Design Potential of Microbial Cellulose in Growing Architecture

Master Thesis Spring 2019
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Micro
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Microbes, essential living organisms which play crucial roles in self-organizing natural systems, are often thought of in a negative light and underestimated in the built environment. Generally denounced for discoloration, damage and decay of buildings and their surfaces, in fact, have the ability to perform as biological engineers which can drive the design.

The involvement of designers into the process of material growth with the use of living organisms, changes their role from materials selection to materials design, from traditional giving to obtaining a formation through the material. Such a practice - co-performed with Nature having its own biological algorithms - limits the designer’s intervention space and makes the outcome unpredictable, resulting in a better understanding of materials. It also gives depth to conceptualisation of Nature, questioning the meaning of term man-made as opposed to natural.

Integration of synthetic biology, materials science, and architectural design is the emerging practice presenting the potential of biofabrication of tomorrow’s structures. The purpose of this thesis is to explore the area where the fabricated and the grown unite. With an interdisciplinary context in focus, the study investigates and elucidates the potential of microbial cellulose in designing an environmentally responsive architecture with a high level of integration across scales, between structure, shape, and material.

The research part of the thesis consists of a series of experiments and prototypes investigating the growth of biofilm produced by symbiotic culture of bacteria and yeast. Particular emphasis is placed on the exploration of bio-composites of bacterial cellulose and other natural fibers, resulting in the development of a fiber-based system implemented in architectural context. Furthermore, design implementation of research findings through large-scale application aims to embrace the invisible, increase the awareness and boost familiarity with biofabrication in architectural discipline, cultivating it towards an integrated and cross-disciplinary practice. A practice that can offer a new way of experiencing architecture and the materiality of designed spaces.

Keywords: microbial cellulose, biologically driven research, material-informed design, biofabrication, fiber-based structure.
“Unless you try to do something beyond what you have already mastered, you will never grow.”

Ronald E. Osborn
Thank you to all of you who have contributed during the process of formation of this thesis.

I am more than grateful to all of you who were supporting me and offered me help every time when I needed.

Thanks to you, things which first seemed to be impossible, have become possible.

Thank you.
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introduction
Is the 21st century the Age of Biology?

The brief history of science shows that the 19th century was the age of chemistry, the 20th century – the age of physics, and the 21st century will be the age of cybernetics, biology, and ecology (Venter and Cohen, 2004). Biological sciences are the disciplines where spectacular progress has been observed over the past few years.

Rapidly developing interdisciplinary practice in various areas of science indicates the importance of different disciplines integration for the benefit of building new enterprises with the expertise to address a wide spectrum of societal and scientific issues (National Research Council, 2009).

Integration of synthetic biology – an interdisciplinary branch of engineering and biology – and materials science is the practice of particular interest, presenting the potential of programmable materials production by genetically encoding their properties (Glieder et al., 2016).

Biofabrication – the process of materials fabrica-

"Architecture and its details are in some way all part of biology.”
Alvar Aalto
When does biology meet design?

Growing design is an emerging practice operating at the intersection of materials science and engineering, biology and design. Spaces of intervention traditionally belonging to such disciplines like chemistry, materials science and biology have become interdisciplinary places of conversation between designers, artists, and scientists (Camere and Karana, 2018).

What is the role of designers in materials science?

An innovative approach to novel means of expression and unique material possibilities are the reasons why design practitioners have started to be involved in the biofabrication processes. Moreover, the limitations deriving from biofabrication, such as the aspect of unpredictability, can result in the development of new features of design practice (Camere and Karana, 2018). Furthermore, they are often becoming experts in the processes of growing materials (Solanki, 2018).

"The great book, always open and which we should make an effort to read, is that of Nature; the other books are taken from it, and in them there are the mistakes and misinterpretations of men."

Antoni Gaudi
How are forms created in Nature?

Biological systems which occur in Nature are characterized by high levels of integration between material, structure, and shape (Oxman et al., 2013). A wide spectrum of variation in distribution of material as well as physical properties are informed by the conditions which derive from the environment (Oxman et al., 2015). Furthermore, natural systems are often described as environmentally responsive, effective and highly efficient (Oxman et al., 2013).

How are forms generated in Digital design?

In digital design, the process of optimization - the distribution of material and its properties - is often informed by the generation of form. Therefore, in general digitally designed shapes, unlike the biological ones, can be characterized by low levels of integration between shape, material and its structure resulting in lower levels of efficiency (Oxman et al., 2013).

Design paradigm shift: is it designing (with) Nature?

The involvement of designers into the process of material growth with the use of living organisms, shifts their role from traditional form-giving to obtaining a formation through the material (Came-re and Karana, 2018). Such a practice - co-performed with Nature having their own biological algorithms - limits the designer’s intervention space and makes the outcome unpredictable, resulting in a better understanding of materials. It also gives depth to conceptualisation of Nature, questioning the meaning of term man-made as opposed to natural.

Can architectural design be driven by biofabrication?

Despite the increasing interest in biomaterials and biofabrication processes in architectural design, the area of bio-based materials implementation is still underdeveloped (Derme, Mitterberger, and Di Tanna, 2016). Moreover, through the link of formation and materialization, the materials with specific functionalities and properties can be achieved (Came-re and Karana, 2018). Furthermore, such applications can range from small architectural components grown in laboratory space to large structures assembled on site. (Derme, Mitterberger, and Di Tanna, 2016).

What is the future of architecture? Is it a ‘Living Architecture’?

The history of architectural discipline is inseparably connected with the evolution of movements and styles which freely define every crucial period. Given the example from the last 50 years, the ’70s is defined as Brutalism, the ’80s - Post Modernism and the ’90s - Deconstructivism. The one style which could describe the current moment is Experimentalism (Kushner, 2015).

The role of experimentation in architectural discipline has always been of a strong interest. Over the past few years, it has become even more visible, especially taking into consideration the strengthening of a cross-disciplinary aspect of architectural practice.

The aim of investigating the overlapping disciplines of biology and architectural design is not to declare biofabricated architecture a living one or to claim that biofabrication is the future of architecture. The aim is to explore what is nowadays happening at the intersection of these fields and elucidate the design potential emerging from the situation where the fabricated and the grown unite (Gruber, 2011).

As Marc Kushner said - "The future of architecture isn’t about one trend. It’s about a hundred — if not a thousand — different things." (Kushner, 2015). Considering his point, biofabricated architecture which could be defined by high levels of structural integration and environmental responsiveness is one of the possible options for the future of architectural evolution.
How can microbial cellulose be implemented in the architectural context?

thesis question

Aim
The aim of this thesis is to explore and elucidate the potential of microbial cellulose as a biomaterial, in architectural design. With an interdisciplinary context in focus, through series of practical experiments and prototypes, the study investigates the growth of biofilm produced by symbiotic culture of bacteria and yeast. Particular emphasis is placed on the exploration of bio-composites of microbial cellulose and other natural fibers and implementation in architectural context, creating an environmentally responsive architecture with a high level of integration between structure, shape, and material across scales - micro, meso and macro.

Methodology
Methodology applied in the thesis work consists of three phases - Experimentation, Prototyping and Design implementation. All the phases were conducted in parallel during the process, influencing each other. During the Experimentation phase the growth of microbial cellulose was investigated as well as the growth factors and their manipulation. During the Prototyping part the properties of microbial cellulose were tested resulting in indication of its limitations as well as the potential of use in large-scale application. This phase mainly consisted of building physical prototypes and models investigating the possibilities of material. The prototyping phase was crucial for development of the system - framework - to introduce microbial cellulose in architectural context. During the Design implementation phase findings concerning biofabrication of microbial cellulose system were constantly evaluated and translated into the competition proposal for the Flamingo Observation Tower in the Al Wathba Wetland Reserve in Abu Dhabi.

Delimitations
Although this thesis operates in an interdisciplinary context of biology and material science, the research is based on design. This means the experimentation phase is driven by biological processes, not focusing on the aspects which demand a specialistic knowledge and biological background.
“Nature has evolved beautiful design solutions to solve critical problems and we shall look at those as inspiration; however it is not about us-human copying them to design a new breed of manmade technologies but rather us-human understanding the dynamical mechanisms underpinning such problem solving machines of ‘nature’ to hack them, to connect directly to them in order to establish direct relationships between observed natural system and observing manmade ones or vice versa.”

