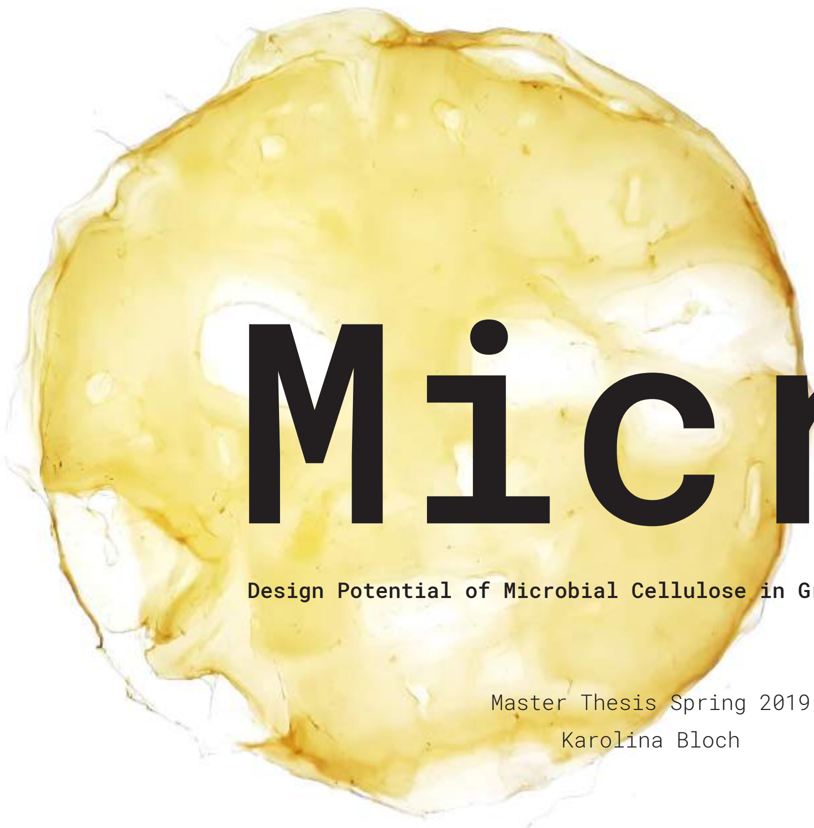
Micro

Design Potential of Microbial Cellulose in Growing Architecture

Master Thesis Spring 2019

Karolina Bloch

Chalmers School of Architecture



Micro

Design Potential of Microbial Cellulose in Growing Architecture

Master Thesis Spring 2019

Karolina Bloch

Supervisors: Kengo Skorick, Jonas Runberger
Examiner: Jonas Lundberg

Chalmers School of Architecture
Department of Architecture and Civil Engineering
Göteborg, Sweden

CHALMERS
UNIVERSITY OF TECHNOLOGY

abstract

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 ***formgiving*** 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 biocomposites 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.

contents

01| introduction

"Architecture and its details are in some way all part of biology."

Alvar Aalto

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).

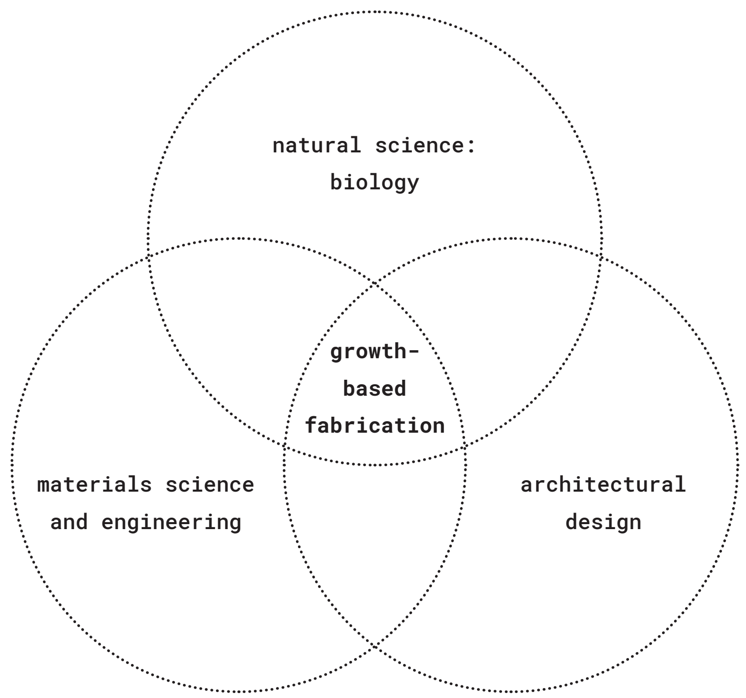
Integration of synthetic biology - an interdisciplinary branch of engineering and biology - and materials science is the practice of particular interest, presenting the potential of programmable materials production by genetically encoding their properties (Glieder et al., 2016).

Biofabrication - the process of materials fabrication through the growth of living cells and organisms - was originally developed for the purposes of biomedical industry. However, nowadays the applications of biofabrication technologies span far beyond the medical field, mainly because of a broad range of exceptional advantages and values offered within this practice (Camere and Karana, 2018). Biomaterials and their fabrication processes have been increasingly investigated in other fields outside of science, such as the area of design.

“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

background



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 future of architecture isn't about one trend. It's about a hundred — if not a thousand — different things."***
>
> Marc Kushner

How are forms created in Nature?

Biological systems which occurs 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 (Camere 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 (Camere 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).

