, textiles and medical application.

In the biomedical world BC has attracted a large interest for research and applications. The main utilization of BC is used for tissue engineering and wound-dressing applications. This is due to its good biocompatibility, high water-holding ability, flexibility and high tensile strength (Betlej & Karajewski, 2021).

In 1992 BC was classified as "generally recognized as safe" material by the Food and Drug Administration, meaning BC can be utilized in food. One of the first commercial uses of BC as a raw material in food was Filipino traditional food "nata-de-coco". Fermented in coconut water, BC creates chewy cubes dressed in sugar syrup and enjoyed worldwide. BC has also shown as a plausible additive for thickening and stabilizing agents for the food industry. BC can be used in processed food to enhance their stability, quality and storage conditions (Betlej & Karajewski, 2021).

BC is used as a nonallergenic polymer in cosmetics. BC facial mask is used for treating dry skin because of its biocompatibility and the ability to hydrate the skin. The paper manufacturing industry is evaluating and researching the use of BC as an additive in high quality paper due to its effective folding endurance. The textile industry is also using BC, because of its modularity and leather like appearance. I will go more into this later on (Betlej & Karajewski, 2021).

Figure 2: «Nata de Coco», 2023

Figure 3: BioCouture by Suzanne Lee developed a collection of garments from self grown bacterial cellulose. She was one of the pioneers in the intersection of design and biology. That resulted in designers starting to fabricate new materials using natural processes of growth (Camere & Karana, 2017).

2.5 Growing Bacterial cellulose

In water containing nutrition, the bacteria will create small fibers that weave together a gelatinous film on the surface. The production of cellulose depends on several factors: the growth medium, environmental conditions and the formation of byproducts. The fermentation medium contains mainly carbon and nitrogen, among other macro and micro nutrients required for bacterial growth. Glucose is the most commonly used carbon source for cellulose production. Using glucose lowers the pH of the culture and decreases the production, this can be avoided by adding organic acids. Other environmental factors that affect the production of bacterial cellulose are temperature, pH and oxygen. Studies have shown that the optimal temperature for the liquid culture is between 30-26 °C.

There are multiple ways to grow bacterial cellulose, in laboratories with specific bacteria strains, using fruit (scraps/leftover) as a carbon source, or liquid culture from fermented tea. Before starting my thesis I experimented with using various recipes. Then I had limited knowledge and learned by doing. The recipe that gave the best results and is the main recipe I used in this thesis was a kombucha recipe from biocouture (Biocouture, u.å), where tea, sugar, SCOBY and vinegar is added in tempered water. In my experiments before the thesis I learned that the environment is key for optimal growing conditions. Norwegian winter is not optimal for growing bacterial cellulose. Therefore I purchased a rising oven, a metal box so I could control the temperature. Time is also an important factor in growing bacterial cellulose, the growing process takes from 30-7 days depending on how robust one wants the material. The longer it grows the stronger the finished material is.

Bacterial cellulose recipe

The recipe can be scaled to preferred amount

1 L water: Tempered tap water, optimal growing temperature is between °30-26 Celsius.

1 dl vinegar: Cellulose grows best in acidic liquid (pH around 4-3). The bacteria creates vinegar as i bi-product, so leftover culture liquid can be used in the next batch instead of vinegar.

1 SCOBY starter culture: SCOBY (symbiotic culture of bacteria and yeast). The main bacteria in SCOBY, gluconacetobacter xylinum produces nanofibrils of cellulose which self-organize to a nano-structure like material. In theory you only need one for your first brewing, afterwards there will be enough bacteria to reuse for the next batch.

It is important to handle the culture as sterilized as possible, to avoid contaminations. The cellulose will take the shape of the container it›s in, use a container made of plastics or glass. The cellulose grows best in room temperature (°30-25 Celsius), and with a cloth covering the container, to ensure oxygen flow and to avoid contaminations.

Figure 4: BC ingredients

Before starting the production of bacterial cellulose I experimented with different adjustments to the recipe seen above, to find the most efficient growing culture. I experimented with the amount of sugar and different culture liquids.

First I made adjustments to the culture liquid, here I used the recommended amount of sugar. I made tre different batches, one with SCOBY, one with leftover liquid from another batch and one combination of the two. All of the tests grew for 14 days in the oven. Figure 5 gave the best result, with SCOBY as culture, with a thickness of 8 mm, compared to leftover culture that was 4mm figure 6 and figure 7, 7mm. Figure 6 grew the slowest and had a more slimy surface. I found that figure 5 were more compact, and a smoother surface than figure 6 and 7 that had a rougher surface (small bumps). There wasn´t much difference from figure 6 and 7, other than that figure 5 had one less step in the making (using SCOBY and leftover culture) and a small difference in thickness.

Figure 5: Experimenting with culture

Figure 6

Figure 7

When conducting my next tests I used the recipe that gave the best result from the last test (figure 5). This time I wanted to test how different amounts of sugar affect the growing conditions. In plastic containers with 5dl liquid i tested with 50g (recommended amount), 100g and 150g. 50g (figure 8) gave satisfying results, smooth, thick and consistent color. Figure 9 with double the amount of sugar, was not as thick and developed a big brown spot. I can´t tell for sure why this spot developed, it can be contamination from the culture but since I used the same culture in figure 8 it´s most likely the amount of sugar that developed the spot. The spot from figure 10 was very similar to figure 9 contamination spot, thin, sticky and fragile

Figure 8: Experimenting with sugar

Figure 9

Figure 10

Sugar

In the first month of production I wasn›t completely satisfied with the results. After 4 weeks the cellulose wasn›t as thick as I would like it and after drying, the material was fragile and easily breakable. After some research and reflection I replaced the white processed sugar with cane sugar. Since it is a natural process I figured that cane sugar would respond better to the bacteria. Cane sugar comes from sugarcanes and is minimally processed, with larger grains and a darker color than regular sugar. This completely changed the growing process, it grew faster, and the results were thicker and more dense, it also gave a much smoother surface than with regular refined sugar.

Figure 11: Sugar

Figure 12: BC made with refined sugar

Figure 13: on the left BC made with refined sugar, on the right BC made with cane sugar

2.7 Working with Bacterial cellulose

While the bacterial cellulose grows it can›t be moved, because the layer on top is easily breakable. So while growing my role is quite inactive. In this section I have a more active role in the material tinkering. I have conducted a series of experimentations to learn and understand the materials properties. In this section I used all of my senses to discover how the material looks, feels, smells and sounds.

Harvest and washing

After growing the material is harvested by hand, and washed also by hand. Since the material has been going through a fermentation process it has a distinct sweet vinegar smell. Washing in soap and water eliminates some of the odor. This can also be done by boiling the cellulose in water for a couple of minutes.

Bacterial cellulose can be harvested after 7 days. This results in a thin, transparent and fragile cellulose layer. Optimal growing time is 3 weeks giving a thicker and robust material. I worked with both to experience the different material properties.

Figure 14: Harvesting BC

Figure 15: Washing BC

Drying and shaping

There are multiple ways to dry bacterial cellulose; on a flat surface, 3 dimensional surface, by hanging the wet material or in the oven. I have tried various techniques and surfaces. The most efficient surface is wood, with the large water capability it dries faster on wood as the wood absorbs the water. For a more polished look it can be dried on plastic, this will take more time as the water needs to evaporate. The water capacity makes the material heavy, this is useful to create texture on the material as it lays on a surface to dry, you can see the structure it›s been drying on (see figure x). It›s also possible to dry it over 3 dimensional objects (see figure x), it will form around the object. Drying using a string and pinches speed up the drying process, but it didn´t dry evenly and curled up. The oven sped up the drying process when that was needed.

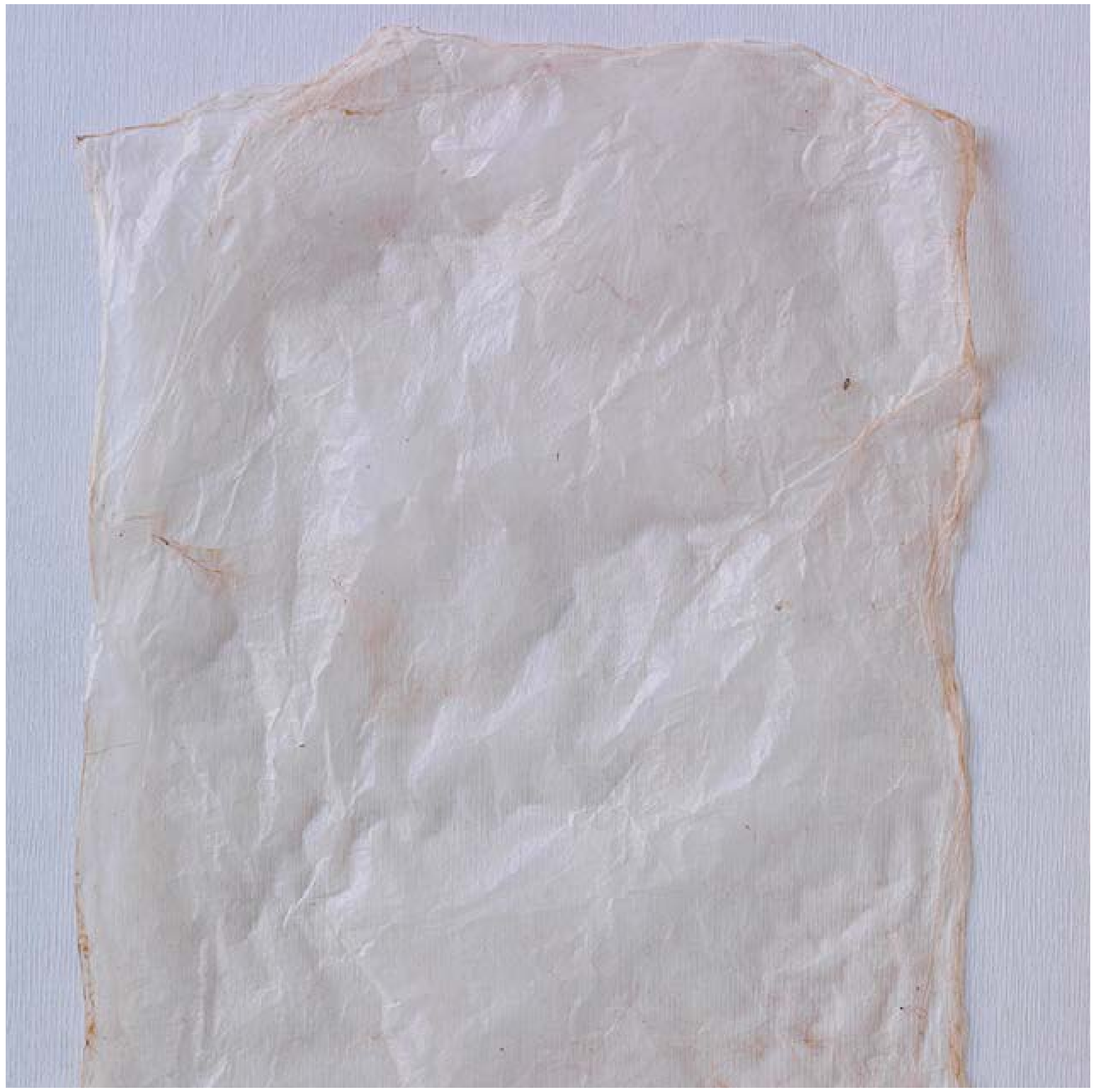


Figure 16: Harvested after 7 days

Figure 17: Harvested after 3 weeks

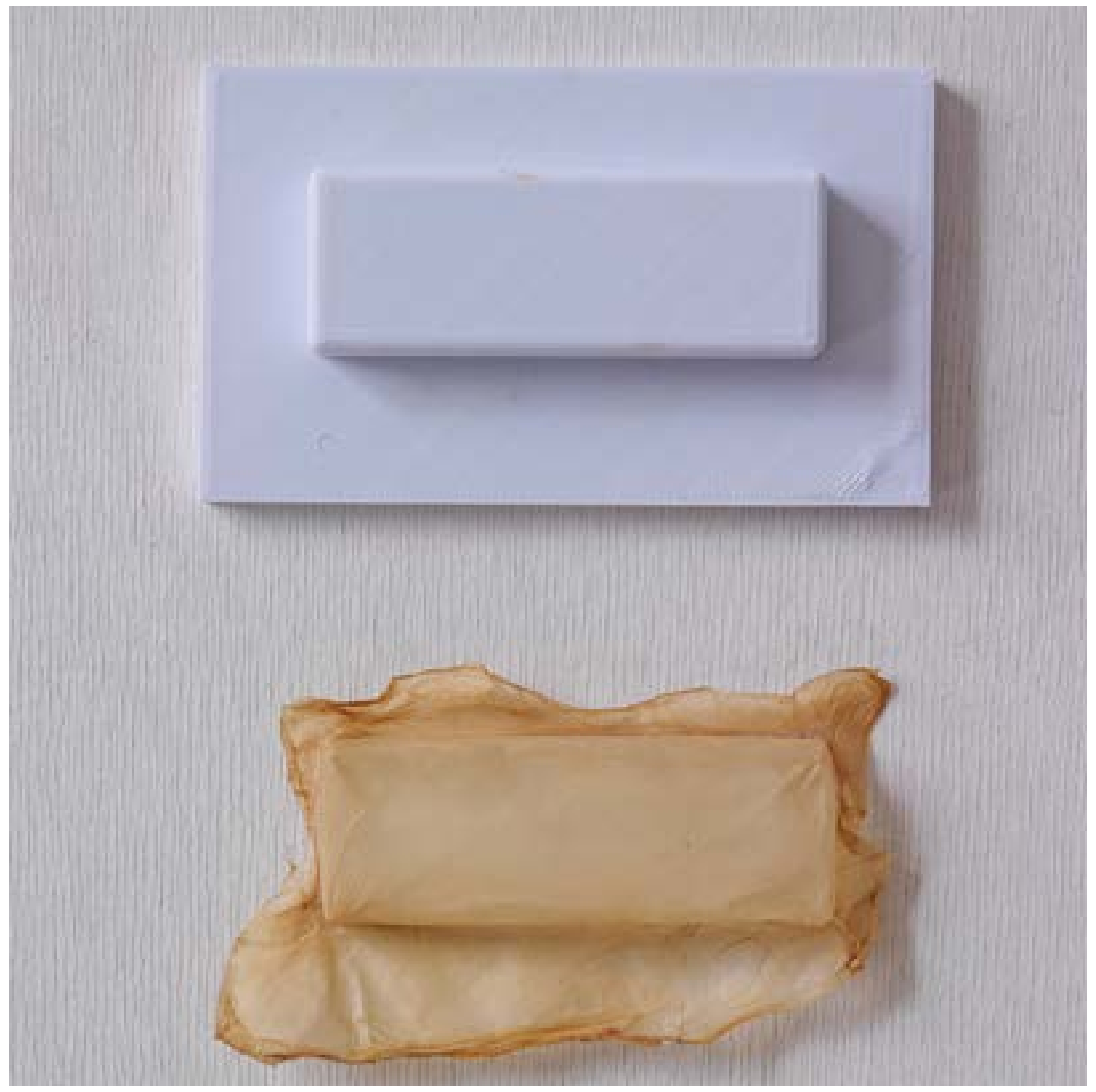


Figure 18: Shaping BC. BC dried over 3D-printed shape in PLA

Figure 19: BC dried over 3D-printed text in PLA

Figure 20: BC dried over battery packaging

Figure 21: Coloring BC**.** The high absorbency of bacterial cellulose makes it possible to color during the growing process and after harvesting. During the growing process I added synthetic color (food coloring) and natural color (beetroot juice) (see figure x). I will go into more detail on this in the next chapter.