Claudia Pasquero & Marco Poletto | ecológicStudio

(Kretzer and Hovestadt, 2014)
The Silk Pavilion project examines the area where the fabricated and the grown unite. It investigates the bond between biological and digital fabrication on large-scale applications. The main inspiration derives from the silkworm’s ability to create a three-dimensional cocoon with the use of a multi-property silk fiber, around 1km long (Oxman et al., 2013).

The base structure consists of 26 polygonal panels fabricated by a CNC machine with the use of woven silk threads. The main geometry was generated with the use of algorithm assigning one continuous silk fiber across fabricated panels creating the variety of thread density. However, the general various degrees of density were informed by the silkworms acting as a biological printers. Around 6,500 silkworms were distributed on the bottom of the preliminary CNC-fabricated panels creating the secondary non-woven skin optimized according to the environment by the silkworm’s biological algorithms (Oxman et al., 2013).

The main aim of the research parallel to the project was the examination of the silkworm’s ability to optimize the material distribution which could inform the protocols for the generation of fiber-based structures.
Aquahoja
Programmable Water-Based Biocomposites for Digital Design and Fabrication across Scales
Mediated Matter research group at the MIT Media Lab | 2018

“Derived from organic matter, printed by a robot, and shaped by water. It embodies the Material Ecology design approach to material formation and decay by design, as well as the realization of the ancient biblical verse ‘from dust to dust’ – from water to water.”

MIT Media Lab’s Mediated Matter

The Aquahoja project explores the nature’s design space of intervention. All the artifacts were designed digitally and fabricated with the use of robotic arms. Materials used for the fabrication are the most abundant ones on Earth and derive from bones, insect exoskeletons, tree branches and fruits such as apples. Calcium carbonate, pectine, cellulose and chitosan were used to produce 100% biodegradable composites achieving the integrity across scales (Oxman, Duro-Royo, and Mogas-Soldevila, 2014).

The method used during the process is the approach which could be defined as water-based design. It works as a platform integrating physical behavior and hierarchical material distribution as well as digital fabrication, similar to the one that happens in biological systems which occur in nature.

All the structures – hojas – were designed and fabricated so there was no need to assemble. They were created as if they were grown (Oxman, Duro-Royo, and Mogas-Soldevila, 2014).
Xylinum Stool project investigates the potential of bio-based materials in the area of furniture design, questioning the future of the profession. Author explores the potential of biofabrication, giving bacteria - Acetobacter xylinum - the framework to create the cellulose fibre structure around wooden scaffolding.
Project investigates the potential of biofabrication with the use of bacteria - Acetobacter xylinum. Bio-manufacturing of modules directly in molds allows to achieve certain sizes and thicknesses depending on the mold’s shape as well as the duration of growth process.

Growing components and their possible assembly into a more complex structure could be explored and implemented into a larger architectural context.
Microbial Cellulose \textit{(Metabolizing Urban Waste)}

Urban Morphogenesis Lab | MArch Urban Design | Bartlett School of Architecture | UCL

Tutors: Claudia Pasquero, Maj Plemenitas | Students: Lipeng Li, Peng Li, Wenjuan Huang, Xue Xiao

2015|2016

Research project combines series of experiments conducted in laboratory with the physical models prototyping. Project explores the microbial cellulose growth and its properties. The main focus of the investigation is materiality, visual aspects such as color and transparency as well as structural performance of reinforced prototypes made of microbial cellulose and natural fibers. Project uses agricultural waste as a base for microbial bio-manufacturing.

References

- Microbial cellulose samples produced with the use of various fruits and vegetables | Courtesy of ecoLogicStudio
- Three-dimensional prototype made of microbial cellulose | Courtesy of ecoLogicStudio
- Experimentation exploring the growth of microbial cellulose | Courtesy of ecoLogicStudio
Project explores the potential of microbial cellulose in design. As in other case studies, project uses Acetobacter xylinum, the most common type of bacteria, mainly because of its cellulose’s unique morphological properties, high mechanical strength as well as material versatility.

Methodology of the research project is based on series of material experiments investigating properties of microbial cellulose. As in previous reference projects, the author uses various ingredients for material production, resulting in development of material catalogue.

In the next phases of the project, the author conducts series of geometrical analysis, working with volume, tension and strength of the material itself as well as with the use of natural fibers as reinforcement.

Last phase of the project focuses on design implementation on the scale of furniture, fabricated with the use of robotic arm.
microbial cellulose

design potential in growing architecture

Given the benefits of biological protocols of shape-generation, can biomaterials and biofabrication processes help to design environmentally responsive forms with high levels of integration between structure, shape, and material, across micro, meso and macro scales (Oxman et al., 2013)?

Considering the aspect of environmental responsiveness of structures, microbial cellulose as a biomaterial with the potential of use in biofabrication processes could be one of the possible answers for the question above. Comparing the protocols of digital design where the optimization processes happen after the form is generated, forms created with the use of living organisms are subjected to constant change and influenced by the environment in which they are built. The main function of microbial cellulose produced by symbiotic culture of bacteria and yeast is the protection from the sun (Gama, Gatenholm, and Klemm, 2013). Taking this aspect into account, biofilm has potential in the creation of 'live adjustment' of its layers thickness, influencing the spatial qualities of the internal environments of the structures.

Furthermore, since microbial cellulose is a 100% biodegradable material, it has an enormous potential regarding biocomposites of biofilm and other natural fibers as well as water-based composites which are currently under development. Therefore, it has a huge advantage over the composites built of the materials which are not biodegradable, i.e. carbon fiber composites which cannot be disassembled after being united. Moreover, considering current rapid advancement in 3D bioprinting technology, i.e. at Mediated Matter research group at the MIT Media Lab, microbial cellulose could be used as a material for additive manufacturing, especially water-based additive manufacture following similar procedures as in case of cellulose extracted from wood. Adding the aspect of self-healing abilities of biofilm produced by microbes gives the overview of possible advantages of its usage in biofabrication processes where the elements could be fabricated in laboratories, merged and 'self-healed' after assembly simply by overgrowth directly on site.

Among the most important properties of microbial cellulose which make this material unique are:

- biodegradability
- high mechanical and tensile strength
- hygroscopy
- material versatility
- self-healing ability
- tendency to grow on natural fibers
- plasticity
- brittleness
- different levels of translucency
- layers
- bubbles: spaces in between layers
- variety of patterns | dots, veins, wrinkles (Gama, Gatenholm, and Klemm, 2013).

Unique properties of microbial cellulose

Among the most important properties of microbial cellulose which make this material unique are:

- biodegradability
- high mechanical and tensile strength
- hygroscopy
- material versatility
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- plasticity
- brittleness
- different levels of translucency
- layers
- bubbles: spaces in between layers
- variety of patterns | dots, veins, wrinkles (Gama, Gatenholm, and Klemm, 2013).

"The reality we live in is different from the reality in a micro world.
There is a whole lot of world with information we cannot see."

Stuart Firestein
Microbial cellulose: a sophisticated multifunctional material

Microbial cellulose is an emerging material produced by several species of bacteria. The most important strain is highly ubiquitous Acetobacter xylinum. These bacteria are found where the process of plant carbohydrates and sugars fermentation takes place (Gama, Gatenholm, and Klemm, 2013).

Growth factors

In order to produce microbial cellulose the following conditions have to be met:

- symbiotic culture of bacteria and yeast (with one of the main strains responsible for producing fibers - Acetobacter xylinum)
- medium
- source of nutrient
- oxygen

(Gama, Gatenholm, and Klemm, 2013).

Acetobacter xylinum
main strain in symbiotic culture of bacteria and yeast

medium
green tea brew or pure water + apple cider vinegar

nutrition
2 types of sugar: fructose + sucrose

oxygen
04 | architectural design implementation
Aim

The design implementation of the research findings through large-scale application in the form of competition proposal for the Flamingo Observation Tower in the Al Wathba Wetland Reserve in Abu Dhabi aims to increase the awareness and boost familiarity with biofabrication in architectural discipline, offering a new way of experiencing architecture and the materiality of designed spaces.

Site | Al Wathba Wetland Reserve in Abu Dhabi

The site selected for a design implementation is located in the north part of the wetland reserve.

"Established in 1998, Al Wathba Wetland Reserve in Abu Dhabi is a nature reserve consisting of both natural and man-made bodies of water located 40 km southeast of central Abu Dhabi. Covering a total of 5 square km, the wetlands are comprised of wetlands, sabkhas (salt flats), fossilized sands and dunes, and are densely packed with animal and plant life. The most spectacular is the flaminggo population, who flock to the reserve in their thousands to enjoy the warmth during the winter months, with some remaining all year round. In addition to the migratory flamingos that make the reserve their winter home, Al Wathba has attracted numerous species of bird and animals, from the Black winged stilt to the Spiny tailed lizard which is indigenous to the region."