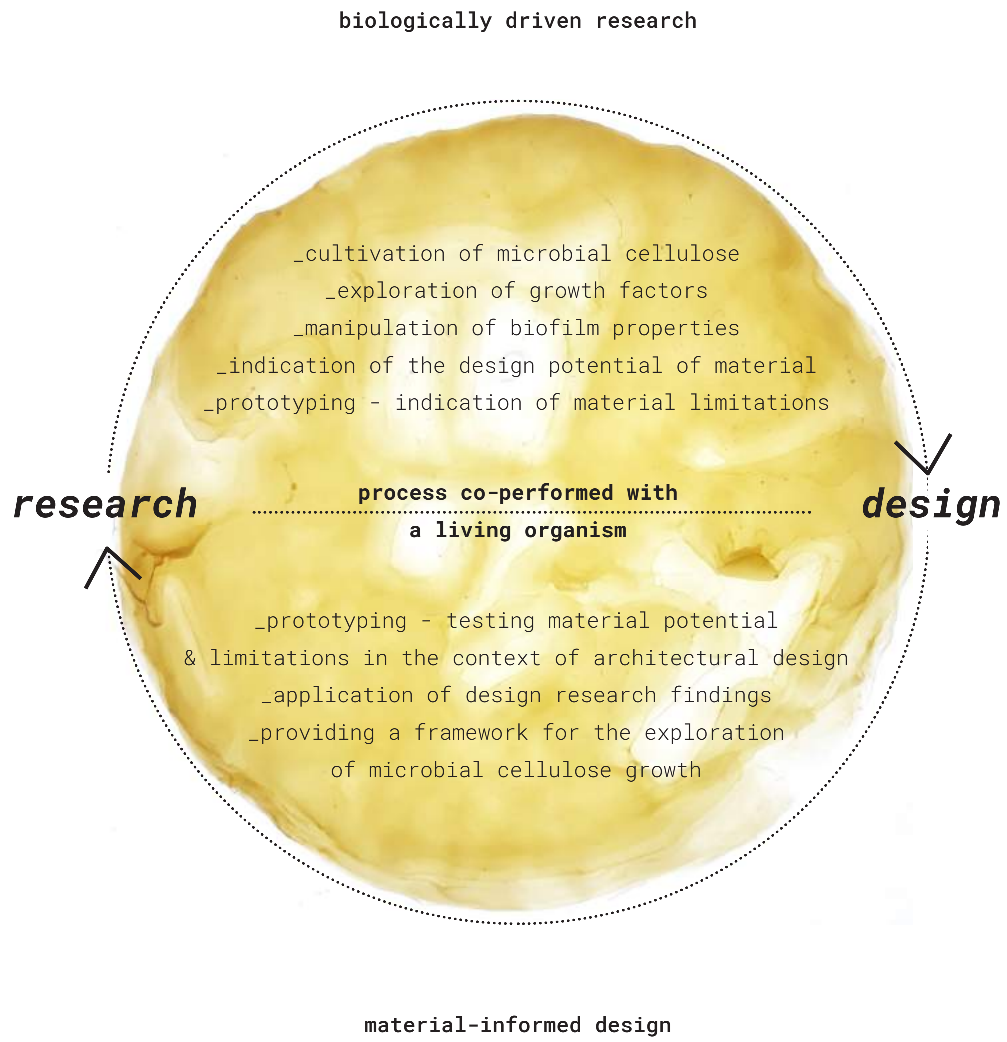
What is the future of architecture? Is it a 'Living Architecture'?

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 biocomposites 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 prallel 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 | ecoLogicStudio

(Kretzer and Hovestadt, 2014)

02| biofabrication

where the fabricated and the grown unite


[01] Silk Pavilion | MIT Media Lab | Courtesy of Steven Keating


[02] Primary structure | MIT Media Lab | Courtesy of Markus Kayser


[03] Biological printer - Silkworm | MIT Media Lab | Courtesy of Steven Keating

biofabrication
where the fabricated and the grown unite | references

Silk Pavilion

Mediated Matter research group at the MIT Media Lab | 2013

„Our research integrates computational form-finding strategies with biologically inspired fabrication"

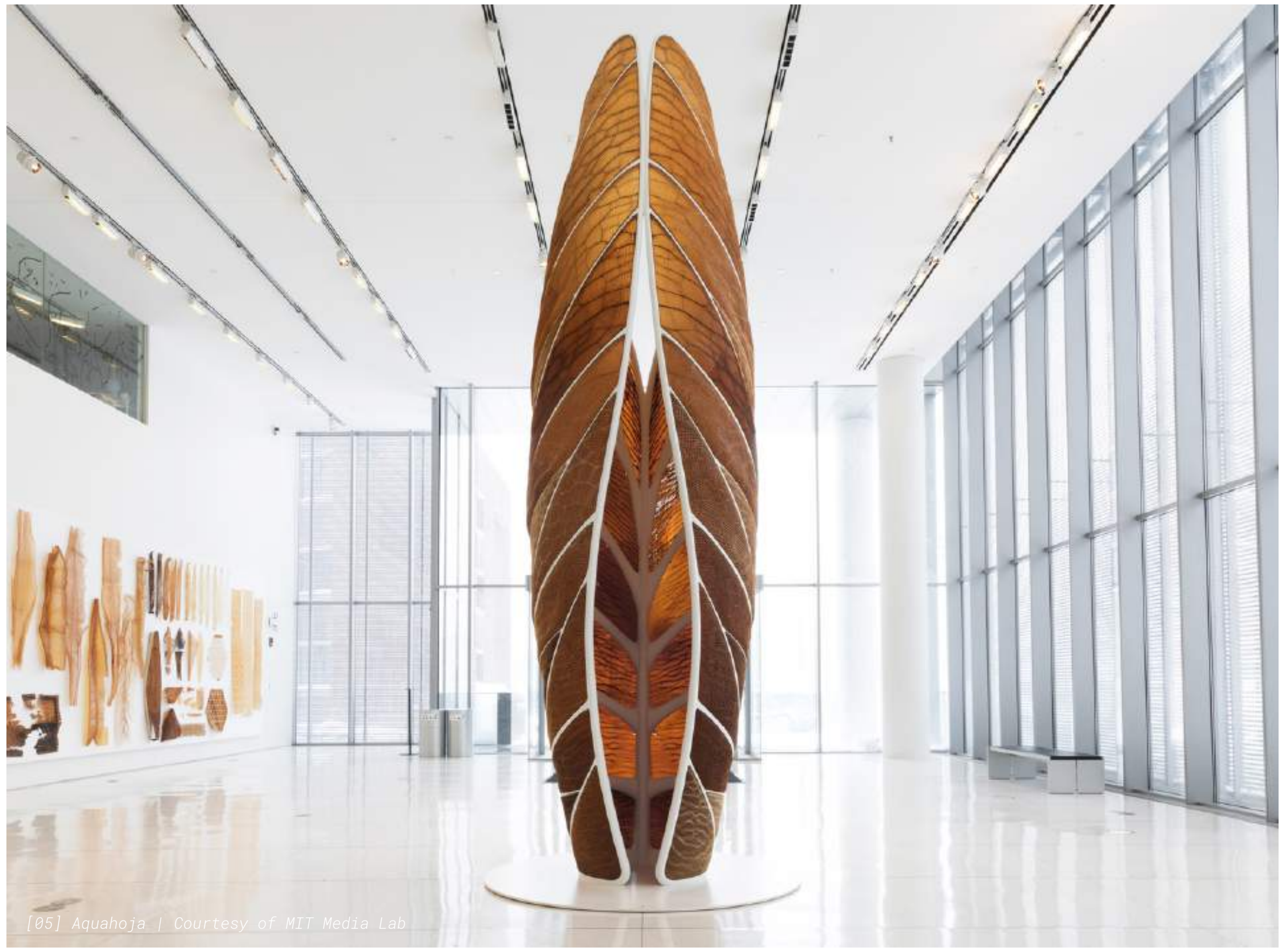
MIT Media Lab's Mediated Matter

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 tree-dimensional cocoon with the use of a multi-property silk fiber, around 1km long (Oxman et al., 2013).