Cutting and joining

The material is easy to cut, during my process I used scissors, a cutting machine and wallpaper knife. To seal the material you only need water. The cellulose still contains sugar, therefore when damped the sugar provides a strong bond and seals the material together. Another way to join the material is sewing, this only works if the material is thick enough, preferably grown for at least 4 weeks. When too fragile the thread will break the material.

Figure 22: Handsewn

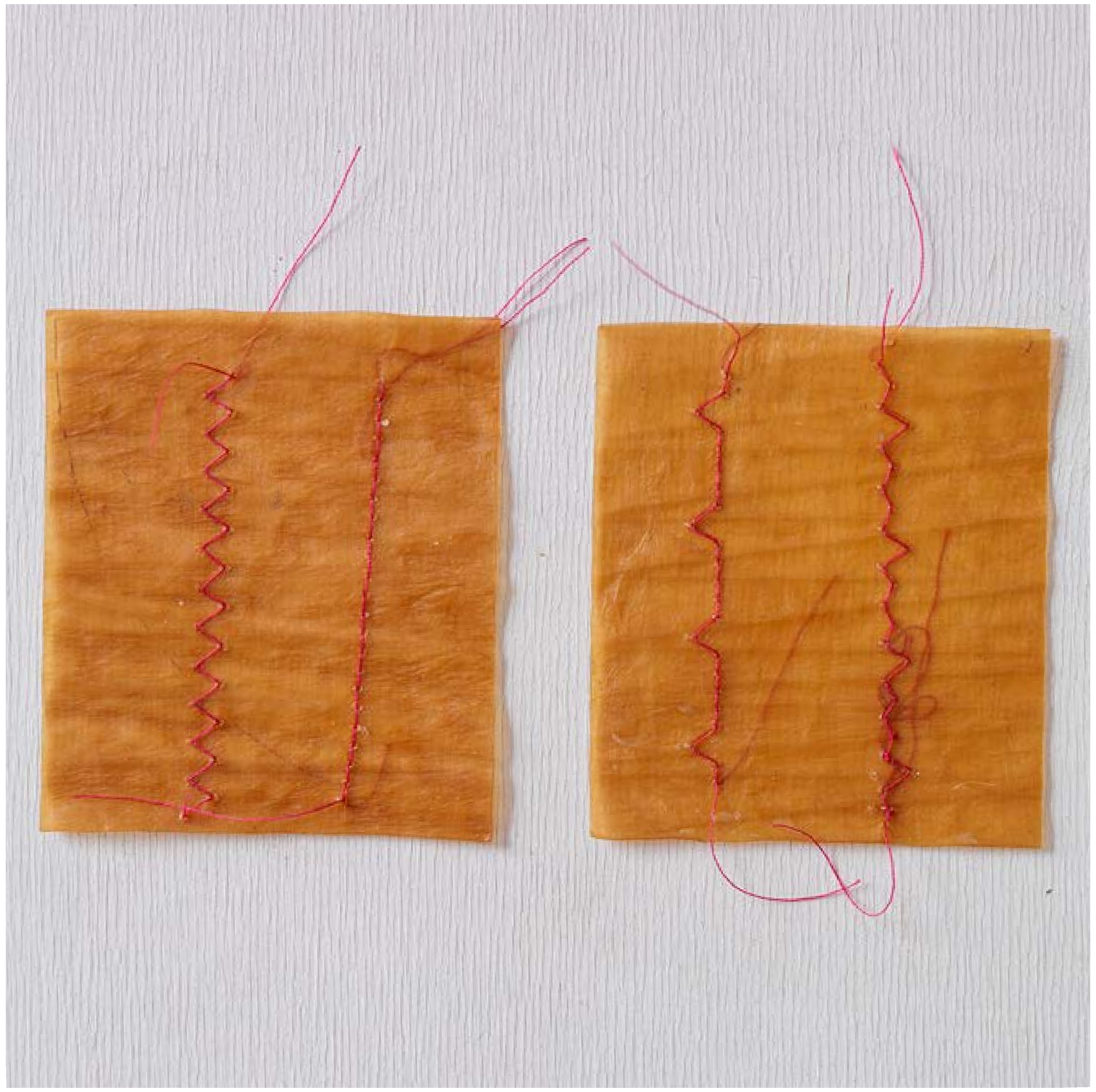


Figure 23: Machine sewn

Heat

As a part of learning about the material I wanted to expose it to heat to see how it reacted. With a lighter I burnt a thin and then a thicker layer. Both caught on fire but the flame on the thicker piece burnt out almost immediately, the thinner layer caught on fire that i had to extinguish. The thinner layer almost evaporated into ash while the thicker layer was filled with bubbles and retained its shape.

Figure 24: Burning BC

2.8 Introducing BC

While evaluating the material I introduced the material to multiple people to get their first impressions, as well their reactions and associations. During the study I tried not to say too much during these interactions unless they asked me questions in order to not influence their experience. The people I introduced the material to did not know what bacterial cellulose was or how it was made.

I have shown the material in its wet and dry state. During growing and the wet state, most commented on the smell and seemed almost repulsed by this. Some were intrigued and asked about production and what it can be used for. People were reluctant to touch the wet material and those who did described it as cold, slimy and gel-like.

In its dry state most started by smelling the material, and described the smell as sweet, or like sugar. They also bended and tested the strength of the material, one said "oh it›s stronger than paper" another said "wow i have never seen something like this". One lifted the material towards the light to see its transparency. Most compared the material with leather or plastics, one said "this basically looks like leather not made from animal skin".

3.1 Experiencing bacterial cellulose

Materials are often a way to attract people´s attention. We can be fascinated with materials, appreciate their application, take pleasure or displeasure in their existence. Material experience is a phrase that acknowledges the experience people have with and through materials, however, Karana and Giccardi argue in the article Foundations of Materials Experience (2016) that the definition of material experience should also acknowledge the active role of materials in shaping our ways of behaving. It should attend to the aesthetic aspect of experience as much as its preformative character (Giccardi & Karana, 2016). In this chapter I work with senses to give bacterial cellulose a higher aesthetic value by adding color, patterns, shape, textures and embracing its imperfections.

3.2 Experiencing materials

In the MDD method they express the importance of comparing/ surrounding the specific material with other existing materials. They call this material benchmarking, and the aim/goal is to discover potential applications (Karana et al, 2015). I surrounded bacterial cellulose with a piece of wood, thin plastic, leather, slate stone, paper, metal and cork. I chose half of the materials based on what I associated bacterial cellulose with; for example the color and structure of leather, the transparency of plastic, the natural texture of cork, and the form of paper. The other half is what I find to be the opposite of bacterial cellulose, for example the weight and color of wood, and the texture of stone and metal. I invited fellow students to look and touch the different materials to see how they react and interact with the different materials.

Figure 25: Material benchmarking

I encouraged them to interact with the material as they wanted to, and tried not to involve myself too much, just observing, unless they started a conversation or asked a question. I wanted to see how they experienced the materials, and hopefully this would lead to some insight on what they found pleasing or unpleasant... what they associated different materials with and where they saw potential applications. I wanted the materials to start the conversation, by inviting people to interact with them.

The first thing I noticed was most of the participants picked up the wood first. Some smelled it, or lifted it up and down, feeling the weight of it. The stone led to a conversation about the temperature of stones, and how wonderful it is to lie on an outcropping of rock to dry after a swim in the ocean. In one conversation we talked about how beautiful wood can be and how important wood is to humans. It›s been there long before us and will be there long after us. I didn›t observe anyone picking up the plastic, but many were fascinated with the pattern on the piece of paper and looked closely at the structure. I laid out two different BC, one grown for 7 days, the other for 3 weeks. The two have substantially different appearances. The one grown for 7 days is more transparent and has almost no color, and feels very fragile. The BC grown for 3 weeks has more color to it and feels more compact and strong, it›s also more sticky. When touching the thin BC they instantly laid it back down, one pointed it toward the light and commented how it can be perfect as a packaging material. One smelled the thicker BC and said it had a sweet smell.

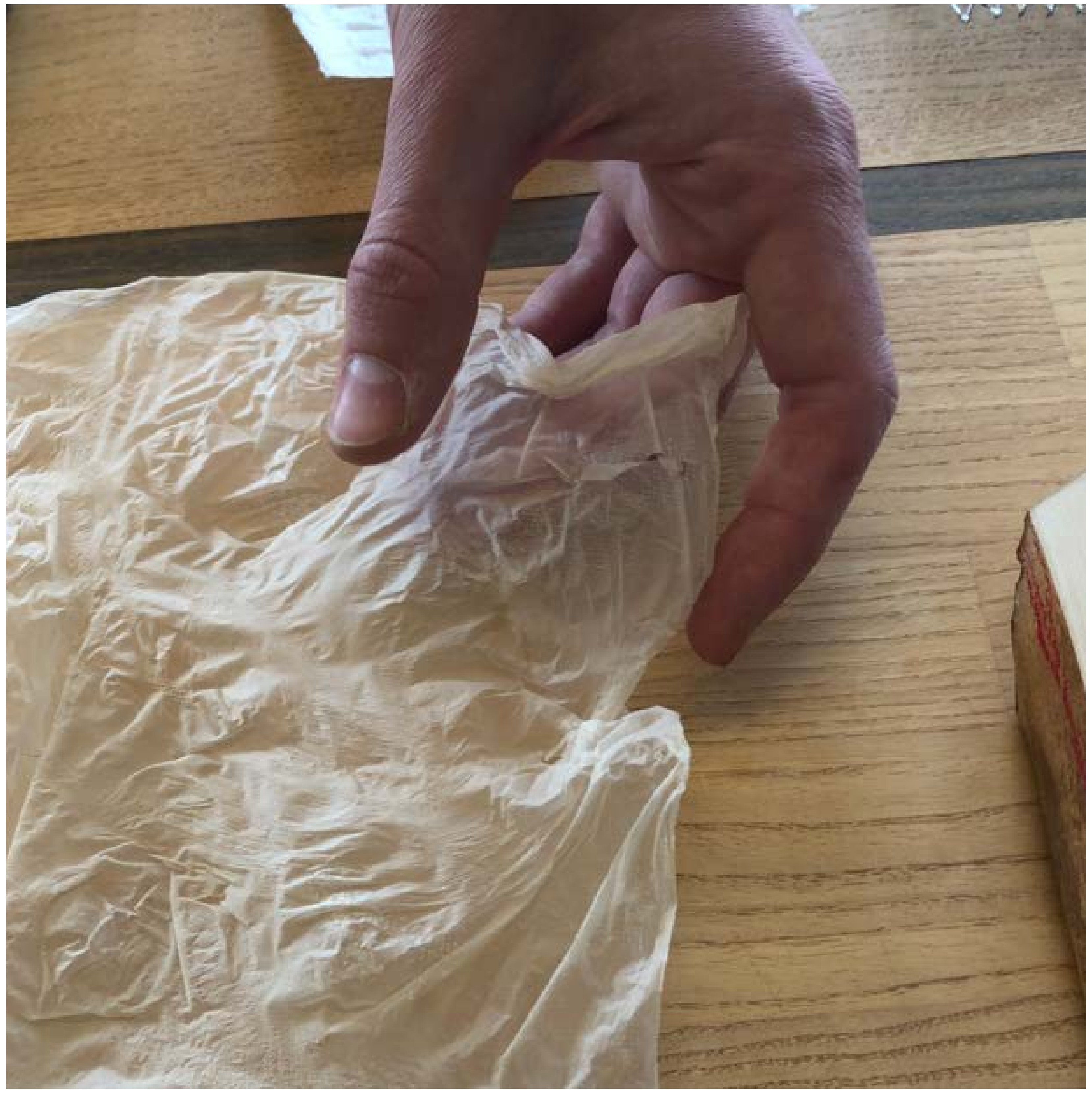


Figure 26: Material benchmarking

3.3 Aesthetics

The word aesthetics refers to the sensory perception and the understanding of the knowledge that the senses give us (Hekkert, 2006). Historically aesthetics is used and measured by art, but people also find nature aesthetically pleasing. Paul Hekkert argues that we aesthetically prefer environmental patterns and features that are beneficial for the functioning and development of our senses.

To understand why we perceive something aesthetically, we have to first understand the sensory system. A dominant way of experiencing our world is through vision. With vision we detect obstacles as well as identifying things. Hekkert argues that we like to look at things that support navigation and identification and that this forms a pattern that makes us see relationships and differences (Hekkert, 2006). Next is the ability to be touched and to touch. When you feel pain you associate it with danger. Our sense of touch also gives us information about the world. We can feel the shape and weight of things. We can also feel textures and temperatures (Hekkert, 2006). Then our chemical senses of smell and taste. These senses are the bodied gatekeepers. They identify what›s good to consume and detect what›s bad. Smell is a rich source of associations and gives us the ability to memorize past places and events. Hekkert also includes the mind as a sense, we perceive our thoughts with our mind just as we perceive a visible object with our eyes (Hekkert, 2006). Paul Hekkert (2006) writes that aesthetic experience refers to the pleasure or experience of delight gained through sensory channels, which is considered to be the immediate feelings evoked when experiencing the product via the sensory system (Hekkert, 2006). Sensory experiences, differing from cognitive experience, are usually rapid and involuntary, and are the core of aesthetic appreciation of a product. As materials are fundamental to a product, sensory experiences with materials contribute significantly to the interpretation of experience with the whole product (Hekkert, 2006).

Hekkert presents four different principles of aesthetic pleasure, operating around our senses. The first principle: maximum effect for minimum means is about preferring the visuals. That is chosing something with less effort than a more damaging alternative. Something is considered beautiful when it only has a few descriptive parameters. A visual pattern is pleasing to the eye when simple design features reveal a range of information (Hekkert, 2006). The second principle: unity in variety concerns gathering information and detecting order in chaos or unity in variety. We like to see connections, and we consider it aesthetically pleasing to invest effort in finding them. We are attracted to designs that do not give everything away at once (Hekkert, 2006). The third principle: most advanced, yet accepted, is about preference for familiar things. We prefer the familiar because it leads us to safe choices rather than risking the unknown. At the same time we are attracted to new and unfamiliar things mostly to overcome boredom. We tend to prefer products with an optimal combination of both aspects (Hekkert, 2006). The fourth principle: Optimal match. Products are always multi-sensorial. You hold the steering wheel while hearing the engine and smelling the leather. This principle is about the relationship between these sensory impressions. Senses such as sound, touch, smell and mind follow function (Hekkert, 2006). This principle is evolutionary. When there are patterns in the environment that contribute to the functions of our senses we continue to expose ourselves to these patterns. Hence we receive aesthetic pleasure from seeing, hearing, touching, smelling/tasting and thinking.