(Abu Dhabi Flamingo Observation Tower Competition Brief, 2018)

Site plan | Al Wathba Wetland Reserve in Abu Dhabi | Courtesy of Bee Breeders Architecture Competition Organisers

Existing observatory place | Courtesy of Bee Breeders Architecture Competition Organisers

(existing images of the site and the tower location)
Concept

Given the benefit of working with living organisms which produce microbial cellulose, the fundamental idea during the research forming design was the aim to achieve the hierarchically structured form with a high level of integrity across micro, meso and macro scales.

The microbes design space of intervention - bio-manufacturing of microbial cellulose fibers - is micro scale while the macro scale, namely design of a tube feeding system providing nutrient for the symbiotic culture of bacteria and yeast growing a biofilm on the surface of fabricated elements - cells - is the designer intervention space.

Where the fabricated and the grown unite

The most interesting and crucial for design implementation part was a meso scale - the area where fabricated by designer and the grown by symbiotic culture of bacteria and yeast unite.
Diagram of bioluminescent bacterium *Photobacterium phosphoreum* implemented in the designed system

Night perspective showing the implementation of bioluminescence

Flamingo observation tower
design composition

- 35% symbiotic culture of bacteria and yeast
- 35% water
- 8% apple cider vinegar
- 22% cut fruits

natural coloration | series of experiments #4

samples of microbial cellulose produced with the use of various fruits
flamingo observation tower
flamingo observation tower

04| architectural design implementation

Isometric view of section and exploded 'feeding' system after fabrication | Initial stage - first few months

northern entrance
level 01

cells with agar* applied on sizal fibers
* cultivation medium with symbiotic culture of bacteria & yeast

southern entrance
level 00

transparent PVC tubes
nutrient transportation

structural core
+ staircase

agar application on sizal fibers
agar with injected symbiotic culture of bacteria and yeast

cell fabrication
sizal fibers weaving with the use of robotic arm

microbial cellulose growth
* biofilm coloration

agar application on sizal fibers
agar with injected symbiotic culture of bacteria and yeast

fabrication of cells and cellulose growth diagram
flamingo observation tower

[42] Northern-east elevation showing the boardwalk integrated with the staircase.

[43] Section showing the structural core and microbial skin consisting of the fabricated cells and tube system. Tower height 11.54 m.
The main aim of this thesis was to explore and elucidate the potential of microbial cellulose in designing an environmentally responsive architecture with high level of integration between structure, shape, and material, across micro, meso and macro scales.

The very extensive research phase consisting of experimentation and prototyping parts and examining the growth of biofilm produced by symbiotic culture of bacteria and yeast led to elucidation of the enormous potential of microbial cellulose as a biomaterial which is precisely described on page 39, in chapter called Research findings.

More importantly, the research phase has helped to understand the importance of exploring the material and its properties through experimentation and prototyping which took over the whole process and became the great design tool during the design formig research. Therefore, the whole thesis work is perceived as experimentation and the design implementation of research findings - the Flamingo Observation Tower - as one of the experiments in itself.

The design composition of the fiber-based ‘feeding’ system designed to provide the growth of microbial cellulose is an analogy to composition of all the conducted experiments where the most important growth factors were symbiotic culture of bacteria and yeast, medium, source of sugar and oxygen.

This project leads to the conclusion that to address the new values elucidated during the exploration of the material, the traditional way of representation is not enough and the new set of methods is needed to be introduced, which would be the great next step in the continuation of this thesis work. The shift of design representation from the use of the traditional naming system to architectural description using the design composition instead, demands the introduction of a new set of drawings types. With an interdisciplinary context in focus, thesis indicates the importance of introduction the new representations which are not borrowed from one of the explored fields but become the result of the cross-disciplinary practice operating at the intersection of architectural design, synthetic biology and materials science.

“\textit{A project ends well when it opens doors for you, when it makes you dream much more.}”

Killian Jornet
“This is an exercise in fictional science, or science fiction, if you like that better. Not for amusement: science fiction in the service of science. Or just science, if you agree that fiction is a part of it, always was, and always will be as long as our brains are only miniscule fragments of the universe, much too small to hold all the facts of the world but not too idle to speculate about them.”

Valentino Braitenberg
This chapter presents the experimentation part of a research investigating the growth of microbial cellulose.

The main aim of conducting the experiments was to explore the conditions for microbial cellulose growth as well as the manipulation of growth factors.

The potential of biofilm growth on scaffolds and natural fibers was explored during the prototyping phase and is described in the next chapter called Prototyping.

Furthermore, the experimentation phase was a crucial part preceding the development of a fiber-based system implemented in architectural context, leading to elucidation of the potential of microbial cellulose in architectural design.

Methodology

Through the whole experimentation process, all the biofilm samples were grown with the use of symbiotic culture of bacteria and yeast (SCoby).

Experimentation phase was started with conducting a few experiments - #1, exploring the primary growth of biofilm using the green tea brew as a liquid cultivation medium.

Further experiments were investigating the manipulation of the following growth factors:

- shape of cultivation medium - experiments #2,
- physical state of medium (change from liquid to solid medium) - experiments #3,
- and nutrients, mainly carbon sources - experiments #4.

Furthermore, during the experimentation part the following elements were explored:

- potential of natural coloration with the use of fruits and vegetables - experiments #4,
- coloration with the use of added colours - experiments #5,
- self-healing abilities of microbial cellulose - experiments #6,
- influence of sunlight on biofilm growth - experiment #7,
- and the potential of 3d extruding - experiment #8.
All the experiments were conducted in different lab spaces according to available options and needed conditions during the research time.

**DIY Micro Lab 01**

The initial experiments investigating the pure cellulose growth according the traditional method of symbiotic culture of bacteria and yeast cultivation were conducted in DIY Micro lab established by the author.

**DIY Micro Lab 02 | Micro Lab 523 at Chalmers School of Architecture**

Most of experiments with manipulation of growth conditions and biofilm properties were carried out in the space of 523 Micro lab at Chalmers School of Architecture.

**Micro Lab 03 | Department of Biology and Biological Engineering**

The experiments demanding more advanced conditions for biofilm growth were conducted in a professional Micro lab at Department of Biology and Biological Engineering at Chalmers.

**DIY Micro Lab 02 | Micro Lab 523 at Chalmers School of Architecture**

Most of experiments with manipulation of growth conditions and biofilm properties were carried...
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The following experiment investigates the growth of microbial cellulose using the green tea brew as a liquid cultivation medium.

**Ingredients**
- 100 g symbiotic culture of bacteria and yeast
- 2000 ml green tea brew
- 100 ml apple cider vinegar
- 200 g white sugar

**Growth conditions**
- deep vessel with cultivation medium
- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

**Result**
Thick, flexible and even sample of biofilm, has grown on the surface of medium and has adjusted to the shape of the vessel in which was located.

- sample thickness before drying: 10 mm
- thickness of a dried sample: <1 mm

After 14 days of fermentation process sample was naturally dried (in room temperature) for 5 days.

**Conclusions**
A biofilm growing on the surface of a medium adjusts to the shape of the vessel in which is located. Sample of biofilm produced during the experiment #1.1 is the example of a flexible, 100% biodegradable bioplastic.
experiment #1.2 | primary biofilm growth

deep vessel | 30 days of fermentation

Primary biofilm growth

The following experiment investigates the growth of microbial cellulose using the green tea brew as a liquid cultivation medium.

Ingredients

- 100 g symbiotic culture of bacteria and yeast
- 2000 ml green tea brew
- 100 ml apple cider vinegar
- 200 g white sugar

Growth conditions

- deep vessel with cultivation medium
- 30 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result

Thick, flexible and even sample of biofilm, has grown on the surface of medium and has adjusted to the shape of the vessel in which it was located.

- sample thickness before drying: 19 mm
- thickness of a dried sample: ~1 mm

After 30 days of fermentation process sample was naturally dried (in room temperature) for 10 days. Comparing to a dried sample from experiment #1.1, sample from experiment #1.2 is more rigid.

Conclusions

The thicker the biofilm grown on the surface of the medium, the more rigid sample is achieved after drying process.
experiment #2.1 | growth medium’s shape manipulation
flat vessel

Growth medium’s shape manipulation

The following experiment investigates the influence of the shape of the vessel in which growth medium is located on the growth of microbial cellulose.