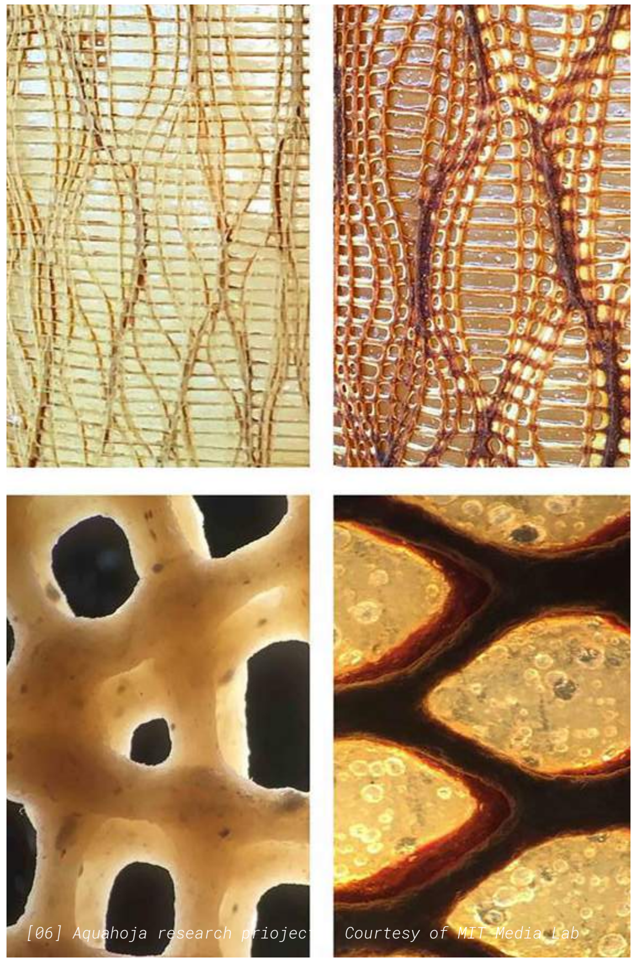
The base structure consists of 26 polygonal panels fabricated by a CNC machine with the use of woven silk threads. The main geometry was generated with the use of algorithm assigning one continuous silk fiber across fabricated panels creating the variety of thread density. However, the general various 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.

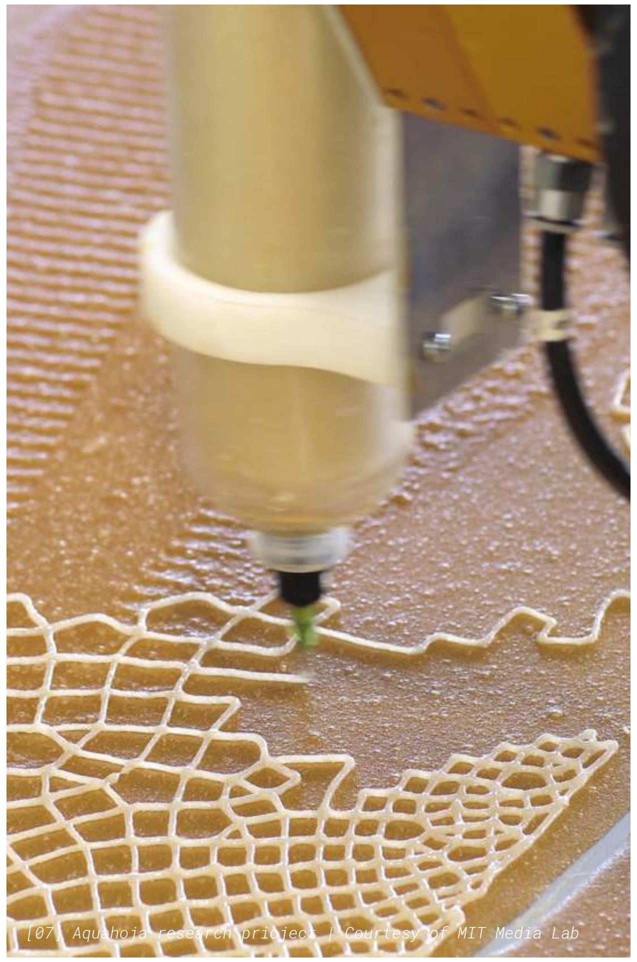

[04] Silk Pavilion | MIT Media Lab | Courtesy of Steven Keating



[05] Aquahoja | Courtesy of MIT Media Lab



[06] Aquahoja research projec Courtesy of MIT Media Lab



[07] Aquahoja research project | Courtesy of MIT Media Lab

biofabrication

where the fabricated and the grown unite | references

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 occure 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).

[08] Artifacts | Courtesy of MIT Media Lab

[09] Close-up of a chair prototype | Microbial cellulose grown on a wooden scaffolding | Courtesy of Jannis Hülsen

[10] Chair prototype | Microbial cellulose grown on a wooden scaffolding | Courtesy of Jannis Hülsen

bacteria related design
references

Xylinum Stool
Jannis Hülsen | 2011

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.

[11] Diagram of microbial cellulose bio-manufacturing | Courtesy of Jannis Hülsen

[12] Microbial cellulose bio-manufacturing | Courtesy of Jannis Hülsen

[13] Dried microbial cellulose element | Courtesy of Jannis Hülsen and Stefan Schwabe

[14] Assembly of the dried microbial cellulose elements | Courtesy of Jannis Hülsen and Stefan Schwabe

bacteria related design
references

Xylinum Cones

Jannis Hülsen, Stefan Schwabe | 2013

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.