These principles can predict and explain peoples aesthetic responses. When they are applied it is most likely people will agree on an object›s aesthetic value. Of course this is more likely if the people more or less have similar backgrounds or previotús experiences (Pedgley & Karana, 2016).

3.4 Leather and plastic

In my experience of seeing others experience bacterial cellulose, most say that it reminds them of plastic or leather. Not strange considering its color and cold surface, and the thinner sheets are almost transparent, like plastics. This inspired me to look more into leather and plastic, specifically fish leather and bio-plastic. I chose these two because I wanted to make leather and plastic with raw materials. With fish leather and bioplastic this was possible.

In Experiencing materials a few commented on what they associated the bacterial cellulose with. As mentioned before one said it would be perfect for packaging, replacing some of the plastic. One commented on the texture and how the raggedy feel reminded them of leather. This inspired me to research different methods of making leather and plastic. I used a DIY-material approach that could potentially result in generating some of the same properties as BC. After some desktop research I choose to make fish leather and different bio-plastic samples.

This feedback and my own associations inspired me to research methods and materials that can be used in developing leather and plastic.

Figure 27: Fish leather

Before the rise of manufactured fabrics, fish leather was sewed into clothing by Indigenous people with easy access to fish around the world. The material is strong and waterproof, it was essential to survival. In Japan, the Ainu crafted salmon skin into boots, which they strapped to their feet with rope (Palomino & Kárádottri, 2020.). Today you don›t see much of fish leather, but some luxury brands have used it in their designs. There is a lot of culture in this craft and there are many different recipes from different countries. Online I found a recipe that seemed operable for someone like myself with limited practical experience in leather making. I contacted my local fishmonger for leftover fish skins. I prepared and tanned the skin with a ceramic plane using a soft touch to not tear the skin. After washing the skin I put it in a glass jar with %96 alcohol and glycerol. For the next 3 days I shook the jar multiple times and then rubbed the washed fish skin with glycerol and nailed it to MDF boards. Then I left them outside to dry for 7 days. The dried material was surprisingly flexible and transparent, which is an important/good quality of bacterial cellulose.

Bioplastics are made of or partly made of renewable biomass sources such as corn, sugarcane, or yeast. Bioplastics are categorized as a sustainable material. Some are biodegradable and compostable. Today bioplastic is used in different industrial applications such as food packaging, agriculture, biomedical etc. Bioplastics made from renewable resources can naturally be recycled by biological processes, and can contribute to limiting the use of fossil fuels (Asher, 2016.). Because of its increasing demand a lot of research explores these materials and looks for new solutions to produce them.

In my research I found a website (materiom.org) which shares recipes for DIY bioplastics. It aided my experimentation with bioplastic. I experimented with different ingredients, such as agar, cellulose gum (CMC), gelatin powder, dried tea and soap. There were many failed attempts, but I was determined to get as close to normal plastic as possible. This exercise made me realize that materials are really all around us, from ingredients to processed material. Being a part of the making of a material makes me so much more aware of my material surroundings.

Foamy bioplastic with sodium and vinegar

Foamy bioplastic with soap

Figure 28: Bioplastic

Bioplastic with agar agar

Bioplastic with cellulose gum

3.5 Visualizing growth

I found it difficult to document the growing process of bacterial cellulose. I tried taking pictures but it didn›t quite capture what I saw first hand. This prompted me to start visualizing the growing process with drawings. My inspiration came from seeing the growing and reading about the process often described as threads being woven together. For me the growing process was very emotional. After finding the best possible recipe I was out of the growing process. Now all I could do was watch it grow. Everyday I would see progress or contaminations forming. This process was alternatively either exciting or disappointing. I wanted to include this in the project to share how I experienced the growing process, which was emotional and aesthetically pleasing.

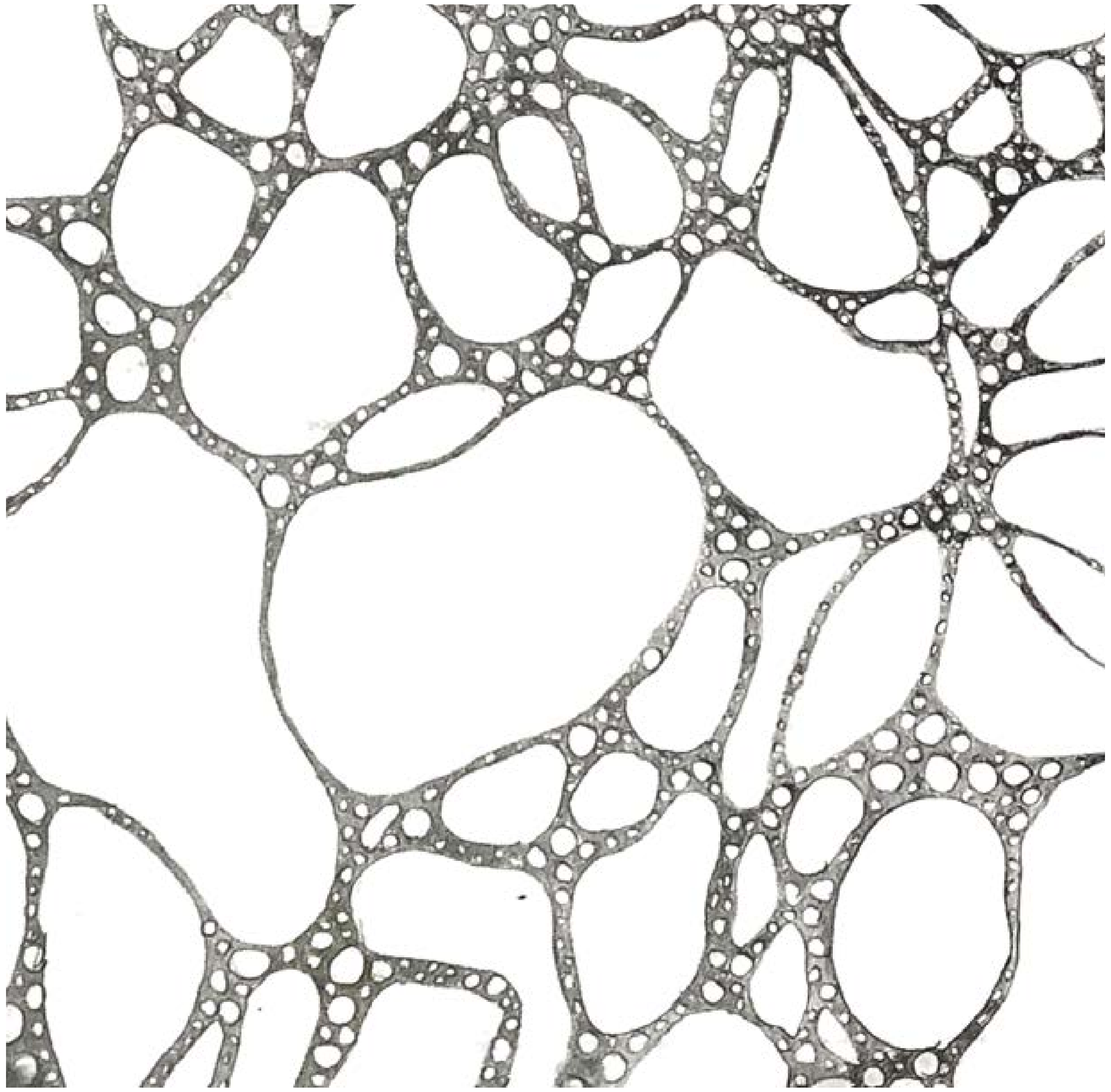
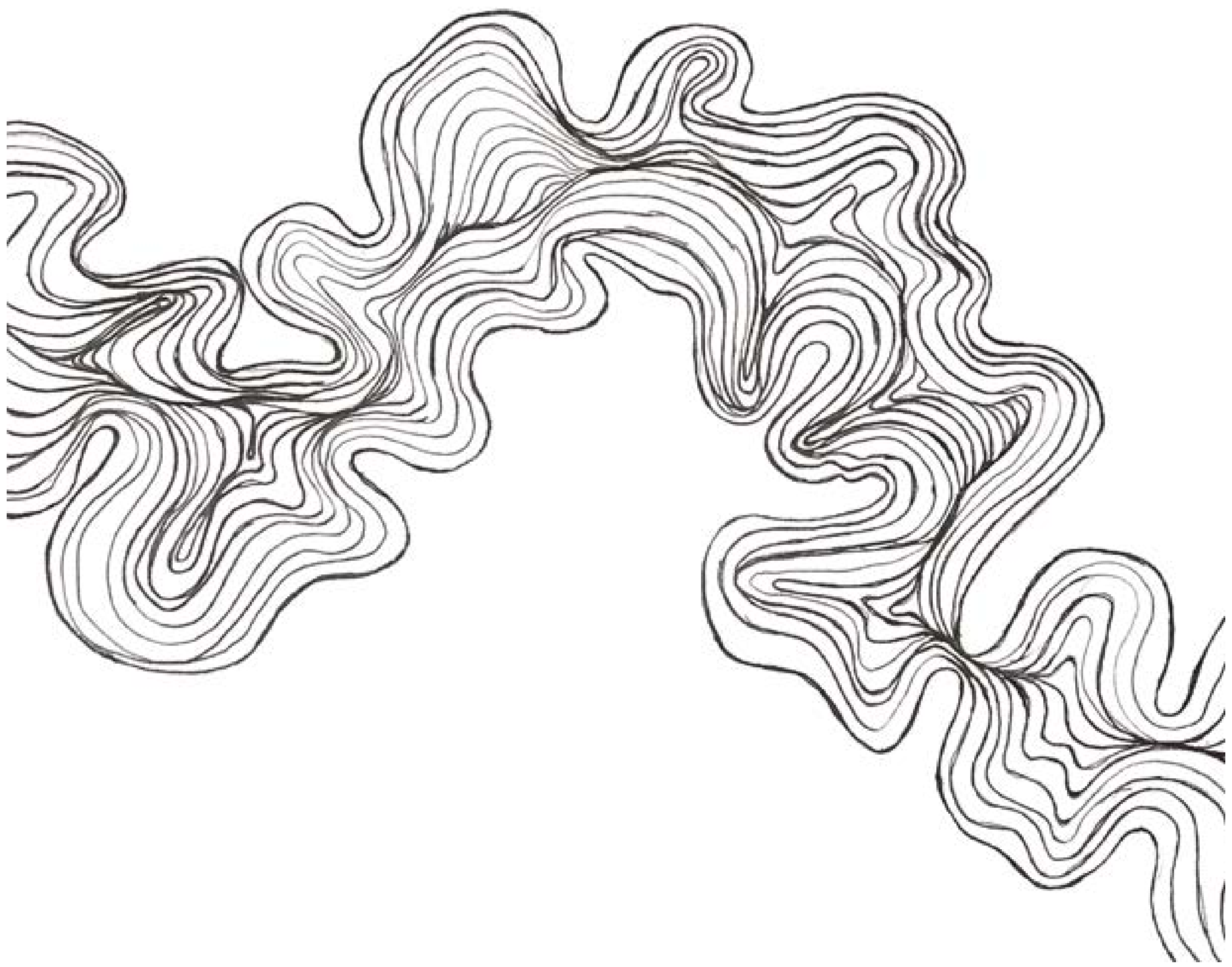
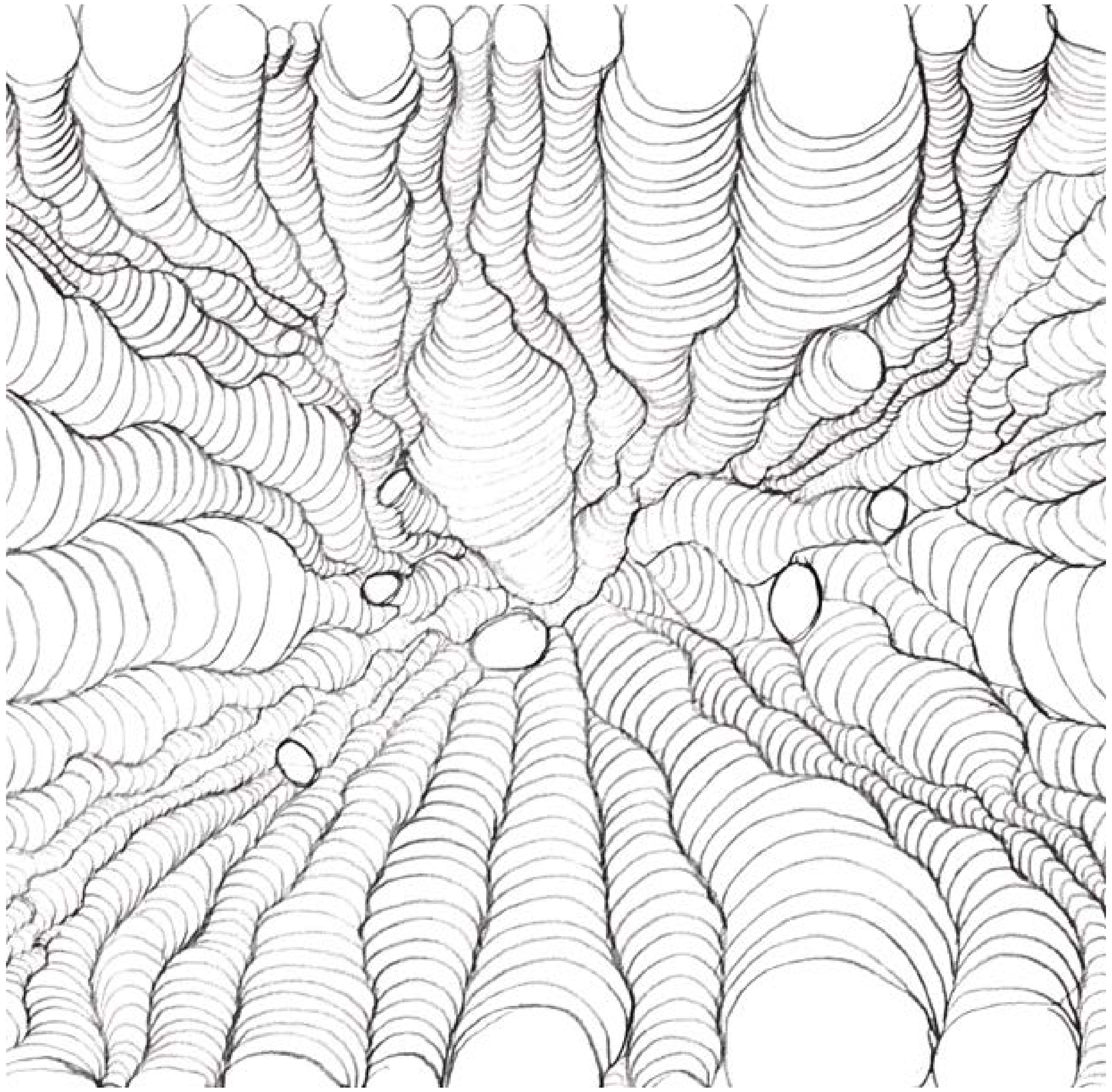
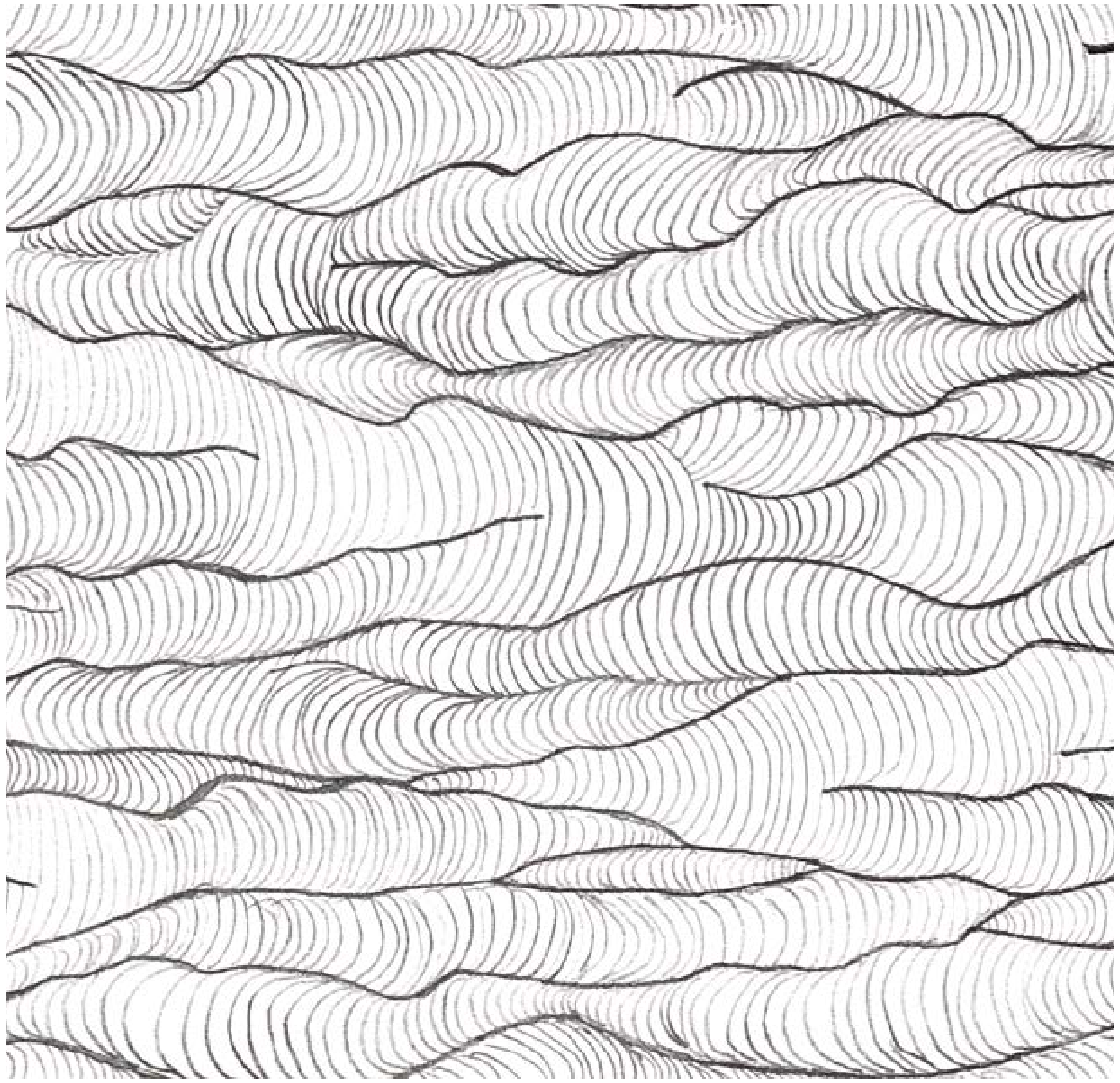
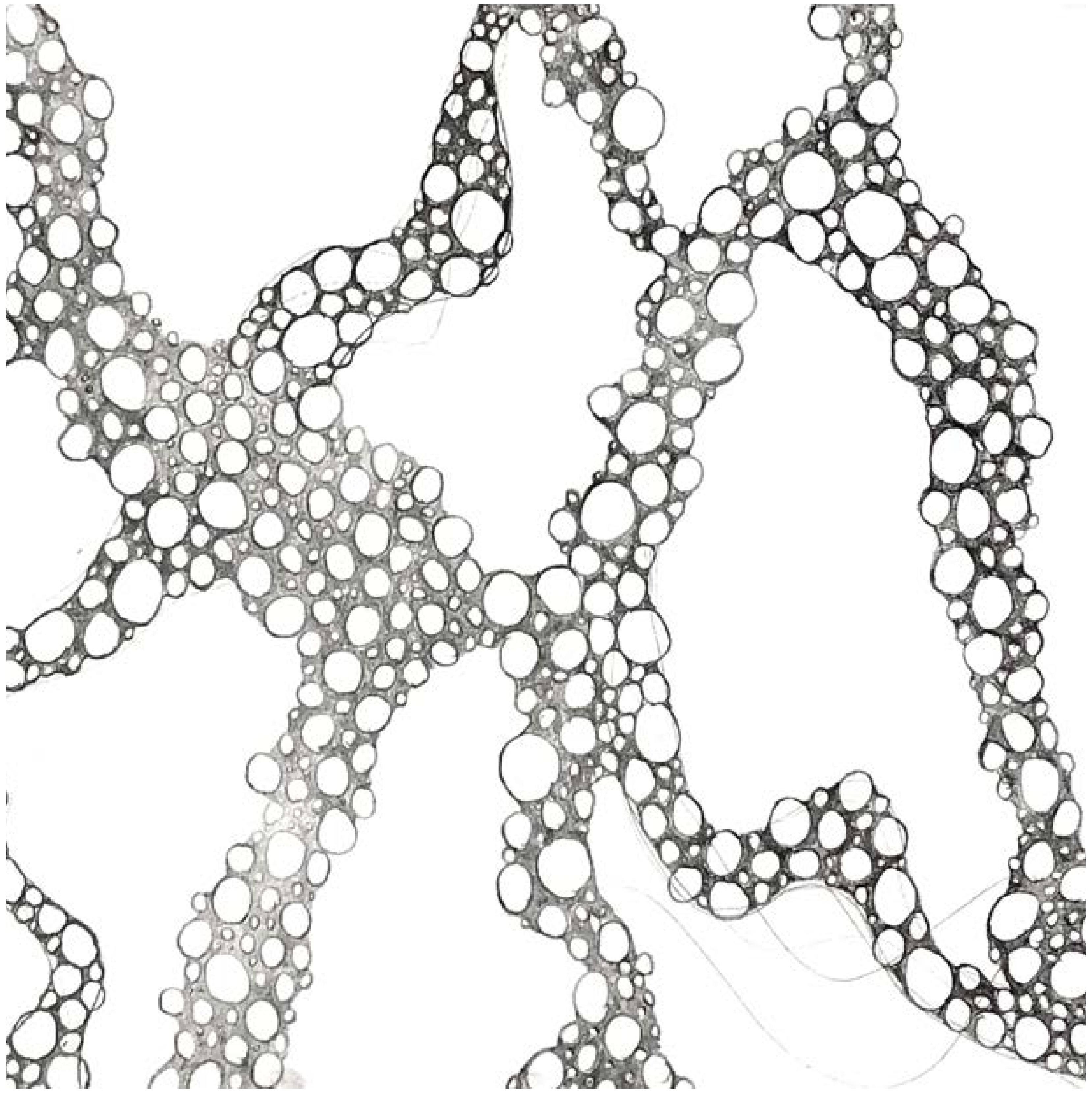