Ingredients

- 50 g symbiotic culture of bacteria and yeast
- 500 ml green tea brew
- 50 ml apple cider vinegar
- 50 g white sugar

Growth conditions

- flat dish with cultivation medium
- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result

Thin, flexible and uneven sample of biofilm, has grown on the surface of medium and has adjusted its shape to the shape of the vessel in which was located.

- wet sample thickness: 6 mm

Conclusions

The cultivation rate of microbial cellulose was influenced by the shape of the vessel (flat dish) in which growth medium is located, resulting in the thinner biofilm grown on the surface, comparing the growth time. The thickness of biofilm varies and depends on the distance of growing biofilm from the initial piece of symbiotic culture of bacteria and yeast added to the cultivation medium.
experiment #2.2 | growth medium’s shape manipulation
flat dish + controlled addition of growth medium

Growth medium’s shape manipulation

The following experiment is based on the result achieved during the experiment #2.1 and investigates the influence of the shape of the vessel with cultivation medium on the growth of microbial cellulose as well as the influence of controlled addition of growth medium.

Ingredients

- 10 ml symbiotic culture of bacteria and yeast
- 100 ml green tea brew
- 10 ml apple cider vinegar
- 10 g white sugar

Growth conditions

- flat dish with cultivation medium - every 2 days ~17 ml of cultivation medium was added (total amount of medium - 120 ml)
- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result

Exceptionally uneven - brain-like sample of biofilm, has grown on the surface of medium.

- sample thickness before drying: 3-10 mm

Conclusions

The cultivation rate of microbial cellulose was influenced by the shape of the vessel (flat dish) in which growth medium is located, resulting in unexpected and exceptionally uneven biofilm grown on the surface. Sample from experiment #2.2 was used in the subsequent experiment #5.1 exploring the potential of uneven biofilm colouration with the use of added colours (page XX).
experiment #3.1 agar | medium shift
solid medium

Manipulation of physical state of medium

The following experiment investigates the growth of microbial cellulose in solid medium - agar plate. The decision to conduct the experiment shifting the physical state of medium from liquid (green tea brew) to solid (agar) was a result of design research phase, where the liquid medium used so far was not appropriate. The experiment examines the design proposal - components which are part of a system developed during the prototyping phase and implemented through large scale application.

Ingredients
- 20 g agar powder
- 1000 ml water
- 4 bags green tea
- 100 g white sugar
- 100 ml symbiotic culture of bacteria and yeast (after concentration 2x5 ml)

Procedural method
1. Distribution of an agar powder in water (100 ml out of 1000 ml).
2. Preparation of the green tea brew (900 ml of water + 4 bags of green tea + 100 g of white sugar).
3. After the green tea brew temperature decreased to 70°C - addition of agar distributed in 100 ml of water.
4. Separation of the symbiotic culture of bacteria and yeast from medium in sample tubes - with the use of centrifuge.
5. Removal of the majority of the medium from sample tubes.
6. Mixing of the concentrated symbiotic culture of bacteria and yeast with the use of Vortex mixer (2x5 ml).
7. After temperature of the green tea brew with agar decreased to 45°C - addition of concentrated symbiotic culture (18 ml).
8. To achieve faster coagulation of agar medium applied on the surface of molds - placement plastic and foam molds in the freezer for 30 minutes.
9. Application of agar on prefrozen molds when the temperature of agar medium reached 48°C (approximate temperature of agar medium coagulation).

Method: observation

Temperature of agar medium coagulation varies depending on different factors like kind of agar powder used during the experiment or temperature of the surrounding. Therefore, the applied medium did not coagulate as fast as it was expected (while reaching the surface of prefrozen molds) resulting in spilling most of the medium around the forms. The conclusion after the first attempt is that the preparation of appropriate method for agar medium application for the future tests is necessary to avoid the repetition from the experiment #3.1.

Growth conditions
- 30 days of fermentation
- temperature ~ 30°C
- access to oxygen

Result
After 30 days of fermentation process the areas of biofilm have appeared growing on the surface of agar. However, the appearance of the microbial cellulose is slightly different - the colour of the biofilm is brown instead of white - comparing to the microbial cellulose grown in the liquid medium.

Conclusions
The change of medium from liquid to solid resulted in the different appearance of microbial cellulose grown on the surface of agar. However, one experiment is not enough to make a conclusion that the change was influenced only by the shift of physical state of the medium. Therefore, further experiments have to be conducted, focusing on the exploration of microbial cellulose growth on agar as a solid cultivation medium.
The following experiment is based on the experiment #3.1 and investigates the growth of microbial cellulose in solid medium - agar - on the natural fibers - cotton gauze. Like the experiment #3.1, the following one also examines the design proposal - the aspect of application of natural fibers in the designed components, resulting in the use of biocomposite of microbial cellulose and other natural fibers.

**Ingredients**
- agar medium from the experiment #3.1
- cotton gauze

**Growth conditions**
- 30 days of fermentation
- temperature ~ 30°C
- access to oxygen

**Manipulation of physical state of medium**

The following experiment is based on the experiment #3.1 and investigates the growth of microbial cellulose in solid medium - agar - on the natural fibers - cotton gauze. Like the experiment #3.1, the following one also examines the design proposal - the aspect of application of natural fibers in the designed components, resulting in the use of biocomposite of microbial cellulose and other natural fibers.

**Procedural method**

Method followed during the experiment #3.2 is the same as the one in experiment #3.1. Additionally, the solid medium - agar with symbiotic culture of bacteria and yeast - was applied on cotton gauze.

**Result**

After 30 days of fermentation process the areas of biofilm have appeared growing on the surface of agar applied on the cotton gauze. However, like in the previous experiment #3.1 with agar as a solid medium, the appearance of the microbial cellulose is slightly different - the colour of the biofilm is brown instead of white - comparing to the microbial cellulose grown in the liquid medium.

**Conclusions**

Like in the experiment #3.1, the change of medium from liquid to solid resulted in the different appearance of microbial cellulose grown on the surface of agar. However, these two experiments are not enough to make a conclusion that the change was influenced only by the shift of physical state of the medium. Therefore, further experiments have to be conducted, focusing on the exploration of microbial cellulose growth on agar as a solid cultivation medium.

**Series #3 Medium shift: general conclusions**

To conclude the series of experiments #3, the exploration of the growth of microbial cellulose in solid medium was an interesting shift indicating the influence of design phase on the research part. The complexity of experiments emphasizes the importance of conducting several further experiments in order to make the conclusions which could become the solid base with scientific background for the further design forming research and exploration of microbial cellulose growth on three-dimensional elements.
During the second phase of experimentation, samples of biofilm were being cultivated with fructose and sucrose as a carbon source. After 7 days 4 kinds of fruits which shown the significant contribution to growth were taken to the second phase - red apple, green apple, pear, mango, kiwi and purple grape.

Additionally, during the second phase some other fruits and vegetables were also used - passion fruit, blueberry, lingonberry, blackberry, carrot, tomato and beetroot.

Phase 1 | Carbon source: fructose

The first phase consists of biofilm samples cultivated with fructose as a carbon source. In this phase the following kinds of fruits were used: red apple, green apple, pear, mango, kiwi, purple grape, green grape and pomegranate.

Phase 2 | Carbon source: fructose + sucrose

During the second phase of experimentation, samples of biofilm were being cultivated with fructose and sucrose as a carbon source. After 7 days 4 kinds of fruits which shown the significant contribution to growth were taken to the second phase - red apple, green apple, pear, mango, kiwi and purple grape.

Additionally, during the second phase some other fruits and vegetables were also used - passion fruit, blueberry, lingonberry, blackberry, carrot, tomato and beetroot.

Conclusions

The main conclusion from the series of experiments #4 is that the cultivation rate of microbial cellulose can be influenced by the manipulation of nutrients in the growth medium, mainly carbon sources - fructose and sucrose.

Furthermore, there is an enormous potential of bioplastic production from industrial waste - fruits and vegetables, with the use of symbiotic culture of bacteria and yeast. Moreover, depending on a kind of used fruits and vegetables, various colours of microbial cellulose can be achieved.

Due to the way of biofilm growth - layer by layer, seeds embedded into the surfaces of some samples show the potential of embedding other elements into the microbial cellulose surface.

What is more, wide variety of surface patterns produced during series of experiments #4 depicts the potential of obtaining the materiality unique for each sample.