[15] Microbial cellulose growth in molds | Courtesy of Jannis Hülsen and Stefan Schwabe

[16] Three-dimensional prototype made of microbial cellulose | Courtesy of ecoLogicStudio

[17] Experimentation exploring the growth of microbial cellulose | Courtesy of ecoLogicStudio

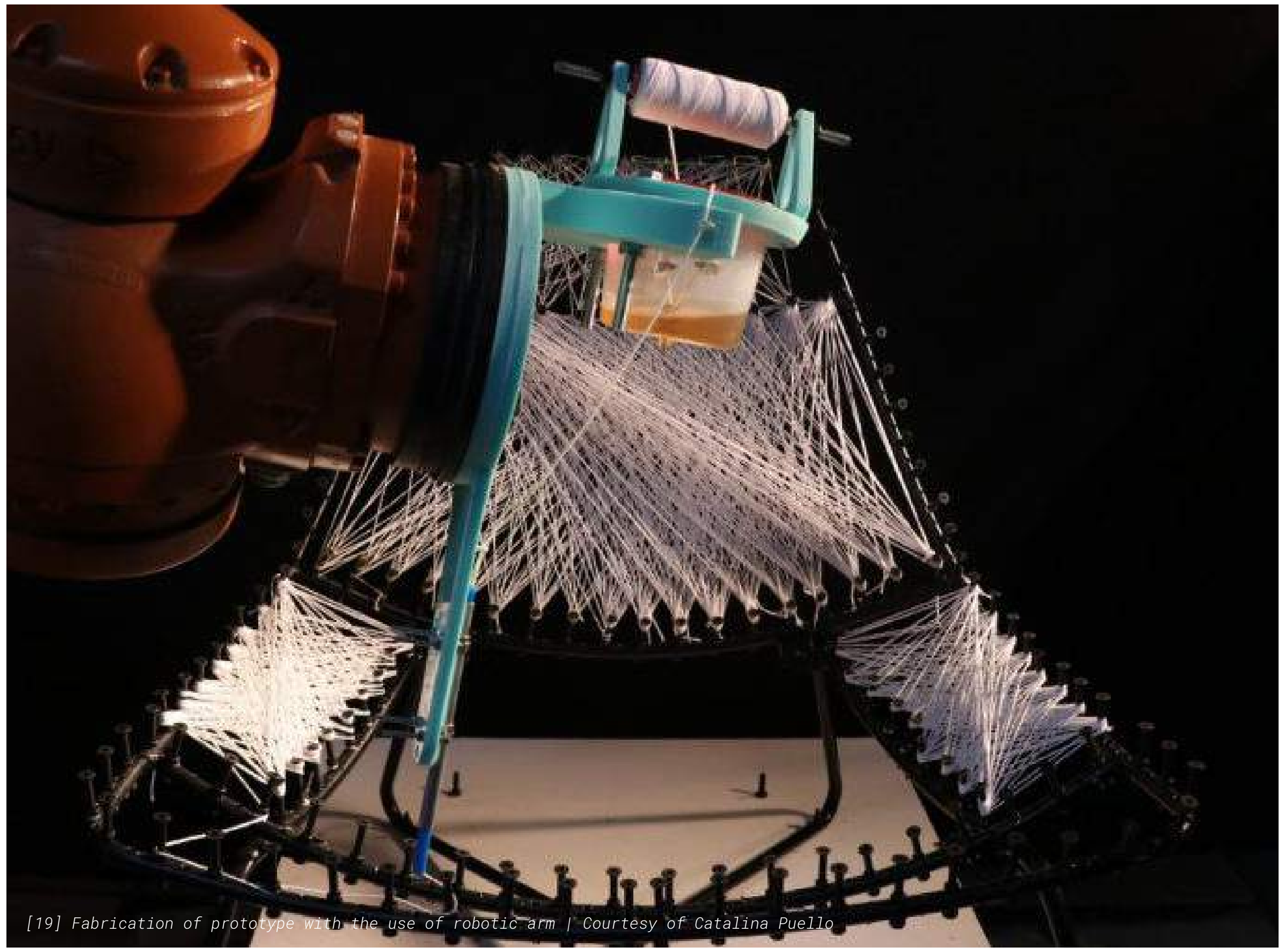
bacteria related design
references

Microbial Cellulose [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-manufaturing.

[18] Microbial cellulose samples produced with the use of various fruits and vegetables | Courtesy of ecoLogicStudio



[19] Fabrication of prototype with the use of robotic arm | Courtesy of Catalina Puello

[20] Prototype of a chair | Courtesy of Catalina Puello

bacteria related design
references

Vibrant Tissue: Augmented Microbial Cellulose

MAA 02 | Master in Advanced Architecture | DvPS: Development Project Studio | The Institute for Advanced Architecture of Catalonia | IAAC
Catalina Puello | tutor: Marcos Cruz
2018

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 a previous reference projects, the author uses various ingredients for material production, resulting in development of material cataloque.