Figure 29: Visualizing BC









3.6 Aesthetics of bacterial cellulose

In chapter 2 I experienced making and working with bacterial cellulose. I used this knowledge in exploring and manipulating in order to find and enhance the aesthetic qualities of the material using different craft methods. Bacterial cellulose has many material properties that give various opportunities for manipulation. The material's water retention capacity makes it easy to shape and create patterns, as well as absorb color. The material's flexibility makes it possible to shape and fold, and sew together.

Color

After preparing the dye, bacterial cellulose was added in a plastic container containing the diy, for 10 days. In an attempt to speed up the drying process I dried it in the oven at 50 degrees, during the drying the material curled up and became brittle. My theory is that it becomes more brittle when drying over room temperature, which makes sense since its growth is based on a specific temperature range. Nevertheless, the color was not impacted by this, and you can see that the material has been dyed in different colors.

Figure 30: BC color

Manipulating

As mentioned, bacterial cellulose is possible to shape during drying. I took advantage of this by drying the material over different patterns, natural and fabricated. I also tested different surfaces, using the CNC milling machine to engrave MDF, 3D printing patterns with plastic, steel wire, paper, and ceramic. The weight of the wet material allows it to absorb into the pattern laying below, since %90 evaporates in the drying process.

Figure 31: BC patterns. BC dried over 3D-ptinted PLA, the pattern is drawn in fusion360, and is ment to mimic bacterial growth

Figure 32: BC dried over bubble wrap

Figure 33: BC dried over paper with structure

Figure 34: BC dried over metal wire

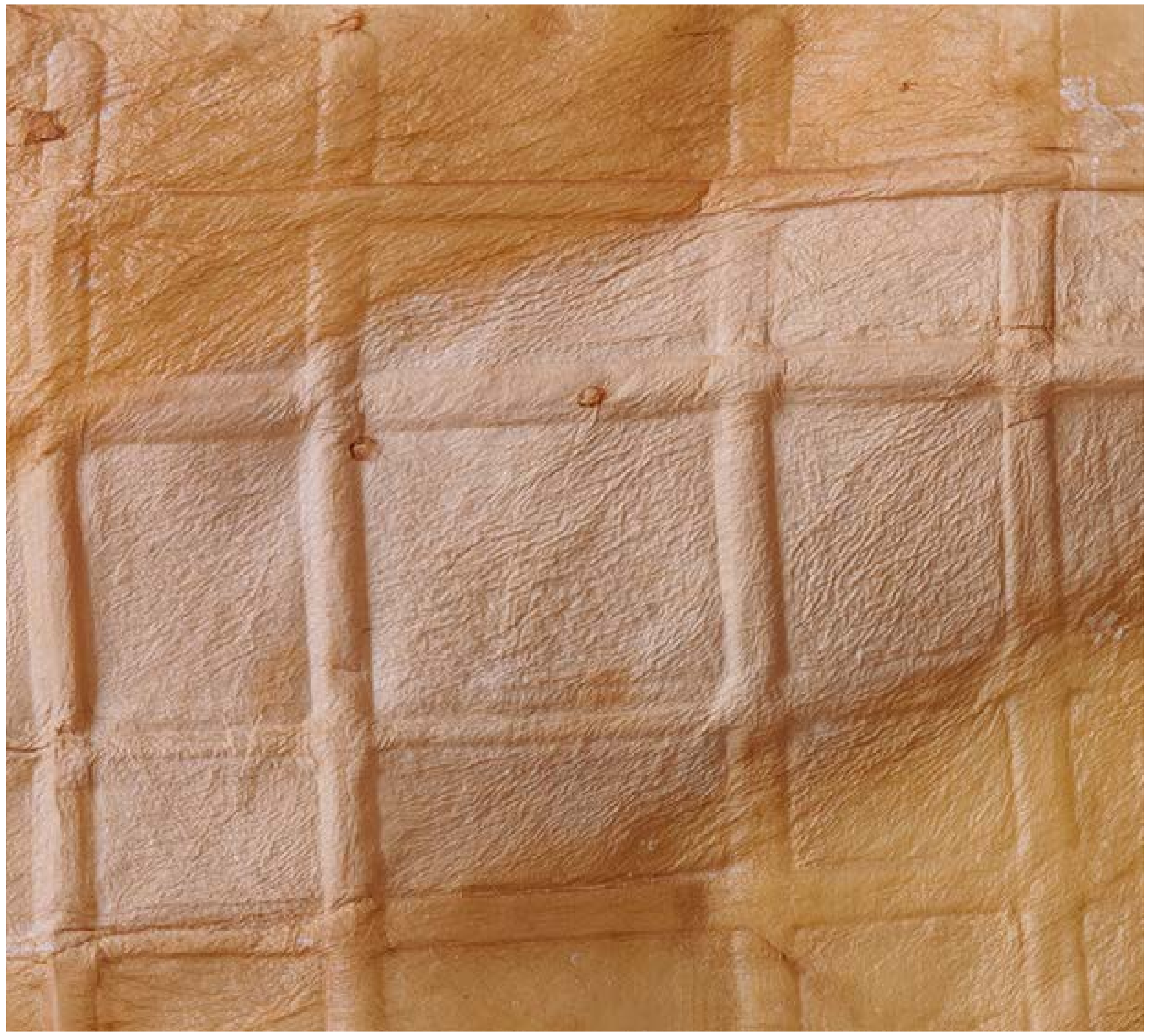


Figure 35: BC dried over MDF with pattern from CNC milling

Figure 36: Cutting BC. BC cut when wet and joined by using basket weave technique

Figure 37: BC cut when dry and joined by using basket weave technique

Figure 38: BC cut with a round metal form

Figure 39: Sewing BC
After visiting a PhD student at KHIO, who has worked with bacterial cellulose, and seeing her samples, I was inspired to use one of her techniques in my material experimentation mimicking sequence fabric. I cut the material into small circles and embroidered it onto a piece of fabric. I did this to encourage the user to touch the material and experience it in a familiar context.