Nutrition manipulation: carbon source

This section presents the most numerous series of experiments conducted during the material research. It investigates the growth of biofilm with the manipulation of carbon sources in focus, mainly fructose (C_{6}H_{12}O_{6}) present in fruits and sucrose (C_{12}H_{22}O_{11}) as one of the most common commercial source of sugar.

The aim of conducting this particular series of experiments was to explore the biofilm growth, the possibility of growth conditions manipulation as well as the potential of cultivation of biofilm in various colours depending on the used fruits.
experiment #4.1a red apple | nutrition manipulation

carbon source: fructose

Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of fructose - carbon source deriving from red apple.

Ingredients

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g cut red apple

Growth conditions

- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result

Thick, flexible and uneven sample of biofilm, with a few holes resulting from the pieces of apple floating on the surface during the cultivation time, has grown on the surface of medium.

- sample thickness before drying: 13 mm
- thickness of a dried sample: <1 mm

Conclusions

During the first 7 days of the experiment #4.1a, the significant growth of biofilm was observed, comparing to the other samples. Therefore, red apple was used during the second part of the experiment - #4.1b.
The following experiment investigates the growth of microbial cellulose based on the use of a combination of carbon sources - fructose deriving from red apple and added sucrose.

Ingredients
- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g cut red apple
- 10 g sucrose

Growth conditions
- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result
Thin, uneven sample of biofilm, with a lot of holes resulting from the pieces of an apple floating on the surface during the cultivation time, has grown on the surface of medium.
- sample thickness before drying: 3 mm
- thickness of a dried sample: <1 mm

Conclusions
During the experiment #4.1b, no significant growth of biofilm was observed, comparing to the sample from the first phase - #4.1a.

The cultivation rate of microbial cellulose was influenced by the ratio of carbon source present in the growth medium, resulting in the thinner biofilm grown on the surface.
experiment #4.2a green apple | nutrition manipulation
carbon source: fructose

Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of fructose - carbon source deriving from green apple.

Ingredients

• 50 ml symbiotic culture of bacteria and yeast
• 50 ml water
• 10 ml apple cider vinegar
• 30 g cut green apple

Growth conditions

• 14 days of fermentation
• room temperature ~ 21°C
• access to oxygen

Result

Thick, flexible and uneven sample of biofilm, with a few holes resulting from the pieces of an apple floating on the surface during the cultivation time, has grown on the surface of medium.

- sample thickness before drying: 14 mm
- thickness of a dried sample: <1 mm

Conclusions

Like in the experiment #4.1a with a red apple, during the first 7 days of the experiment #4.2a, the significant growth of biofilm was observed, comparing to the other samples. Therefore, green apple was used during the second part of the experiment - #4.2b.
Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of a combination of carbon sources - fructose deriving from green apple and added sucrose.

Ingredients

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g cut green apple
- 10 g sucrose

Growth conditions

- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result

Thin, uneven sample of biofilm, with a few holes resulting from the pieces of an apple floating on the surface during the cultivation time, has grown on the surface of medium.

- sample thickness before drying: 4 mm
- thickness of a dried sample: <1 mm

Conclusions

During the experiment #4.2b, no significant growth of biofilm was observed, comparing to the sample from the first phase - #4.2a.

Like in the experiment #4.1b with a red apple, the cultivation rate of microbial cellulose was influenced by the ratio of carbon source from green apple present in the growth medium, resulting in the thinner biofilm in the second phase.
Experiment #4.3a: Nutrition manipulation

Carbon source: Fructose

The following experiment investigates the growth of microbial cellulose based on the use of fructose - carbon source deriving from pear.

**Ingredients**
- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g cut pear

**Growth conditions**
- 14 days of fermentation
- Room temperature ~ 21°C
- Access to oxygen

**Result**
Thick, flexible sample of biofilm has grown on the surface of the cultivation medium.
- Sample thickness before drying: 9 mm
- Thickness of a dried sample: <1 mm

**Conclusions**
During the first 7 days of the experiment #4.3a, the significant growth of biofilm was observed, comparing to the other samples. Therefore, pear was used during the second part of the experiment - #4.3b.
experiment #4.3b pear | nutrition manipulation
carbon source: fructose + sucrose

Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of a combination of carbon sources - fructose deriving from pear and added sucrose.

Ingredients

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g cut pear
- 10 g sucrose

Growth conditions

- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result

Thin, flexible and even sample of biofilm has grown on the surface of cultivation medium.
- sample thickness before drying: 3 mm
- thickness of a dried sample: <1 mm

Conclusions

During the experiment #4.3b, no significant growth of biofilm was observed, comparing to the sample from the first phase - #4.3a.

Like in the previous experiments with apples, the cultivation rate of microbial cellulose was influenced by the ratio of carbon source from pear present in the growth medium, resulting in the thinner biofilm in the second phase of experiment - #4.3b.
Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of fructose - carbon source deriving from mango.

Ingredients

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g cut mango

Growth conditions

- 14 days of fermentation
- room temperature: ~21°C
- access to oxygen

Result

Thick, flexible and uneven sample of biofilm with a few holes has grown on the surface of cultivation medium.

- sample thickness before drying: 11 mm
- thickness of a dried sample: <1 mm

Conclusions

During the first 7 days of the experiment #4.4a, the significant growth of biofilm was observed, comparing to the other samples. Therefore, mango was used during the second part of the experiment - #4.4b.
experiment #4.4b mango | nutrition manipulation
carbon source: fructose + sucrose

Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of a combination of carbon sources - fructose deriving from mango and added sucrose.

Ingredients

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g cut mango
- 10 g sucrose

Growth conditions

- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result

Thick, flexible and uneven sample of biofilm has grown on the surface of cultivation medium.

- sample thickness before drying: 10 mm
- thickness of a dried sample: <1 mm

Conclusions

During the experiment #4.4b, a similar growth of biofilm was observed, comparing to the sample from the first phase - #4.4a.

Unlike in the previous experiments with apples and pear, the cultivation rate of microbial cellulose was not influenced significantly by the ratio of carbon source from mango present in the growth medium, resulting in a similar thickness of biofilm in the second phase of experiment - #4.4b.
experiment #4.5a kiwi | nutrition manipulation
carbon source: fructose

Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of fructose - carbon source deriving from kiwi fruit.

Ingredients

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g cut kiwi

Growth conditions

- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result

Thin and uneven sample of biofilm has grown on the surface of cultivation medium.

- sample thickness before drying: 4 mm
- thickness of a dried sample: <1 mm

Conclusions

During the first 7 days of the experiment #4.5a, no significant growth of biofilm was observed, comparing to the previous experiments with apples, pear and mango. However, due to the fact of lower, than in fruits mentioned above, total content of sugar in kiwi, it was also used during the second part of the experiment - #4.5b, mainly to investigate the result after addition of sucrose.
experiment #4.5b kiwi | nutrition manipulation

Carbon source: fructose + sucrose

The following experiment investigates the growth of microbial cellulose based on the use of a combination of carbon sources - fructose deriving from kiwi fruit and added sucrose.

Ingredients

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g cut kiwi
- 10 g sucrose

Growth conditions

- 14 days of fermentation
- Room temperature ~ 21°C
- Access to oxygen

Result

Thick, flexible and even sample of biofilm has grown on the surface of cultivation medium. During the fermentation process, some seeds were also embedded into the surface of a biofilm.

- Sample thickness before drying: 7 mm
- Thickness of a dried sample: <1 mm

Conclusions

Comparing to the sample from the first phase - #4.5a, during the experiment #4.5b the significant growth of biofilm was observed - contrary to the previous experiments with apples and pear. The cultivation rate of microbial cellulose was influenced significantly by the ratio of carbon source from kiwi present in the growth medium, resulting in a thicker biofilm in the second phase of experiment - #4.5b.
Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of fructose - carbon source deriving from a purple grape. What is more, the experiment explores also the potential of natural coloration with the use of pigments which occur naturally in purple grapes.

Ingredients

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g cut purple grape

Growth conditions

- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result

Thick and uneven sample of biofilm, with exceptional pattern and a strong burgundy colour has grown on the surface of cultivation medium.

- sample thickness before drying: 11 mm
- thickness of a dried sample: <1 mm

Conclusions

During the first 7 days of the experiment #4.6a, the significant growth of biofilm was observed. Therefore, purple grape was also used during the second part of the experiment - #4.5b.