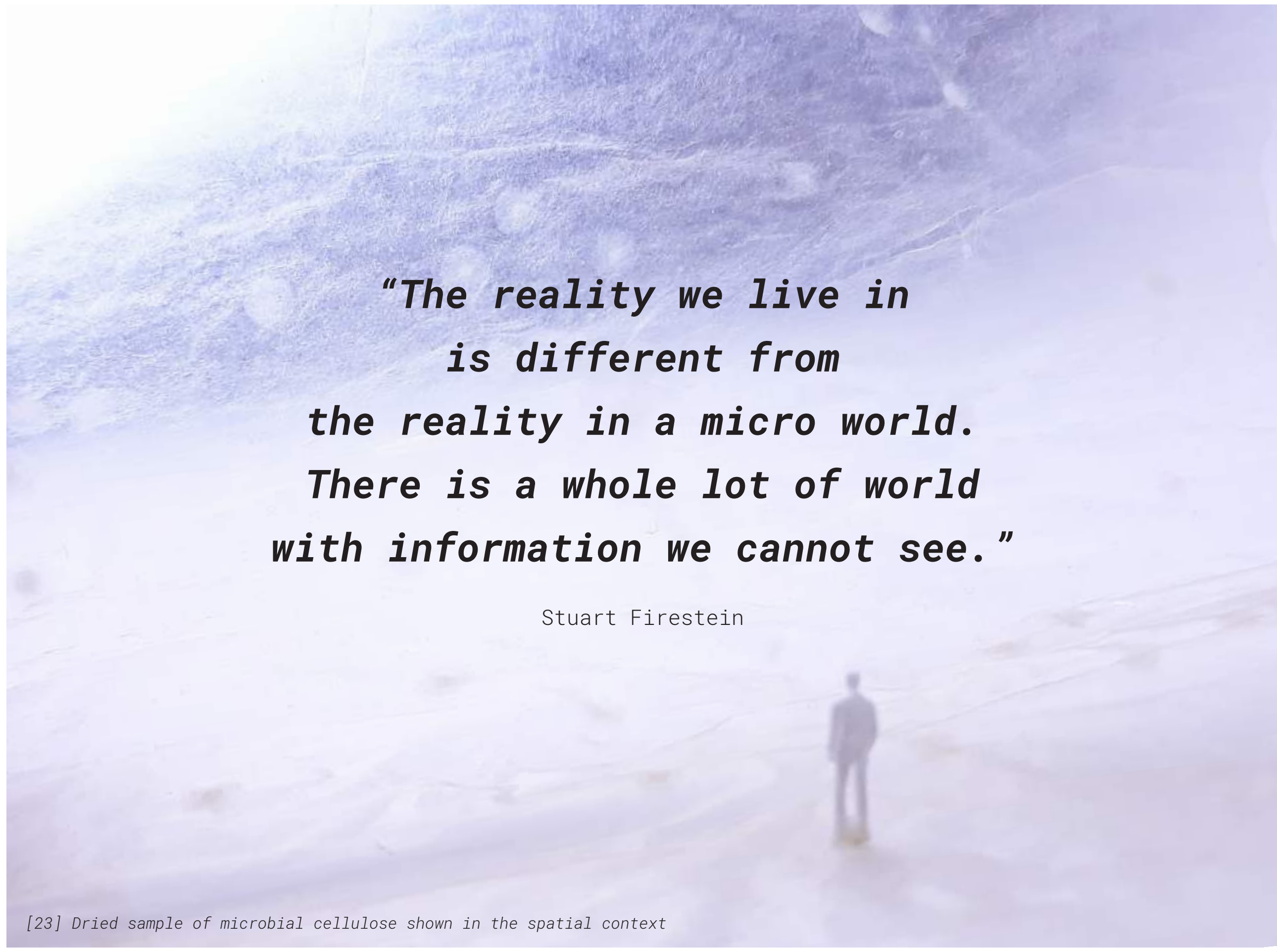
In the next phases of the project, the author conducts series of geometrical analysis, working with volume, tension and strength of the material itself as well as with the use of natural fibers as reinforcement.

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

[21] Samples of microbial cellulose | Courtesy of Catalina Puello

[22] Microbial cellulose growth with the use of various fruits | Courtesy of Catalina Puello

03| research findings



[23] Dried sample of microbial cellulose shown in the spatial context

[24] Dried sample of microbial cellulose shown in the spatial context

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 bifabrication processes where the elements could be fabricated in laboratories, merged and 'self-healed' after assembly simply by overgrowth directly on site.

Unique properties of microbial cellulose

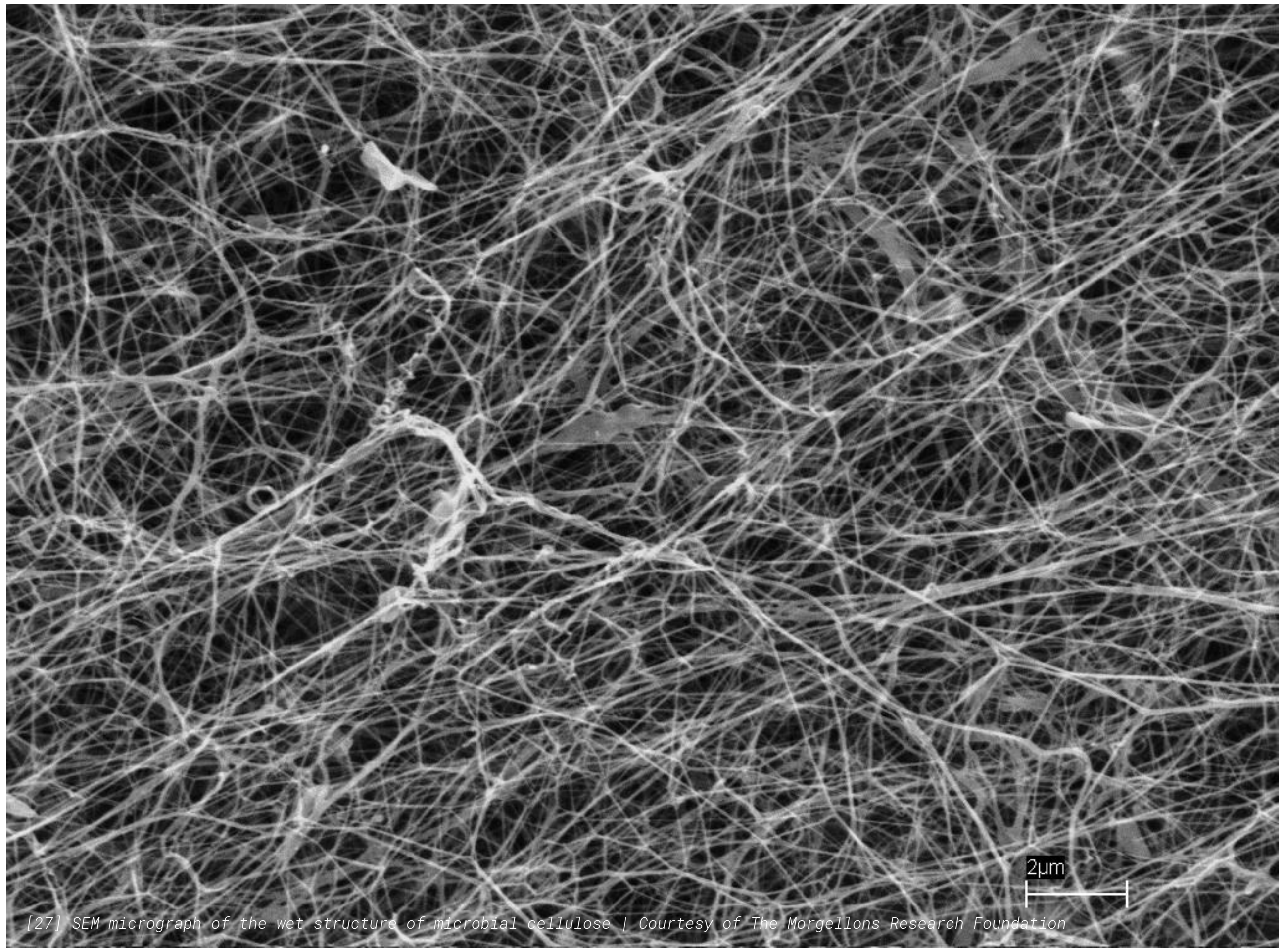
Among the most important properties of microbial cellulose which make this material unique are:

- biodegradability
- high mechanical and tensile strength
- hygroscopy
- material versatility
- 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).

[25] Dried sample of biofilm shown in the spatial context

[26] Scanning electron microscope image of bacteria Acetobacter xylinum | Courtesy of Marc Zienkiewicz



[27] SEM micrograph of the wet structure of microbial cellulose | Courtesy of The Morgellons Research Foundation

microbial cellulose

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

\+

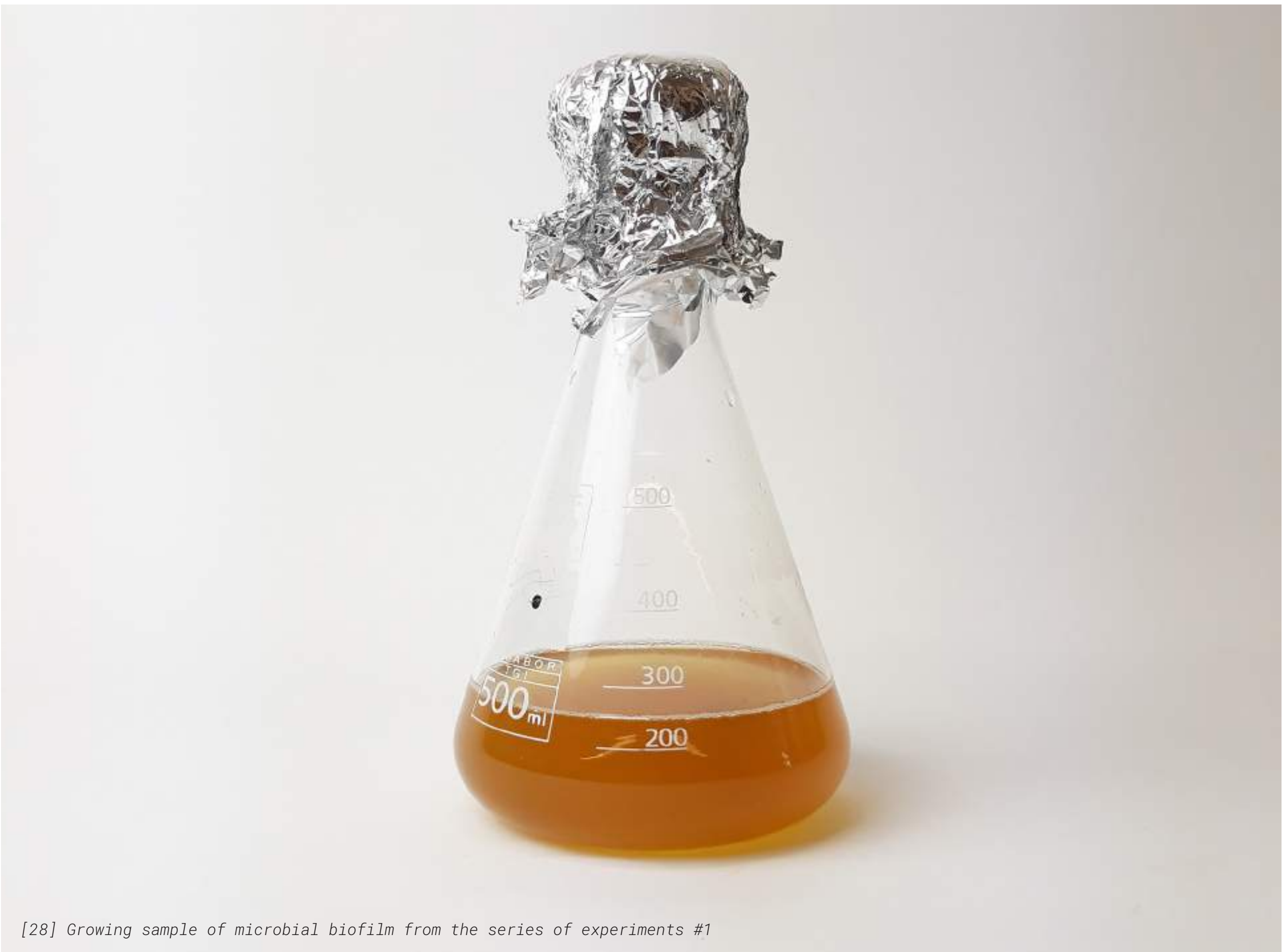
medium
green tea brew
or pure water
\+ apple cider vinegar

\+

nutrition
2 types of sugar:
fructose + sucrose

\+

oxygen



[28] Growing sample of microbial biofilm from the series of experiments #1

04| architectural design implementation

[29] Existing observatory place | Courtesy of Bee Breeders Architecture Competition Organisers

[30] Al Wathba Wetland Reserve in Abu Dhabi | Courtesy of Bee Breeders Architecture Competition Organisers

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.