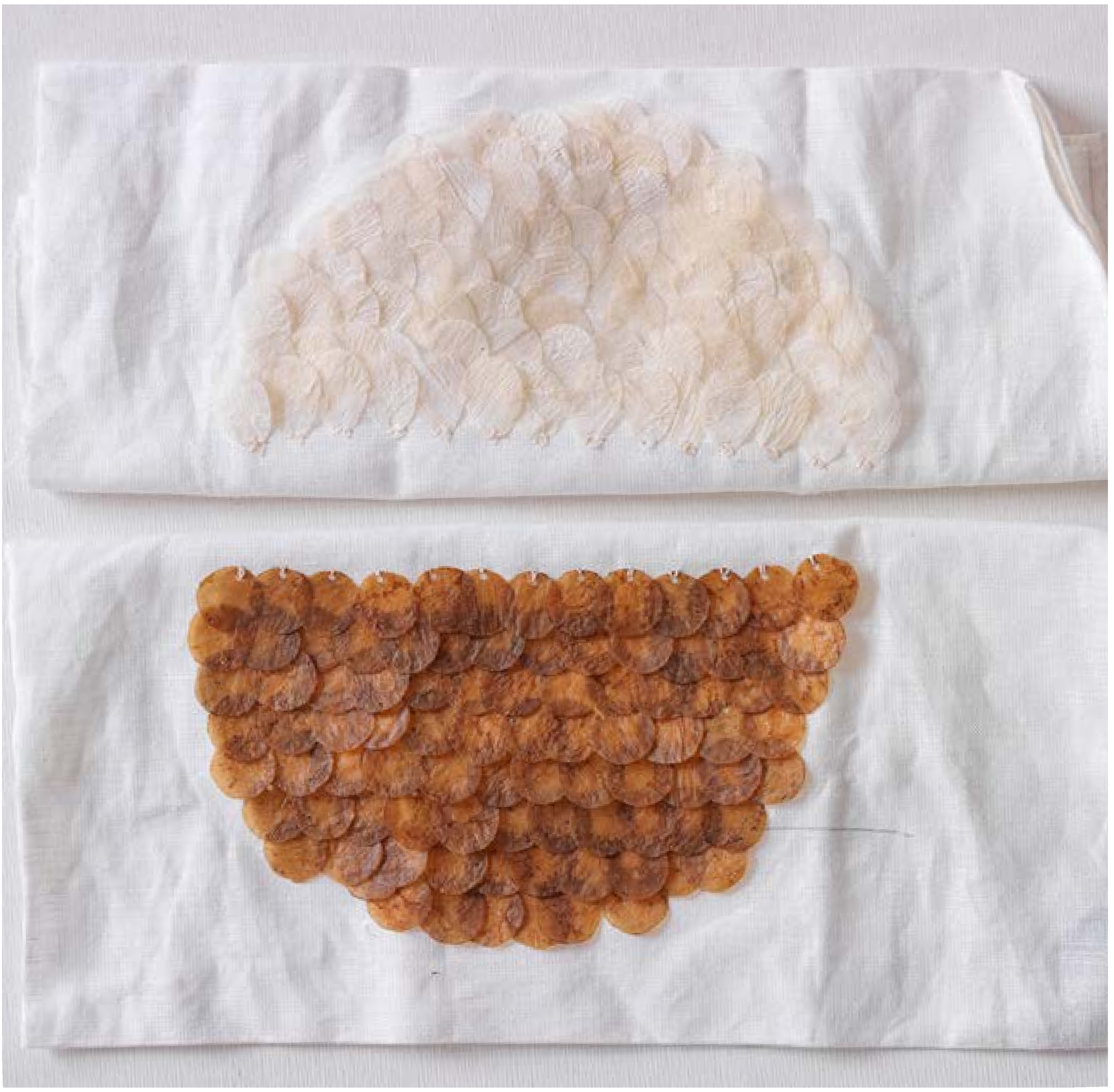
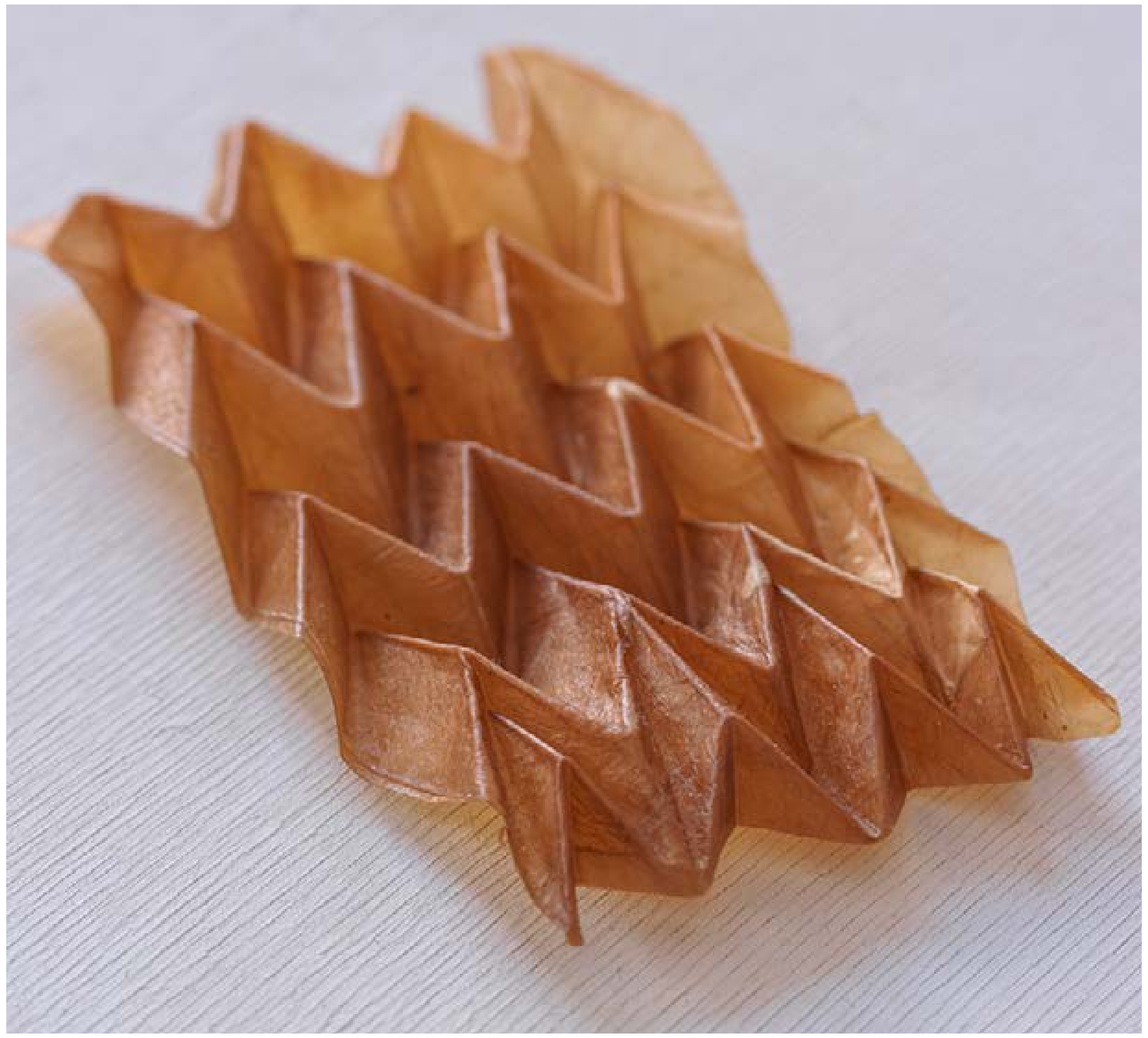


Figure 40: Bacterial cellulose that is over 5 mm and grown on a good culture is flexible and durable when dried. This makes it possible to sew with. It can be joined this way to create patterns.

Figure 41: BC sewn with a honeycomb technique

I wanted to enhance the material's aesthetics with as few tools and steps as possible. I found the best way to do this is origami. Origami is the art of folding paper. Origami celebrates the importance of minimalism in art, and its aesthetic appeal comes from its geometrical patterns and minimalist appearances (Formfluent, 2020). The human race is attracted to natural patterns and origami celebrates this by making a material such as paper resemble natural things, creating a visual association to nature.

Figure 42: BC origami



3.7 Imperfections

Imperfections are defined as the quality or state of being imperfect. It is something flawed, defect or incomplete. Gaetano Pesce was one of the first designers to communicate the importance of imperfections, with regards to its expressive and symbolic potential (Rognoli & Karana, 2014). He was interested in this because imperfections are able to reflect human imperfection. When reading the book Material Experiences: Fundamentals of Materials and Design, I came across the article Toward a New Materials Aesthetic Based on Imperfection and Graceful Aging, which inspired me to explore the imperfections occurring in my self-produced cellulose. The authors argue that valorizing imperfections is a way of expressing workday reality and creating innovation. By bending imperfections to our will, intensifying them, and imbuing them with aesthetic value, a new image can emerge (Rognoli & Karana, 2014).

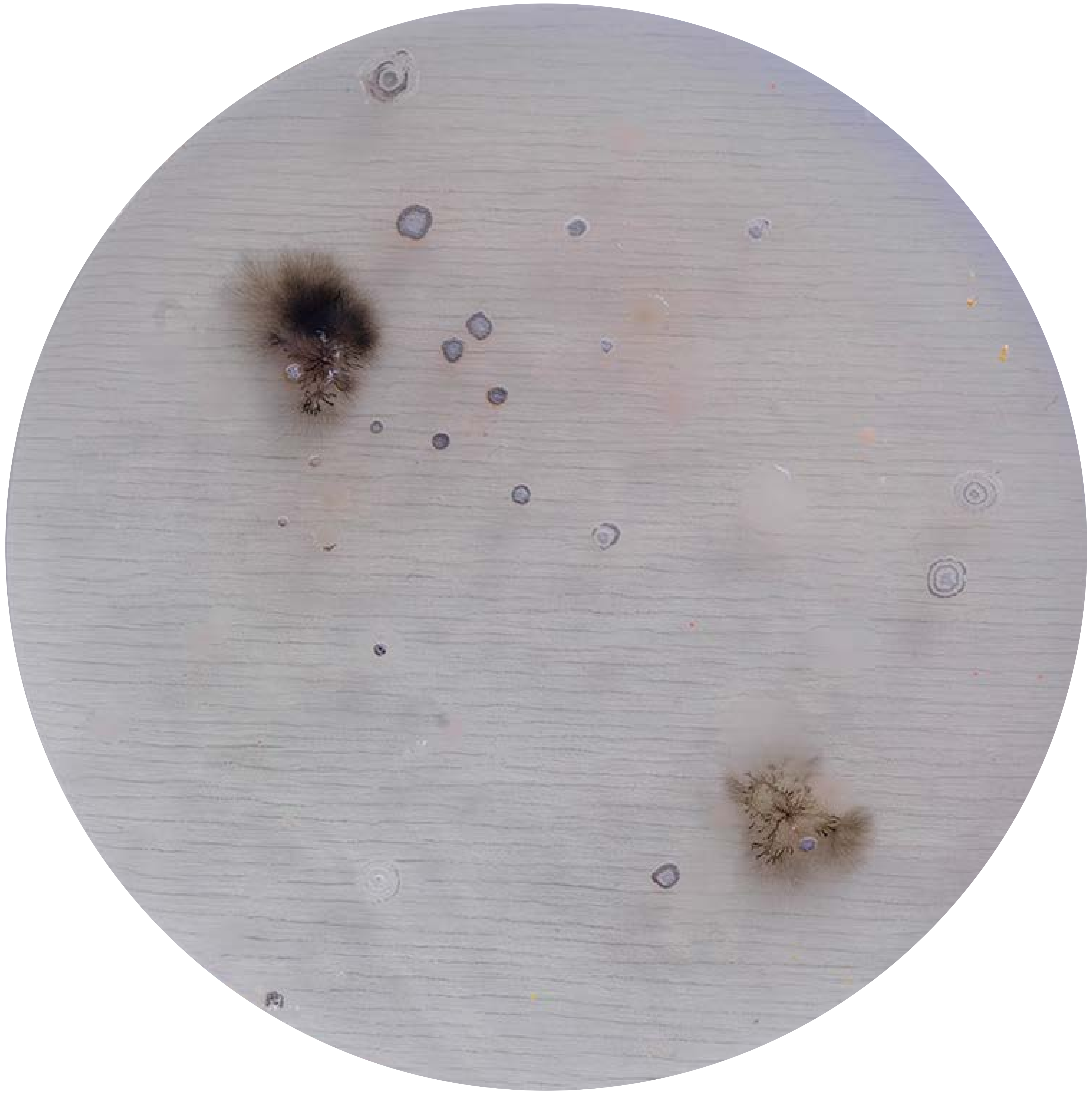
Figure 43: Wabi-sabi is a good example of embracing imperfections, it takes pleasure in the imperfect, escaping from the modern world obsession for perfection.

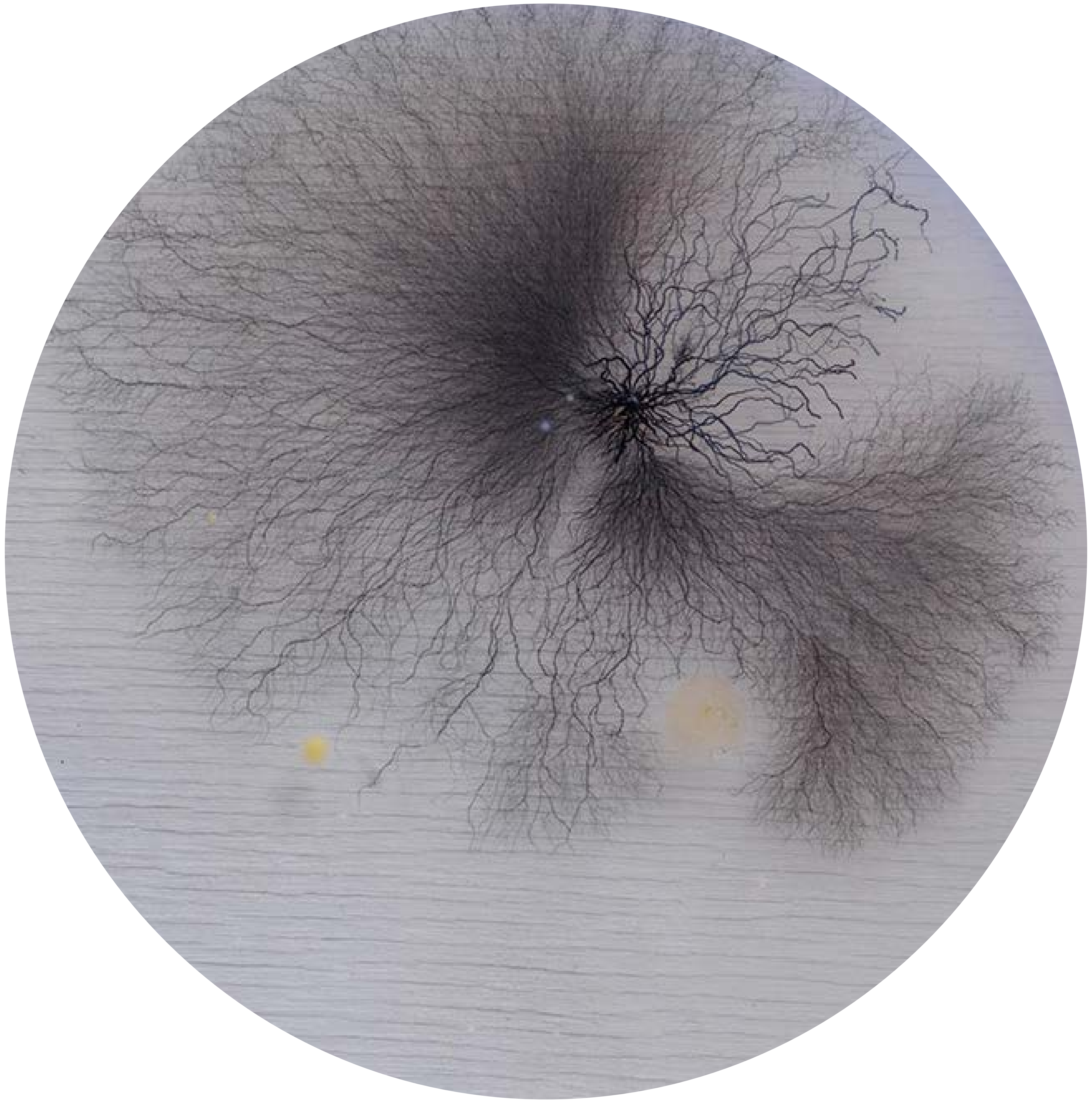
Figure 44: BC contaminated in the growing process, resulting in a frigile material

Figure 45: BC contaminated in the growing process, resulting in a frigile material

I collected samples of the environment around me because I wanted to visualize and promote our invincible everyday workers, bacteria. Bacteria is all around us, and even though we can›t see them, they play an important role in human existence. I wanted to get a better visualization of how bacteria actually grows and see their natural pattern of growth. I wanted to show this by swabbing different surfaces (door-handles, mobile, bacterial cellulose, etc) and smearing it onto petri dishes containing agar and letting it grow for a couple of weeks. I found the natural bacterial growing patterns and structures to be surprisingly aesthetically pleasing

Figure 46: Growing bacteria





I always try to give the material maximum of freedom. I pretend that matter surprises me. This is the beauty that interests me: the one that appears suddenly in the course of a trial. It's an unexpected, fresh, unique, unrepeatable beauty that enchants me.