Moreover, pigments naturally occurring in purple grapes influenced the colour of the grown biofilm. What is more, the process of drying did not influence the coloration level of a sample.
Experiment #4.6b: Purple Grape Nutrition Manipulation

Carbon Source: Fructose + Sucrose

Ingredients
- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g cut purple grape
- 10 g sucrose

Growth Conditions
- 14 days of fermentation
- Room temperature ~ 21°C
- Access to oxygen

Result
Thick, flexible and uneven sample of biofilm, with exceptional pattern has grown on the surface of cultivation medium.
- Sample thickness before drying: 10 mm
- Thickness of a dried sample: <1 mm

Conclusions
During the experiment #4.6b, a similar growth of biofilm was observed, comparing to the sample from the first phase - #4.6a. Therefore, the cultivation rate of microbial cellulose was not influenced significantly by the ratio of carbon source from purple grape present in the growth medium, resulting in a similar thickness of biofilm in the second phase of experiment - #4.6b. What is more, pigments naturally occurring in purple grapes influenced the colour of the grown biofilm. However, the achieved appearance of a sample is completely different than the sample from the first phase of experiment - #4.6a.
experiments 4.7 green grape | nutrition manipulation

carbon source: fructose

Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of fructose - carbon source deriving from green grape.

Result

Even and very thin sample of biofilm has grown on the surface of cultivation medium.

- sample thickness before drying: 2 mm
- thickness of a dried sample: <1 mm

Ingredients

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g cut green grape

Growth conditions

- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Conclusions

During the first 7 days of the experiment #4.7, no significant growth of biofilm was observed, comparing to the previous experiments, especially to the experiment #4.6a and #4.6b with purple grapes. Therefore, green grape was not used during the second part of the experiment.
**experiment #4.8 pomegranate | nutrition manipulation**

**carbon source: fructose**

**Nutrition manipulation: carbon source**

The following experiment investigates the growth of microbial cellulose based on the use of fructose - carbon source deriving from pomegranate. It explores also the potential of natural coloration with the use of pigments which occur naturally in pomegranate.

**Ingredients**

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g pomegranate seeds

**Growth conditions**

- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

**Result**

Uneven sample of biofilm, thick on the edges and thin in the middle, has grown on the surface of cultivation medium.

- sample thickness before drying: 7 mm - 2 mm
- thickness of a dried sample: <1 mm

**Conclusions**

Pigments naturally occurring in pomegranate influenced the colour of the grown biofilm. What is more, the process of drying did not influence the coloration level of a sample.
experiment #4.9 passion fruit | nutrition manipulation

carbon source: fructose + sucrose

Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of a combination of carbon sources - fructose deriving from passion fruit and added sucrose.

Ingredients

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 18 ml apple cider vinegar
- 30 g passion fruit seeds
- 10 g sucrose

Growth conditions

- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result

Thin, flexible and uneven sample of biofilm, with a few holes has grown on the surface of cultivation medium. During the fermentation process, some seeds were also embedded into the surface of a biofilm.

- sample thickness before drying: 5 mm
- thickness of a dried sample: <1 mm

Conclusions

Comparing to the samples from previous experiments, no significant growth of biofilm was observed. The seeds embedded into the surface show that during the fermentation process, due to the way of biofilm growth - in layers - there is a potential of embedding other elements into the microbial cellulose surface.
experiment #4.10 blueberry | nutrition manipulation
carbon source: fructose + sucrose

Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of a combination of carbon sources - fructose deriving from blueberries and added sucrose. It explores also the potential of natural coloration with the use of pigments which occur naturally in blueberries.

Ingredients

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g blueberries
- 10 g sucrose

Growth conditions

- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result

Exceptionally consistent, thick and flexible sample of biofilm, with a strong purple colour and blueberry seeds embedded on the edges, has grown on the surface of cultivation medium.

- sample thickness before drying: 9 mm
- thickness of a dried sample: <1 mm

Conclusions

The intense pigments naturally occurring in blueberries influenced the colour of the grown biofilm. What is more, the process of drying did not influence the coloration level of a biofilm.

Comparing to all of the biofilm samples produced during the series #4, dried sample from experiment #4.10 is an exceptional example of bioplastic grown with the use of symbiotic culture of bacteria and yeast.
experiment #4.11 lingonberry | nutrition manipulation

carbon source: fructose + sucrose

Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of a combination of carbon sources - fructose deriving from lingonberries and added sucrose. It explores also the potential of natural coloration with the use of pigments which occur naturally in lingonberries.

Ingredients
- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g lingonberry jam
- 10 g sucrose

Growth conditions
- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result
Thin and uneven sample of biofilm, with embedded lingonberry seeds has grown on the surface of cultivation medium.
- sample thickness before drying: 6 mm
- thickness of a dried sample: <1 mm

Conclusions
An intense pigments naturally occurring in lingonberries influenced the colour of the grown biofilm. What is more, the process of drying did not influence the coloration level of a biofilm.
Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of a combination of carbon sources - fructose deriving from blackberries and added sucrose, depending on the ratio of juice added to cultivation medium. It explores also the potential of natural coloration with the use of pigments which occur naturally in lingonberries.

**Ingredients**

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 5/15/45 ml blackberry concentrated juice
- 10 g sucrose

**Growth conditions**

- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

**Result**

Thin and uneven samples of biofilm, with a lot of holes have grown on the surfaces of all of the tree cultivation media (with different ratio of blackberry juice added to cultivation medium).

- sample thickness before drying: 2 mm
- thickness of a dried sample: <1 mm

**Conclusions**

An intense pigments naturally occurring in blackberries influenced the colour of the grown bio-
experiment #4.13 carrot | nutrition manipulation

carbon source: fructose + sucrose

Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of a combination of carbon sources - fructose deriving from carrot and added sucrose. It explores also the potential of natural coloration with the use of an orange pigment which occurs naturally in carrot.

Growth conditions

- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result

Thin and uneven sample of biofilm, has grown on the surfaces of cultivation medium.

- sample thickness before drying: 4 mm – 2 mm
- thickness of a dried sample: <1 mm

Conclusions

An intense pigments naturally occuring in carrot did not influence the colour of the grown biofilm.

Ingredients

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g grated carrot
- 10 g sucrose

Ingredients for #4.13 carrot sample

Top view of #4.13 carrot sample

Front view of #4.13 carrot sample of microbial biofilm grown for 14 days

Close-up of #4.13 carrot sample of microbial biofilm grown for 14 days

Drying #4.13 carrot sample of microbial biofilm grown for 14 days
Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of a combination of carbon sources - fructose deriving from tomato and added sucrose. It explores also the potential of natural coloration with the use of pigments which occur naturally in tomatoes.

Ingredients

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g crushed tomato
- 10 g sucrose

Growth conditions

- 14 days of fermentation
- room temperature ~ 21ºC
- access to oxygen

Result

Thick and even sample of biofilm, has grown on the surfaces of cultivation medium.

- sample thickness before drying: 7 mm
- thickness of a dried sample: <1 mm

Conclusions

Pigments naturally occurring in tomatoes did not influence the colour of the grown biofilm.
experiment #4.15 beetroot | nutrition manipulation

carbon source: fructose + sucrose

Nutrition manipulation: carbon source

The following experiment investigates the growth of microbial cellulose based on the use of a combination of carbon sources - fructose deriving from beetroot and added sucrose. It explores also the potential of natural coloration with the use of an intense burgundy pigments which occur naturally in beetroots.

Ingredients

- 50 ml symbiotic culture of bacteria and yeast
- 50 ml water
- 10 ml apple cider vinegar
- 30 g grated beetroot
- 10 g sucrose

Growth conditions

- 14 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result

Thin and uneven sample of biofilm with a strong burgundy colour has grown on the surfaces of cultivation medium.
- sample thickness before drying: 4 mm
- thickness of a dried sample: <1 mm

Conclusions

An intense pigments naturally occurring in beetroots influenced the colour of the grown biofilm.
The following experiment investigates the potential of microbial cellulose coloration with the use of added pigments. The response of the biofilm on the added colours is also examined. During the experiment #5.1 sample from experiment #2.2 was used.

**Ingredients**
- biofilm sample from experiment #2.2
- few drops of a blue dye

**Result**
The blue dye distributed on the surface resulted in the green tint of the sample. Moreover, colour was unevenly absorbed by the biofilm - thinner parts absorbed more colour while the thick ones remained less coloured. After the drying process an uneven distribution of dye is still visible.