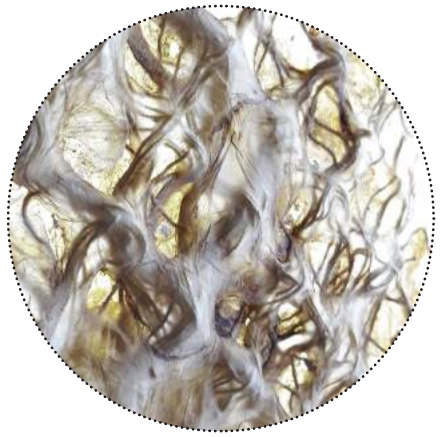
Site | Al Wathba Wetland Reserve in Abu Dhabi

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

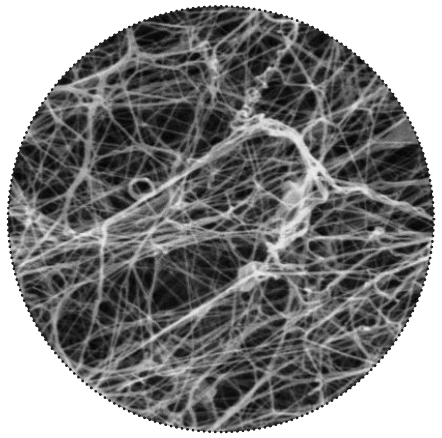
"Established in 1998, Al Wathba Wetland Reserve in Abu Dhabi is a nature reserve consisting of both natural and man-made bodies of water located 40 km southeast of central Abu Dhabi. Covering a total of 5 square km, the wetlands are comprised of wetlands, sabkhas (salt flats), fossilized sands and dunes, and are densely packed with animal and plant life. The most spectacular is the flamingo 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)

[31] Site plan

macro scale
cells: agar* extruded on sizal fibers
microbial cellulose growth on fabricated cells + coloration
*agar with injected symbiotic culture of bacteria and yeast

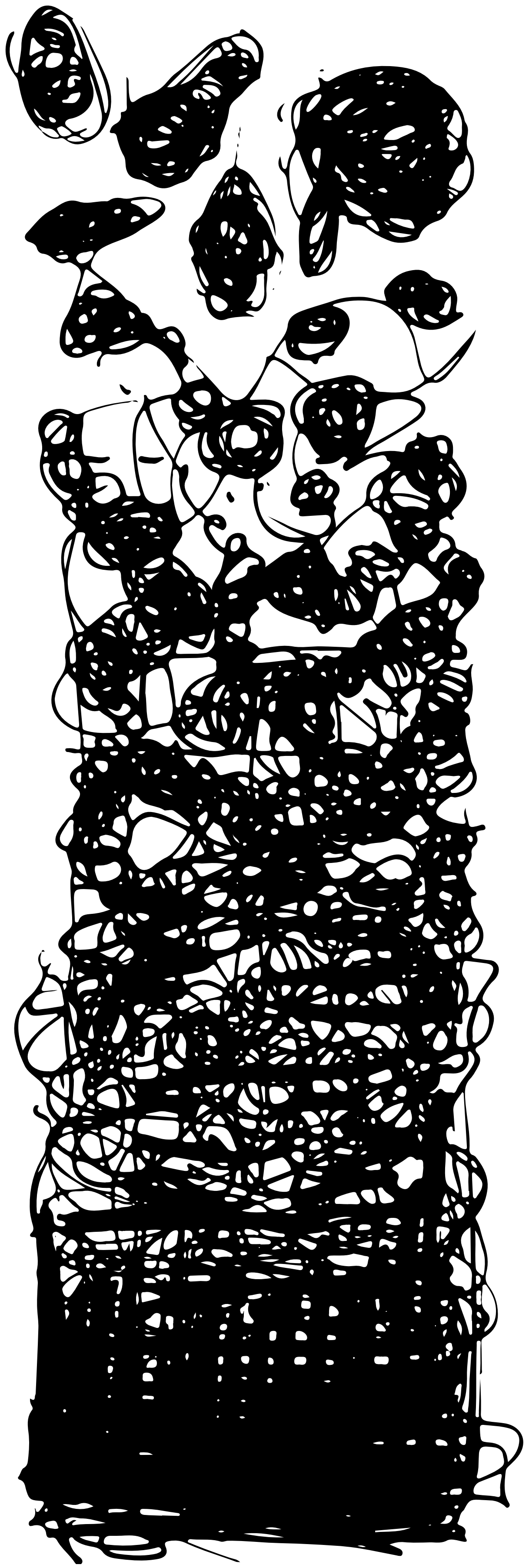


meso scale
biocomposite:
bacterial cellulose + sizal fibers



micro scale
SEM micrograph of a wet microbial cellulose structure

structural integrity across scales
hierarchically structured form



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*.

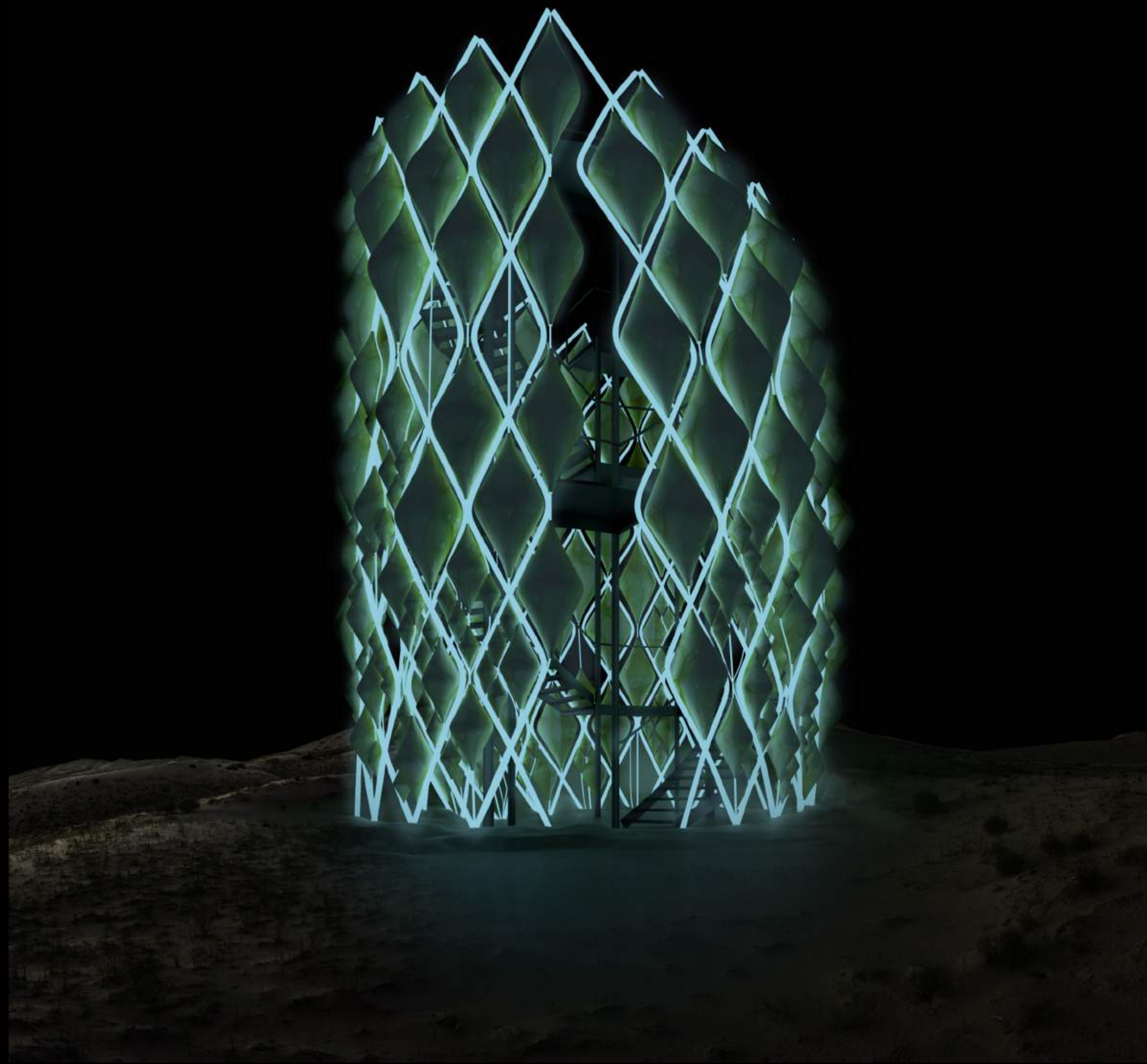
The microbes design space of intervention - biomanufacturing of microbial cellulose fibers - is *micro scale* while the *macro scale*, namely design of a tube *feeding system* providing nutrient for the symbiotic culture of bacteria and yeast growing a biofilm on the surface of fabricated elements - 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 t*he grown* by symbiotic culture of bacteria and yeast *unite*.