(G. Pesce, in an interview conducted by Annicchiarico, 2005)

Figure 47: Imperfections of BC. Framing BC to embrace its imperfections

4.1 Discovering findings

In this chapter I will present and discuss my most important findings from understanding the material and experiencing the material, bacterial celluloses technical and experiential characterization. I have sorted the findings in four different categories: *Growing condition, Working with bacterial cellulose, Experiencing bacterial cellulose* and *Aesthetics of bacterial cellulose.*

Bacteria are dependent on carbon and oxygen to grow. In my experience and research I have found that sugar is the most efficient carbon source for growing cellulose. In my first batch of bacterial cellulose I used common refined sugar. I experienced the growing process to be slower than expected, and the cellulose had many brown spots. It also shrunk considerably in the drying process, resulting in a porous and fragile material. Knowing I couldn›t work with this result, I had to try to understand why and how this happened. In a conversation with a Phd student who had experience with growing cellulose I learned about the differences between good and bad cultures. Most of the time she was unable to give an exact answer on why a culture is considered bad. It can be temperature, contaminations, a low pH or the bacteria strain itself. She recommended that when I attained a good batch, I should keep some of the leftover liquid to add to the next batch, securing a good bacteria culture. I decided to test a different type of sugar; cane sugar. This change in **nutrient** gave a considerably different result which I considered an improvement. Using the less refined cane sugar the culture grew faster, it was thicker, and had a smoother surface without any spots. I have done some research on cane sugar vs regular refined sugar, and couldn›t find any easily apparent substantial differences. Cane sugar contains more nutrients, since it is less processed than refined sugar. These differences are so slight that it is not widely thought among nutritional experts to provide much benefits for people consuming it. But it might make a difference for the bacteria. This small change in nutrient was my most important find in the growing process, and made it possible to continue understanding the properties of the material I was working with.

In my experience, Norwegian winter does not provide the optimal temperature for growing bacterial cellulose. The bacteria prefers a temperature between 30-25 degrees. It will grow at a lower temperature, but at a slower pace. Also important to mention is that the bacteria cannot survive in temperatures over 30 degrees. To ensure a good growing **environment** I purchased an oven, specifically a rising oven, where I could regulate the temperature within the desired range. It took some time to find the right operational setting for an even distribution of temperature. The heat came from the bottom, resulting in some useless batches that were on the lowest rack. The temperature was too high for optimal fermentation. Depending on material properties one would like the bacterial cellulose to have, time plays an important factor. After 7 days the cellulose is ready to harvest, a 5-4 mm thick sheet has formed on the surface of the culture liquid. This gives a thin, semi-transparent bacterial cellulose sheet, that is fragile and easily breakable, very similar to a piece of paper. Bacterial cellulose grown for 3 weeks is 15-10 8 mm thick, making the final result stronger and more robust. It also has a deeper color from longer contact with the tea, making it less transparent than the 7 days sheet. These qualities of the 3 week cellulose sheet made it an easier material to work with.

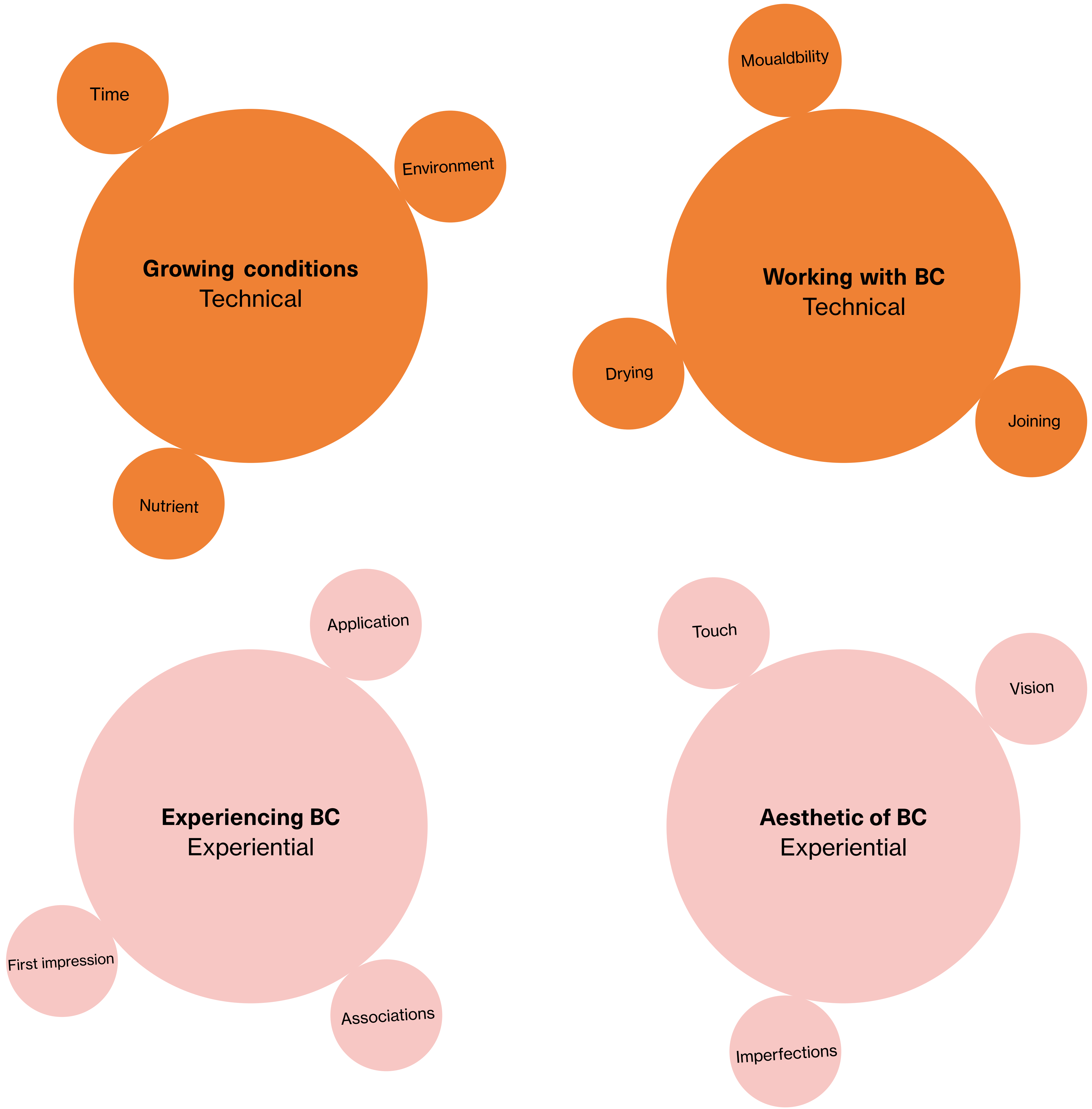


Figure 48: Characterization of findings

There are many different ways to **dry** the cellulose sheet and many different surfaces to dry it on. In my experience I found drying in air and on wood at room temperature to be the best technique. Wood absorbs the excess water and helps to speed up the drying process without affecting the finished material. When dried in the oven at -55 60 degrees the cellulose sheet tended towards brittleness. Natural air drying at room temperature avoided this result. The water capacity in its wet state is at 90%, making the material very moldable, due to its weight. The wet sheet can be formed around a preferred shape and when dried it retains that shape. Bacterial cellulose can be joined by sewing it together or using water as glue. The sugar binds the material together when moistened with water, avoiding any toxic contamination that might occur with glue.

I have used fellow students, friends and acquaintances as users, and introduced them to the material to see their reactions and interactions with the material. First impressions varied. Fellow students have been familiar with the growing process due to the rising oven's proximity as well, and were quick to smell the material pointing out that it wasn›t as bad as they imagined. The fermentation process gives a strong vinegar smell that is hard to ignore. Main **association** for the 7 day cellulose sheet was plastic, because of its transparency and feel. The 3 weeks cellulose sheet was compared to leather, or a thick fabric because of its flexibility. One pointed out that it could replace some of the plastic in packaging. The 3 week cellulose sheet's color and texture made it difficult for them to imagine it being directly applied to food, but that was not thought to be an issue with the 7 day cellulose. Because of its translucency many suggested applying it to lamps.

Plant cellulose sourced fibers develop directionally, meaning that the fibers grow from one point to another in parallel. BC on the other hand grows unidirectionally with fibers extending in many different directions, overlapping. This is important for water retention. The unidirectional fiber structure retains more water due to increased surface area. It is also a stronger base structure. The increased surface area binds more oxygen, and makes it harder to break when folded. In short, the unidirectional fiber structure of BC is desirable for its formability. Directional fibers will either be difficult to fold over the grain of the fibers, or be weak when formed along the grain (Park et al, 2014).

In experiencing the material I wanted to manipulate and adjust it to achieve an aesthetic pleasure. Its natural color depends on the nutrient and especially how much or what type of tea is being used. I choose to embrace its natural color, and not to dedicate too many resources on dyeing the material. Naturalness is a contribution to its aesthetics. Vision is essential in experiencing products, and I wanted to enhance this by applying origami techniques to bacterial cellulose. Origami gives the material a 3 dimensional shape and the geometric patterns give us familiarity. It also invites the user to experience the material by touch, adding pattern and structure to the material. I have observed that recognizing the pattern on the cellulose sheet gives an element of surprise and joy. Through my reading I learned to appreciate imperfections, and to give them meaning. I embraced this by framing the material between two plastic sheets highlighting patterns the contaminations gave the finished material.

Technical properties of bacterial cellulose	Description
Moldable	Has a high moldability, can be molded into 2D and 3D shapes
Transparency	The transparency of the material varies, depends on thickness and color
Joining	Can be "glued" together with water, and using other techniques (sewing)
Strength	The fibers grows unidirectional, making the material resistant and strong
Purity	Pure form of cellulose, free from hemicellulose, lignin, pectin
Biodegradability	Biodegradable, recyclable, renewable

Experiential properties	Description
Associations	Paper, plastic and leather
Sensorial	Cold, soft, the thicker one raggedy
Emotional	Surprised, joy, skepticism
Interpretive	Many found it strange in its wet state
Preformative	Bending and stretching, smelling

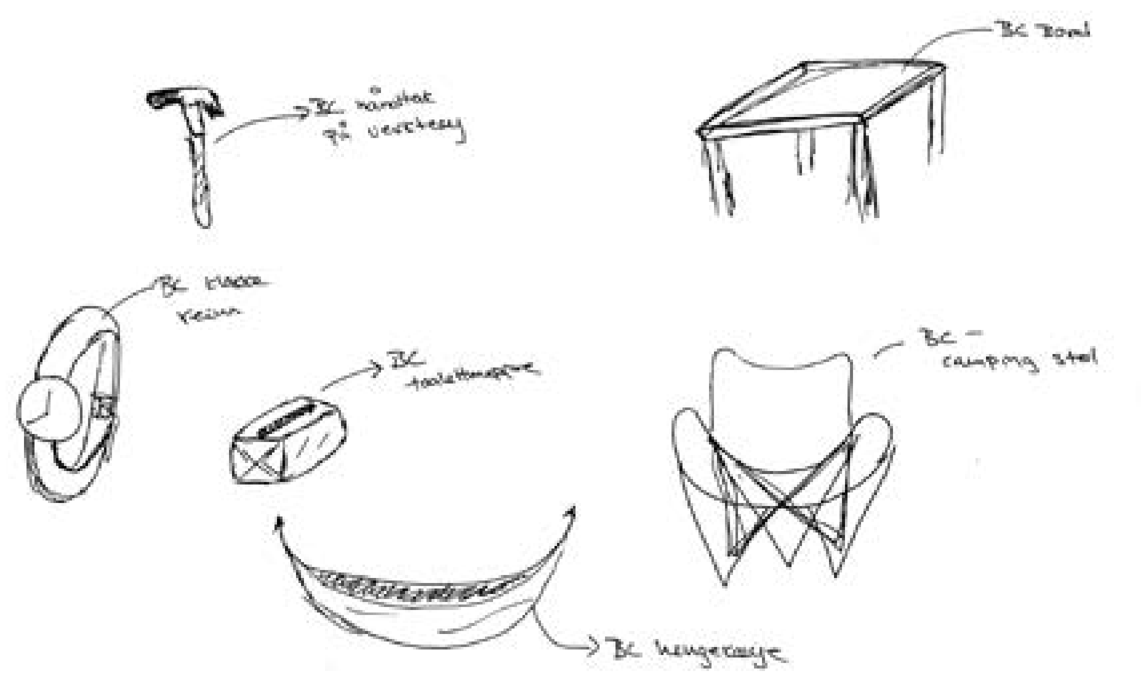
Figure 49: List of most imortant findings