**Conclusions**
The experiment shows that there is an enormous potential of biofilm coloration with the use of added colours which are absorbed unevenly by different part of microbial cellulose resulting in creation of various patterns, unique for each sample.
experiment #5.2 | coloration

blue dye

Coloration

The following experiment investigates the potential of microbial cellulose coloration with the use of added pigments. The response of the biofilm on the added colours is also examined.

During the experiment #5.2 sample from series of experiments #1 was used.

Ingredients

- biofilm sample from series of experiments #1
- few drops of a blue dye

Result

As in the experiment #5.1 color distributed on the surface was unevenly absorbed by the biofilm. Thinner parts absorbed more colour while the thick ones remained less coloured. Unlike in experiment #5.1, blue dye applied on biofilm sample resulted in blue tint not green. However, due to oxidation process sample eventually turned green.

Conclusions

The experiment shows that there is an enormous potential of biofilm coloration with the use of added colours which are absorbed unevenly by different part of microbial cellulose resulting in creation of various patterns, unique for each sample.
experiment #5.3 | coloration
blue dye

Coloration

The following experiment investigates the potential of microbial cellulose coloration with the use of added pigments. The response of the biofilm on the added colours is also examined. During the experiment #5.3 sample from series of experiments #1 was used.

Ingredients

• biofilm sample from series of experiments #1
• few drops of a blue dye

Result

Unlike in the experiment #5.1 and #5.2, the blue dye distributed on the surface is evenly absorbed by the biofilm. What is more, after drying process, sample didn’t change the colour and remained blue.

Conclusions

The experiment shows that there is an enormous potential of biofilm coloration with the use of added colours which are absorbed by microbial cellulose resulting in creation of various patterns, unique for each sample.
Experiment #5.4 | Coloration

Black Dye

Coloration

The following experiment investigates the potential of microbial cellulose coloration with the use of added pigments. The response of the biofilm on the added colours is also examined. During the experiment #5.4 sample from the series of experiments #1 was used.

Ingredients

- Biofilm sample from experiments #1
- Few drops of a black dye

Result

The black dye distributed on the surface was unevenly absorbed by the biofilm - thinner parts absorbed more colour while the thick ones remained less coloured. After the drying process an uneven distribution of dye is still visible.

Conclusions

As in the previous experiments from series #5, the experiment #5.4 shows an enormous potential of biofilm coloration with the use of added colours which are absorbed unevenly by different parts of microbial cellulose resulting in creation of various patterns, unique for each sample.
The following experiment investigates the potential of microbial cellulose coloration with the use of added pigments. The response of the biofilm on the added colours is also examined. During the experiment #5.5 sample from the series of experiments #1 was used.

**Ingredients**
- biofilm sample from experiments #1
- few drops of a black dye

**Result**
The black dye distributed on the surface was unevenly absorbed by the biofilm - thinner parts absorbed more colour while the thick ones remained less coloured. After the drying process an uneven distribution of dye is visible.

**Conclusions**
The experiment shows that there is an enormous potential of biofilm coloration with the use of added colours which are absorbed unevenly by different part of microbial cellulose resulting in creation of various patterns, unique for each sample.
The following experiment investigates the potential of microbial cellulose coloration with the use of added pigments. The response of the biofilm on the added colours is also examined. During the experiment #5.4 sample from series of experiments #1 was used.

**Ingredients**

- biofilm sample from series of experiments #1
- few drops of a red dye

**Result**

The red dye distributed on the surface was unevenly absorbed by the biofilm - thinner parts absorbed more colour while the thick ones remained less coloured. After the drying process an uneven distribution of dye is still visible.

**Conclusions**

As in the previous experiments from series #5, the experiment #5.6 shows an enormous potential of biofilm coloration with the use of added colours which are absorbed unevenly by different parts of microbial cellulose resulting in creation of various patterns, unique for each sample.
Self-healing

The following experiment investigates the self-healing abilities of microbial cellulose.

During the experiment #6.1 sample from series of experiments #1 was used. Moreover, the examined sample was placed in the liquid medium used also during the experiments #1.

Growth conditions

- 30 days of fermentation
- room temperature ~ 21°C
- access to oxygen

Result

After 30 days, previously cut pieces of biofilm grown together resulting in one piece of microbial cellulose. After the drying process, the cutting marks are still visible.

Conclusions

The following experiment shows the potential of microbial cellulose in fabrication of homogeneous elements or structures. It shows the potential of achieving material integrity of elements connected (grown) together without additional heterogeneous materials.
Self-healing

The following experiment investigates the self-healing abilities of microbial cellulose.

During the experiment #6.2 sample were placed in the cultivation medium used during the experiments #1. Moreover, used sample derive from coloration experiments #5.5 and #5.6. Therefore the experiment investigates also the influence of pigments used during the coloration process on the growth of biofilm.

Growth conditions

• 14 days of fermentation
• room temperature ~ 21°C
• access to oxygen

Result

After 14 days, previously colored pieces of biofilm grown together resulting in one colorful piece of microbial cellulose.

Conclusions

Like the previous experiment #6.1, the following one shows the potential of microbial cellulose in fabrication of homogeneous elements or structures. It shows the potential of achieving material integrity of elements grown together without additional heterogeneous materials.
experiment #7.1 | sunlight access

Sunlight access
The following experiment investigates the influence of sunlight on the cultivation rate of microbial cellulose.

Procedural method
During the experiment, two samples of microbial cellulose were examined to compare the result. The first sample was cultivated with the access to sunlight while the second was cultivated without the access to sunlight.

Growth conditions
- 30 days of fermentation
- Room temperature ~21°C
- Access to oxygen

Result
After 30 days of fermentation process, both samples were compared. Sample #1 grew thicker than sample #2, which was growing without the access to sunlight.

Conclusions
The experiment shows that sunlight has the influence on the cultivation rate of microbial cellulose. It shows the potential of microbial cellulose as a material which can contribute to creation of environmentally responsive structures, where the thickness of the biofilm growing on the structure depends on its location according to the sun.
The following experiment investigates the potential of microbial cellulose in 3D bio-printing.

**Procedural method**

Piece of microbial cellulose was blended and extruded with the use of syringe.

**Result**

Microbial cellulose is characterised by high water absorption - hygroscopy. Therefore the result was an uneven extrusion of biofilm and water without keeping any particular form.

**Conclusions**

The extrusion of 100% blended microbial cellulose did not meet the expectations. However, there is a possibility of addition of other ingredients which could improve the properties of microbial cellulose extrusion. To examine that the future experiments have to be conducted.
“Well, there is nothing to do but work with what we have and make the best of it. Which is exactly how it's been done in science for hundreds of years - make an approximation; work up an imperfect model; look for someplace where progress can be made; accept, measure, and include the uncertainty; and be patient for the idea or finding that will emerge from all this tinkering and questioning. Here we go. Expect failure.”

Stuart Firestein
This chapter presents the prototyping phase of a research investigating the growth of microbial cellulose. It was, along with experimentation phase, the most important part of design research process. The main aim of this part was to examine the potential of microbial cellulose growth on scaffolds and natural fibers.

Methodology

Methodology applied in the prototyping phase of the project derives from the microbiologist and writer Stuart Firestein’s quotation opening this chapter.

Namely, the prototyping phase was about:
1. Making an approximation of what was going to be built and more importantly why;
2. Working up an imperfect prototype;
3. Looking for someplace / some part of the prototype where design progress could be made.

What is more, during the prototyping phase the high level of uncertainty was not only included but also accepted as a source of design knowledge - ideas and findings which were about to emerge from design thinking, asking good questions and looking for the better answers.

Process

During the process the material and design findings were evaluated and tested for the potential of microbial cellulose growth on natural fibers and scaffolds - series of prototypes #1 and #2.

Further prototypes were investigating the potential of biofilm in formation of three-dimensional elements - prototypes #3. What is more, series of prototypes #4 was exploring translucency of microbial cellulose - an important biofilm property chosen during the experimentation phase as the one worth further exploration.

During the series #5, microbial cellulose was substituted with natural liquid latex for the purpose of increasing the degree of prototyping freedom and abilities, especially taking into account time - the crucial aspect in fabrication any material cultivated with the use of living organisms.

What is more, prototyping series #5 led to conducting the experiments #3 (page XX) examining the influence of changing the physical state of cultivation medium - from liquid to solid - on the growth of microbial cellulose.

Result

Final result of the prototyping phase is the development of a tube feeding system providing nutrient for the symbiotic culture of bacteria and yeast growing a biofilm on the surface of the tower, precisely described in the chapter Architectural Design Implementation.