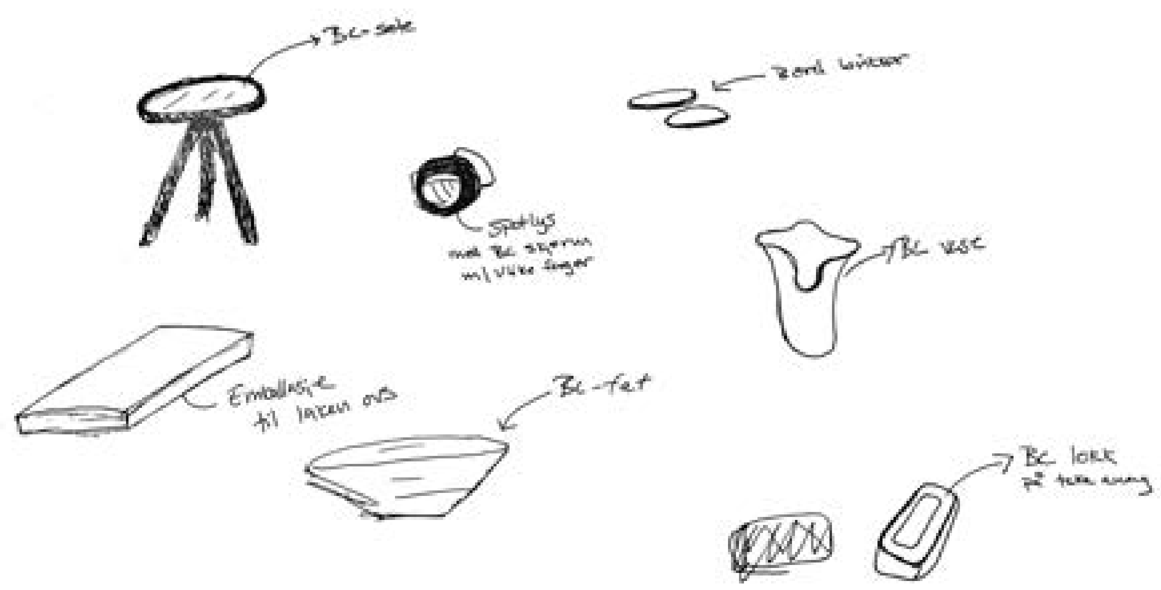
5.1 Material application

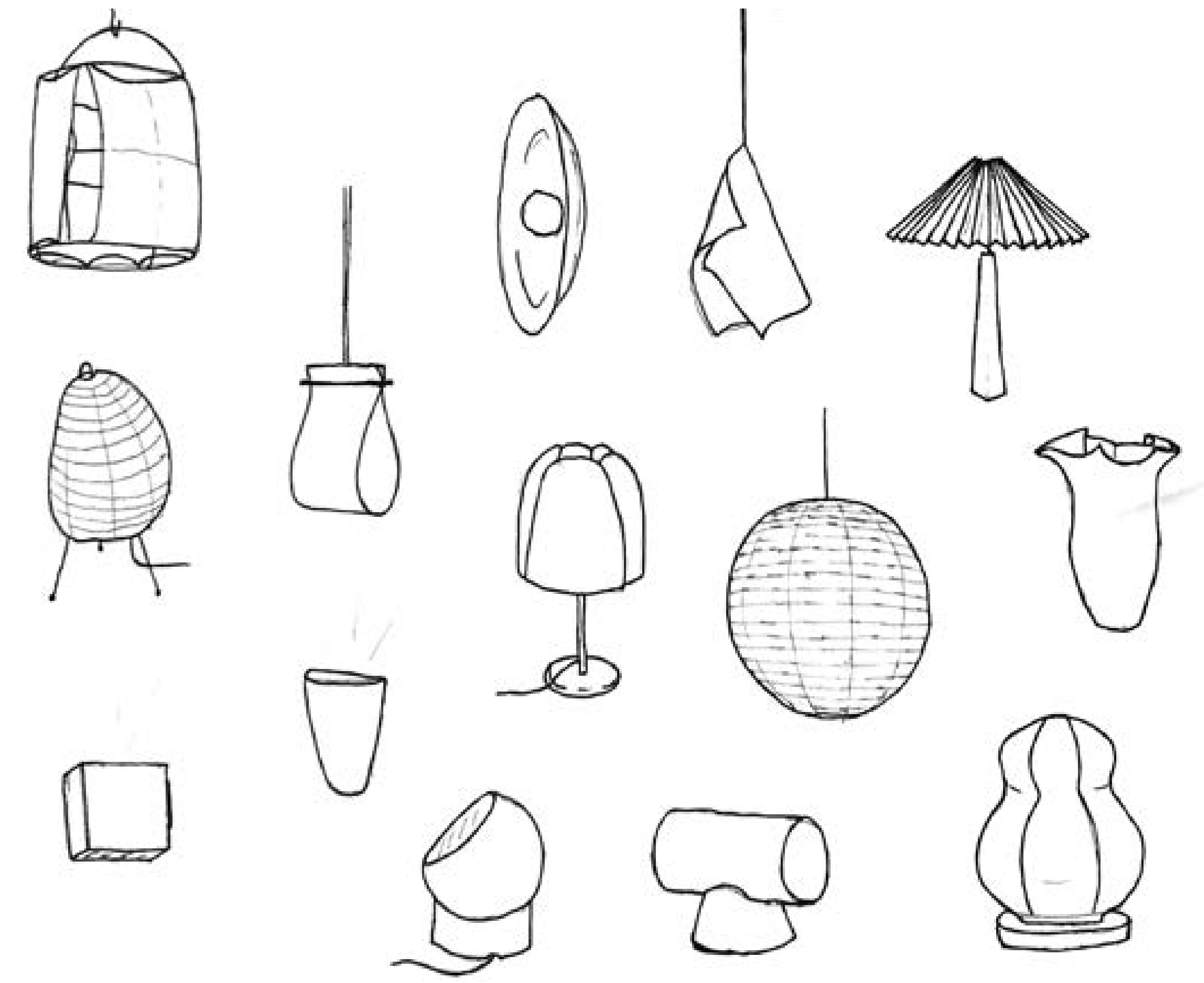
After discovering and reflecting on my findings I started sketching and making models. I listed up my most important findings and started brainstorming, visualizing my ideas doing quick and rough sketches. I didn›t have an infinite amount of material, which gave some limitations for prototyping, resulting in small models. In my application, I am inspired by existing solutions, either applying or replacing material, to show and highlight the materials qualities, also to ease into social acceptance, by applying the material to something familiar.

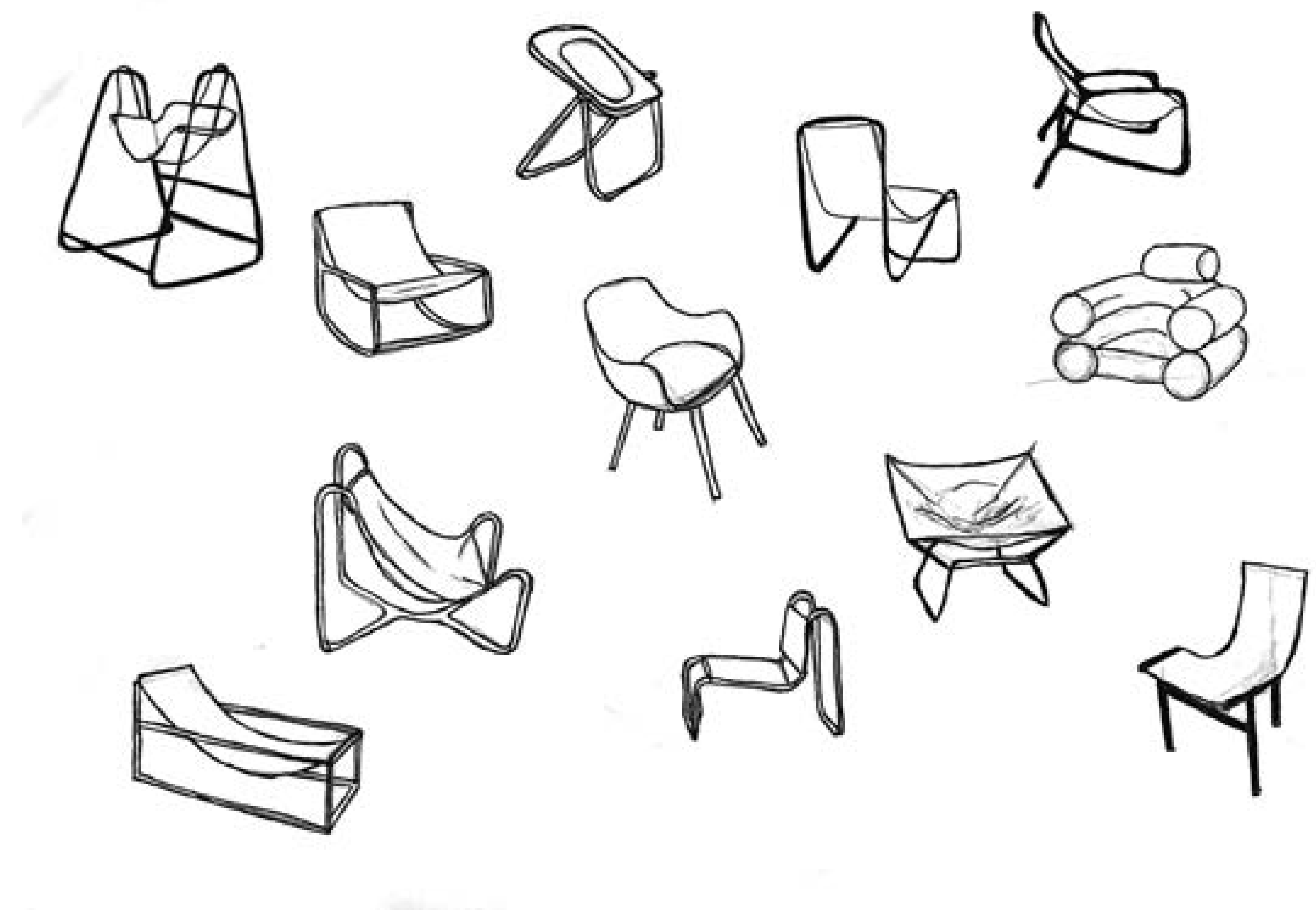
Figure 50: Material applications

Figure 51: Sketches from brainstorming









BChair

These were my first models. BC´s color and surface reminded me and others of leather, and I wanted to visualize this by applying bacterial cellulose to chairs. Knowing that the material is degradable, making it not the best material for long lasting interior design and uncertain if the material is strong enough to hold a human, I still wanted to see what it would look like.

BClight

These are also no functioning models, purly for appearance. Many suggested the material for light design. With its transparency and color it gives a warm and calm light. Here there is only a small part of the design that is bacterial cellulose, it can also be applied more, maybe an entire lamp shape made of bacterial cellulose.

BCpackaging

During my research I found multiple bacterial cellulose applied in packaging design. The transparency and smoothness is associated with plastic and it has similar qualities to paper. I wanted to demonstrate this by replacing the plastic with bacterial cellulose, for example, little windows in packaging for pasta and salt, or the plastic wrapped around a bar of soap. The bar of soap is just wrapt with bacterial cellulose, using water to glue it together. Contact with water bacterial cellulose will absorb it, limiting the usage only for dried goods.

BCbowl

Perhaps not a model, more a result of an experiment. I wanted to scale up, both the growing process and shape. The experiment resulted in a bowl, even though it is not particularly useful, I found it aesthetically pleasing.

6.1 Discussion

Materials are often a way to attract people›s attention. We can be fascinated with materials, appreciate their application, take pleasure or displeasure in their existence. Using the MDD as an inspiration for my design process has been essential for me to understand this and has provided me with relevant and helpful theory and methods. A lot of time was concentrated on understanding and experiencing bacterial cellulose, as it was previously unknown for me. Being unknown, many unexpected events occurred, which at times slowed me down. A primary concern was just producing enough material to design with. At that point two things became more obvious. First, I needed to improve the recipe for BC to increase productivity. Second, I was actually invested in designing the raw material at least as much as I was in designing any specific product that could be made by that material. I was being inspired by a material that I had never seen before, and was developing in front of me in real time. A lot of energy was devoted to that process. I needed to see what kind of interactions this material produced with people before I could easily see a way to a finished design object. I did this perhaps in a more casual way than might have been best in terms of classic designing. But it was an organic process and the material itself doesn't really have the kind of standard qualities that something like paper or wood veneer has. Every piece is unique.

While it isn't fair to say tending to BC is like having a pet, the growth process creates a special bond with the designer. Really it is more caretaking than traditional design in the early phases of production. BC is a living thing, reacting to its environment in real time. Depending on different factors it either thrives or not. In that sense it is no different than the designer.

Growing bacterial cellulose has been a collaborative process, as the designer I am able to control the matter and give back the creator/maker role to the living organisms in the growing process. At the same time the organism is guided and driven by me, as I provided it with a good growing environment

As consumers we are often primarily concerned with a final product far removed from any natural form. A wooden spoon, after all, barely resembles a tree and a plastic shopping bag does not visually invoke the extinct dinosaurs of its petrochemical beginning. By using something living as a foundation for design the design itself is likely to be more alive aesthetically. An object that is formed with BC is bound to communicate its organic starting point as long as the designer embraces the natural look and feel of the material. Think about the difference between a fur coat and a vinyl rain jacket. Both are practical in their own ways, but one achieves practicality through a lot of chemical and physical manipulation and the other archives it through its natural, evolutionary design. So much so that many consumers find fur to be "too much animal" to be comfortable wearing. Not to mention that vinyl can be seen as unnatural and low status. But if a material can be used that communicates natural origins while being completely renewable, recyclable and responsible, the product can be embraced without shame.

Bacterial cellulose is produced from growth and reproduction of living organisms, which happens at an impressive rate compared to more conventional production. Instead of harvesting trees alive, shredding them into pulp and then adding a large amount of water and chemicals to produce paper, BC provides a similar material with overlapping areas of use without anywhere near the energy or environmental footprint. At the scale of my project it was obvious that BC was a good alternative to both paper and plastic. For me alone at school and at home it was easier to produce the material I made through the bacterial process than it would have been to make my own plastic, or even paper. The question remains, however, if this is still true at a larger scale. The question of scale is a good one. If BC is ever going to be useful as anything other than a niche material this question will have to be looked at. Certainly a smaller scale company that wants to devote itself to local supply chains and environmentally friendly packaging might be able to scale up production with a reasonable investment in equipment and nutrients. Here I am referring to a system to control the temperature and of course the sugar, which might seem to be the most problematic. A rising oven plus containers for growing are probably reasonable one-time expenses, but sugar as a nutrient is consumed and it is only available at a market price that changes over time. It also is not locally produced and has an environmental and social cost due to transport and farming techniques. But what if some local alternative is available? Could a fruit presser in Telemark make BC using leftover fruit pulp as a nutrient? This could turn a waste product into an additional source of income. Mass production has not really been something I have focused on. I feel that it is important to look at productions that fit the characterization of the material, for the time being at least.

Bacteria can be described as the dominant organism on this planet, at least in terms of how much there is of it and how many different types there are. As a resource it is plentiful and very renewable. Often people have a negative view of bacteria as a source of disease. They see it as dirty. But we could never survive without the bacteria in our bodies. Probably the first life on this planet was either bacteria or something very much like bacteria. Every other living thing has evolved from it. I have written about the strength of BC due to its unidirectional fiber structure but during this master project I have been reminded of bacteria's strength as an organism. I could start a culture, harvest it, dry it and form it and with little physical effort from me the bacteria started the whole process up again, as long as I provided it with a good environment.

The aesthetics of sustainability has emerged as an important factor when designing with the environment in mind. Does the material and/or the design communicate naturalness? If it comes from nature, can it be returned to nature when its human applications are used up? In other words, will it function reliably and then leave no trace after it stops functioning? I think bacterial cellulose answers yes to all these questions.

7.1 Conclusion

At first look, BC does not present itself as an attractive option for design applications. It smells, it is rather slimy and its shape and texture can be a bit odd and undefined. By using the MDD model to tinker with the living material I was able to define a process that turned this less attractive material into something with properties desirable in a number of design applications. Added benefits are its renewability and sustainability across many fronts. The project has helped me to see how nature and living materials deserve a larger role in the future as building blocks for more organic design processes.

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9.1 Figure list

Appendix

Process pictures

Figure 1: Growing BC coverd in a duvay to isolate the heat from the radiator

Figure 2: Rise oven

Figure 2: Growing B, with cane sugar

Figure 4: Growing B, with refined sugar

Figure 5: Harvest BC, made with cane sugar

Figure 6: Harvest BC, made with cane sugar

Figure 7: Harvest BC, made with refined sugar

Figuer 8: Harvest BC, made with refined sugar

Figure 9: Cutting BC, and joining using basket weave technique

Figure 10: Cutting out circles and joining them for patterns

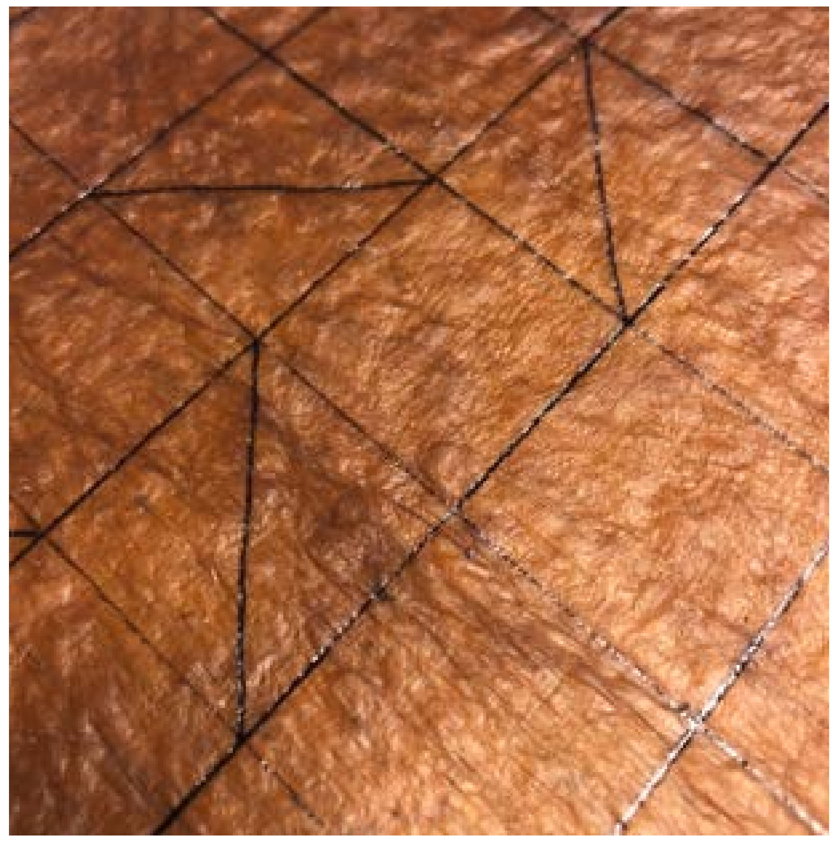

Figure 11: You can directly write on BC, and erase it with water

Figure 12: sewing BC, thicknes makes it harder to sew into that regular fabric

Figure 13: BC grown in layers

Figur 14: Harvesting a big sheet of BC

Figure 15: BC layed over

Figur 16: BC dried over wood form

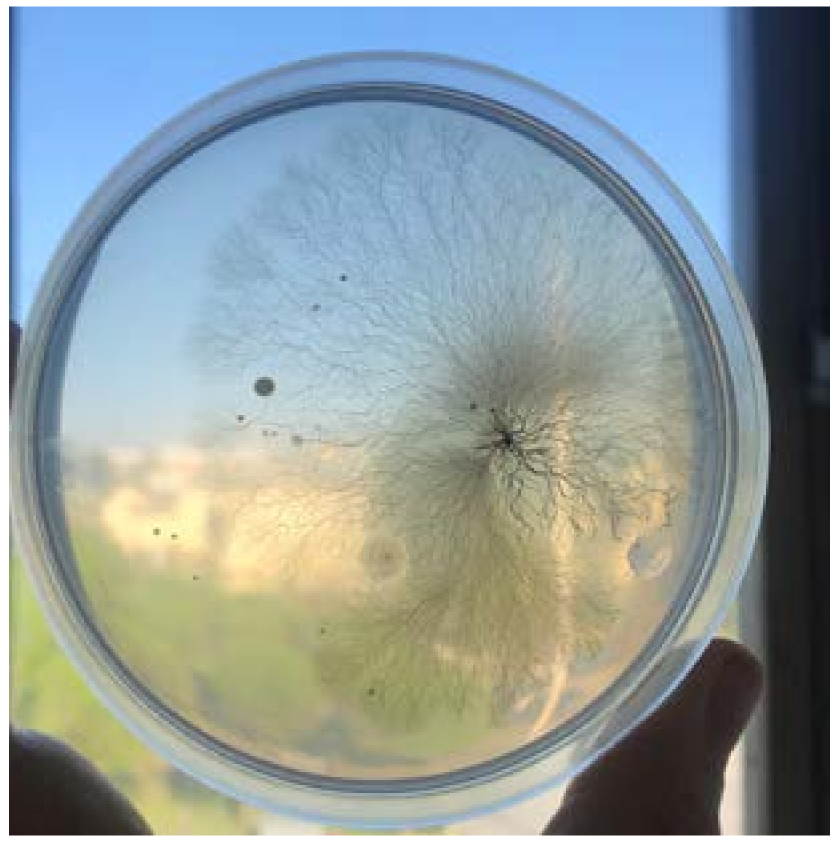

Figure 17: Bacteria from my surrounding, I was facinated by the bacterias growing direction

Figure 18: These are random test I didn´t label, the purpose was to visulize bacteria to see their growing pattern

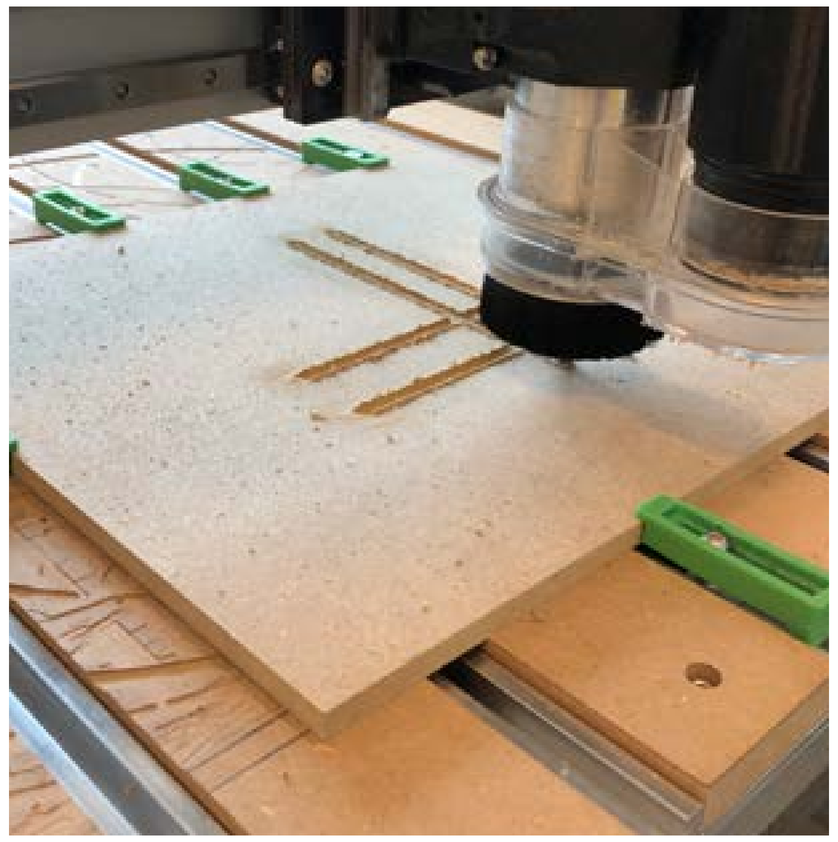

Figure 19: CnC milling MDF

Figure 20: Drying BC on CnC milling MDF, to adapt its pattern

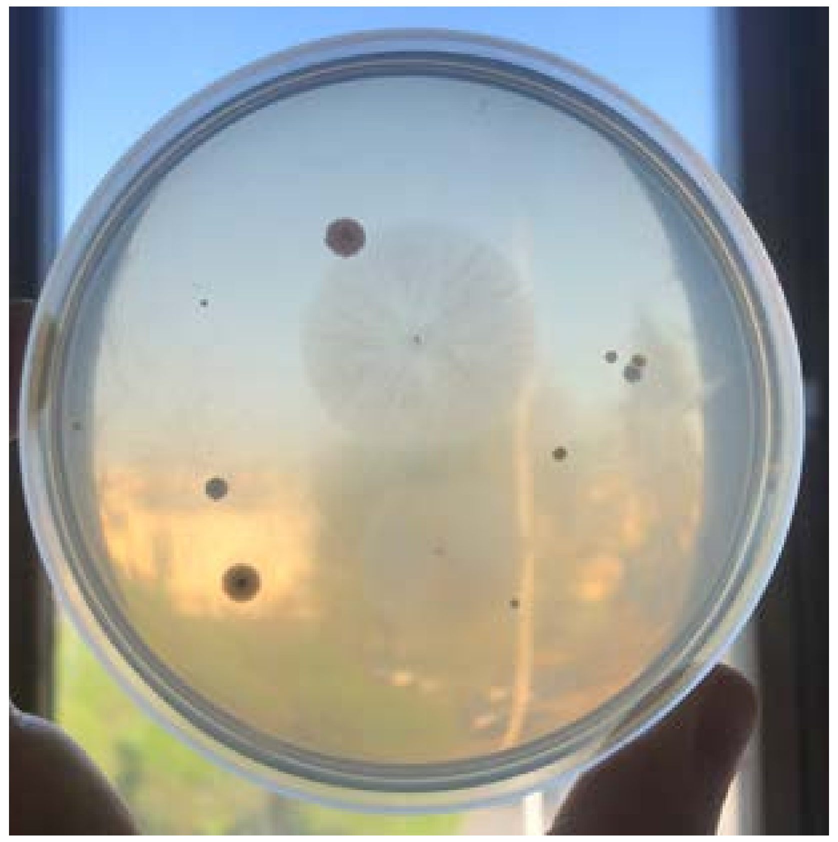

Figure 21: BC diy after harveting, and dried in the oven

Figure 22: BC drying by hangning using klipps and thread

Figure 23: Tanning the fish skin

Figure 24: washing the fish skin after tanning

Figure 25: fish skin in a glass jar containing antibac anf glycerol

Figure 26: nailing the fish skin to MDF for drying

Figure 27: Harvesting contaminated BC

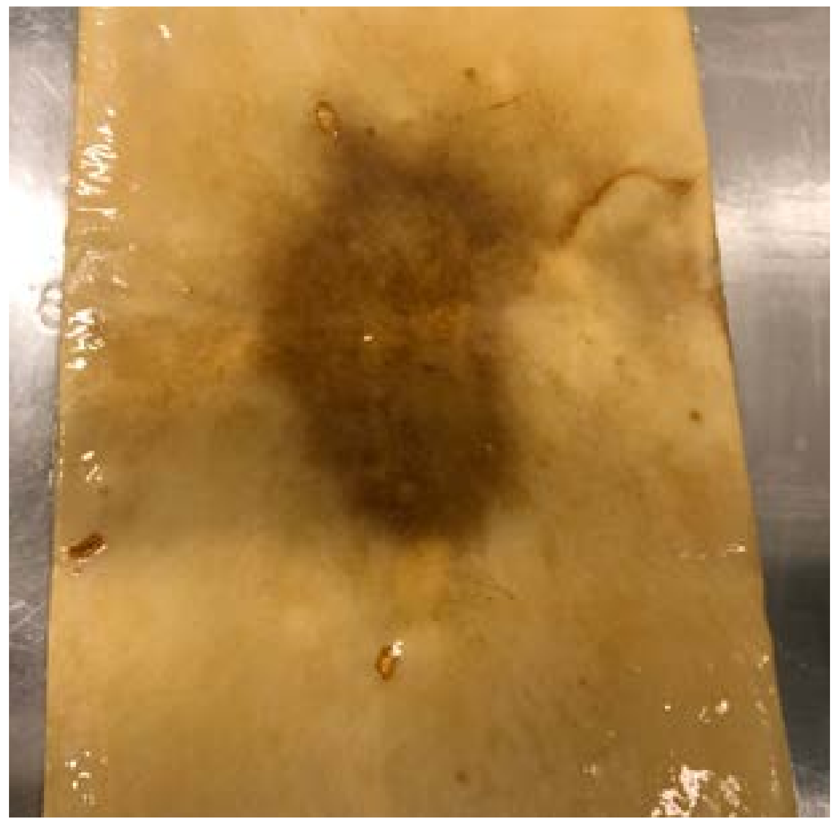

Figure 28: contaminated BC

Figure 29: Growing, contaminated BC

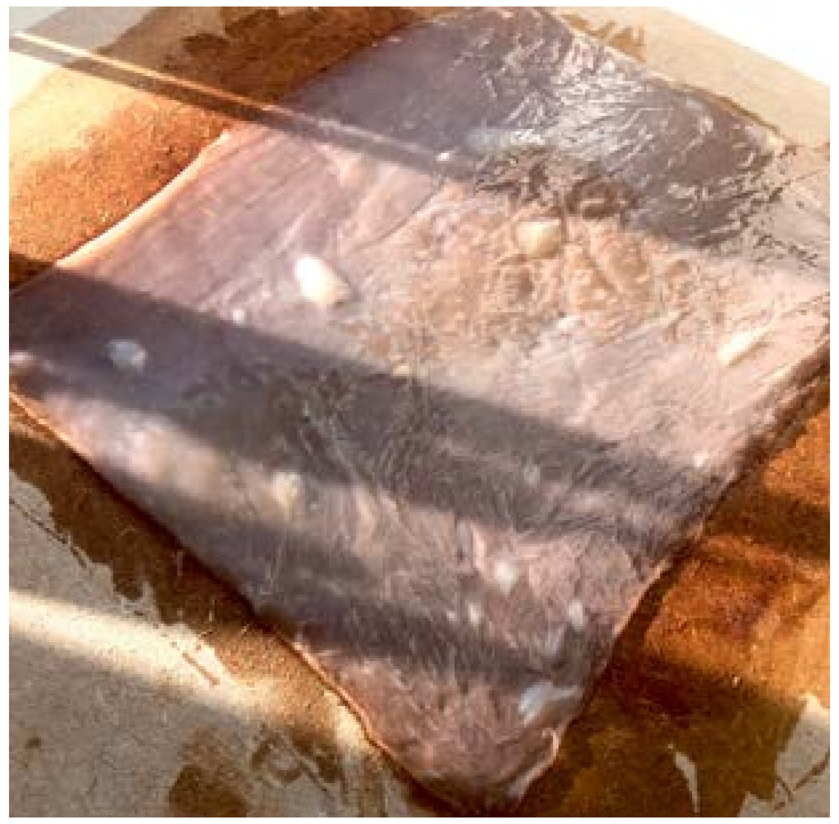

Figure 30: drying BC on MDF