<table>
<thead>
<tr>
<th>list of prototypes</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
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<tr>
<td>#2</td>
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<tr>
<td>#3</td>
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<tr>
<td>#4</td>
</tr>
<tr>
<td>#5</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>prototype number</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1.1</td>
<td>biofilm on a fiber surface</td>
</tr>
<tr>
<td>#1.2</td>
<td>3D woven fibers</td>
</tr>
<tr>
<td>#1.3</td>
<td>various fibers</td>
</tr>
<tr>
<td>#1.4</td>
<td>cotton gauze</td>
</tr>
<tr>
<td>#2.1</td>
<td>growth on wooden scaffolding</td>
</tr>
<tr>
<td>#3.1</td>
<td>biofilm + wooden molds</td>
</tr>
<tr>
<td>#3.2</td>
<td>biofilm + wooden molds + cotton gauze</td>
</tr>
<tr>
<td>#4.1</td>
<td>translucency</td>
</tr>
<tr>
<td>#4.2</td>
<td>translucency</td>
</tr>
<tr>
<td>#4.3</td>
<td>translucency</td>
</tr>
<tr>
<td>#5.1</td>
<td>latex + plastic</td>
</tr>
<tr>
<td>#5.2</td>
<td>latex + plastic</td>
</tr>
<tr>
<td>#5.3</td>
<td>latex + plastic + fibers</td>
</tr>
</tbody>
</table>
Prototype #1.1 | biofilm on a fiber surface
composites of bacterial cellulose + natural fibers

**Biocomposites of microbial cellulose**

The following prototype investigates the tendency of microbial cellulose to grow on other natural fibers.

**Result**

After 14 days of fermentation process, a thin microbial cellulose film has grown on the surface of natural fibers introduced into a cultivation medium.

**Conclusions**

Prototype shows the potential of formation biocomposites of microbial cellulose and other natural fibers which are 100% biodegradable. Therefore, microbial cellulose has a huge advantage over the composites built of the materials which are not biodegradable, i.e. carbon fiber composites which cannot be disassembled after being united.
prototype #1.2 | 3D woven fibers
composites of bacterial cellulose + natural fibers

Biocomposites of microbial cellulose

The following prototype investigates the tendency of microbial cellulose to grow on other natural fibers. The prototype #1.2 was made with the use of cotton thread from prototype #1.1.

Result

After 14 days of constant application of cultivation medium with introduced the symbiotic culture of bacteria and yeast on the 3D woven fibers, no significant growth of microbial cellulose was observed. However, the application of cultivation medium resulted in the improvement of fibers stiffness.

Conclusions

Prototype #1.2 shows that to achieve the growth of microbial cellulose, the fibers need to be introduced into the cultivation medium with symbiotic culture of bacteria and yeast. Furthermore, it is not enough to apply the medium on the fibers and let it be exposed to the drying process. To explore the potential of microbial cellulose growth on natural fibers further experiments examining the distance of fibers have to be conducted.
Biocomposites of microbial cellulose

The following prototype investigates the tendency of microbial cellulose to grow on other natural fibers.

Result

After 14 days of fermentation process, a thin microbial cellulose film has grown on the surface of various natural fibers introduced into a cultivation medium.

Conclusions

Like the prototype #1.1, prototype #1.3 also shows the potential of formation the biocomposites of microbial cellulose and other natural fibers which are 100% biodegradable. Therefore, microbial cellulose has a huge advantage over the composites built of the materials which are not biodegradable, i.e. carbon fiber composites which cannot be disassembled after being united.
prototype #1.4 | cotton gauze
composites of bacterial cellulose + natural fibers

Biocomposites of microbial cellulose

The following prototype investigates the tendency of microbial cellulose to grow on other natural fibers.

Result

After 14 days of fermentation process, a thin microbial cellulose film has grown on the surface of cotton gauze introduced into a cultivation medium.

Conclusions

Like the previous prototypes from the series #1, prototype #1.4 shows the potential of formation the bio-composites of microbial cellulose and other natural fibers which are 100% biodegradable. Therefore, microbial cellulose has a huge advantage over the composites built of the materials which are not biodegradable, i.e., carbon fiber composites which cannot be disassembled after being united.
Biocomposites of microbial cellulose

The following prototype investigates the potential of microbial cellulose in growing on wooden scaffolding.

Result

Thin biofilm has grown on the surface of wooden cube not only in the place where the wooden cube was touching the surface of the medium but also above as a result of medium soaked in the wood.

Conclusions

Prototype shows the potential of using wooden scaffoldings as molds to biofabricate 3D elements directly in shape of the mold.
Biocomposites of microbial cellulose

The following prototype investigates the potential of microbial cellulose in formation of three-dimensional elements.

Procedural method

Wet microbial cellulose was applied on the wooden molds resulting in formation of 3D elements. After that all the elements were oven-dried in the temperature of 70°C.

Result

The formation of elements with the use of microbial cellulose resulted in creation of stiff and thick components.

Conclusions

The prototype shows the potential of formation 3D elements which could be assembled into larger structures.

Biocomposites of microbial cellulose

The following prototype investigates the potential of microbial cellulose in formation of three-dimensional elements with the use of other natural fibers.

Procedural method

Unlike in the prototype #3.1, wet microbial cellulose was applied first on the cotton gauze and subsequently on the wooden molds resulting in formation of 3D elements. After that all the elements were oven-dried in the temperature of 70°C.

Result

The formation of elements with the use of microbial cellulose resulted in creation of stiff and thick components. Comparing to the prototype #3.1, the use of cotton gauze resulted in creation of more stiff elements.

Conclusions

The prototype shows the potential of formation three-dimensional elements with the use of other natural fibers, which could be assembled into larger structures.
The aim of the prototype was to explore translucency of microbial cellulose - an important biofilm property chosen during the experimentation phase as the one worth further exploration.

Prototype shows the very unique materiality of microbial cellulose together with the natural fibers. It depicts the hierarchy of fibre structure as well as the transition of levels of translucency achieved within one continuous surface.
The aim of the prototype was to explore translucency of microbial cellulose - an important biofilm property chosen during the experimentation phase as the one worth further exploration.

Prototype shows the very unique materiality of microbial cellulose together with the natural fibers. In some parts the thicker layer of biofilm creates less translucent skin with pockets of air inbetween, while other parts are almost transparent.
Translucency

The aim of the prototype was to explore translucency of microbial cellulose - an important biofilm property chosen during the experimentation phase as the one worth further exploration.

Conclusions

Prototype shows the very unique materiality of microbial cellulose together with the natural fibers. Some parts of the prototype are more translucent than the other, revealing the fibers placed in between the biofilm layers.
**prototype #5.1 | latex: material substitute**

**latex + plastic | elements: cells**

The aim of the prototype was to explore the possibilities of using a material substitute in development of a fiber-based system, increasing the degree of prototyping freedom, taking into account time - the crucial aspect in fabrication any material cultivated with the use of living organisms.

Liquid latex was chosen as an appropriate material which materiality, after drying process, reminds of dry biofilm explored in the project.

Building the prototype influenced the change of designed system - from flat surface designed to be overgrown by microbial cellulose towards three-dimensional skin built of cells - the smallest elements of the system.
The aim of the prototype was the continuation of the development of system applied through a large-scale application.

Prototype #5.2 led directly to conducting the experiments #3 examining the influence of changing the physical state of cultivation medium - from liquid to solid - on the growth of microbial cellulose. Moreover, it influenced significantly the development of a tube system.
Material substitute

The aim of the prototype was finalizing the design of a fiber-based system consisting of biocomposites of microbial cellulose and other natural fibers.

Conclusions

Prototype #5.3 led directly to finalization of the system of woven elements (cells) with agar layer applied on the top.
The reality we live is a whole. Each time, it is like life starting all over again.

Renzo Piano
student background

Education

• MSc in Architecture and Urban Design | 2017 - 2019
  Chalmers University of Technology | Gothenburg, Sweden
• Scholarship | Erasmus+ Programme | 2015 - 2016
  Chalmers University of Technology | Gothenburg, Sweden
• BSc in Architecture and Urban Design | 2011 - 2015
  Wroclaw University of Technology | Wroclaw, Poland

Professional practice

• CGI Artist | freelance | 2015 - current
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• JSK Architects | Wroclaw, Poland | 2016 - 2017
• Atelier Starzak Strebicki | Poznan, Poland | 2014
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"The future belongs to those who believe in the beauty of their dreams."

Eleanor Roosevelt
b bibliography

Literature


Talks


Reference projects

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