[32] Diagram of structural integrity across scales

flamingo observation tower



[33] Diagrams of bioluminescent bacterium Photobacterium phosphoreum implemented in the designed system

[34] Night perspective showing the implementation of bioluminescence

design composition

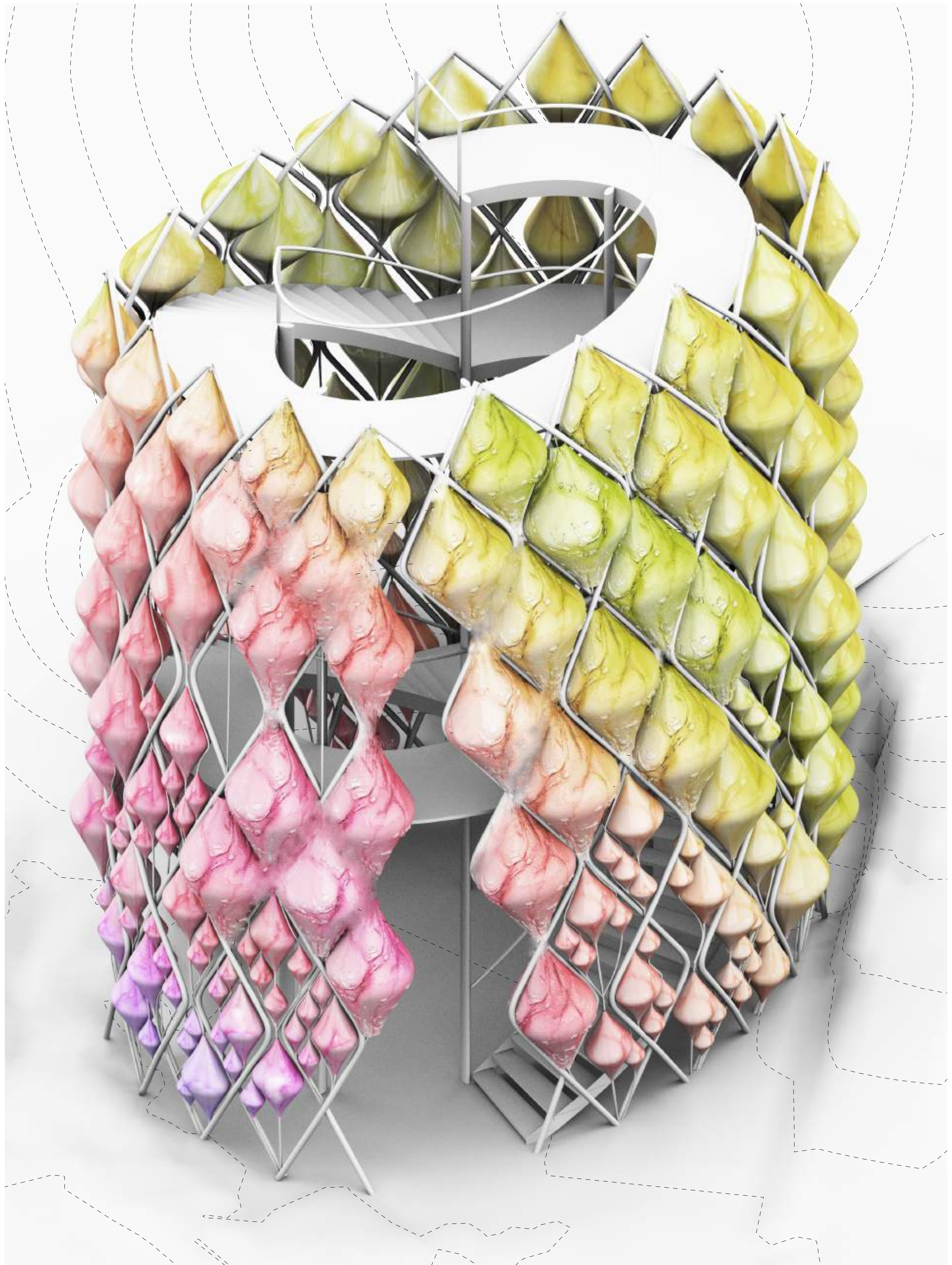
- 35% symbiotic culture of bacteria and yeast
- 35% water
- 8% apple cider vinegar
- 22% cut fruits

natural coloration | series of experiments #4

samples of microbial cellulose produced with the use of variuos fruits

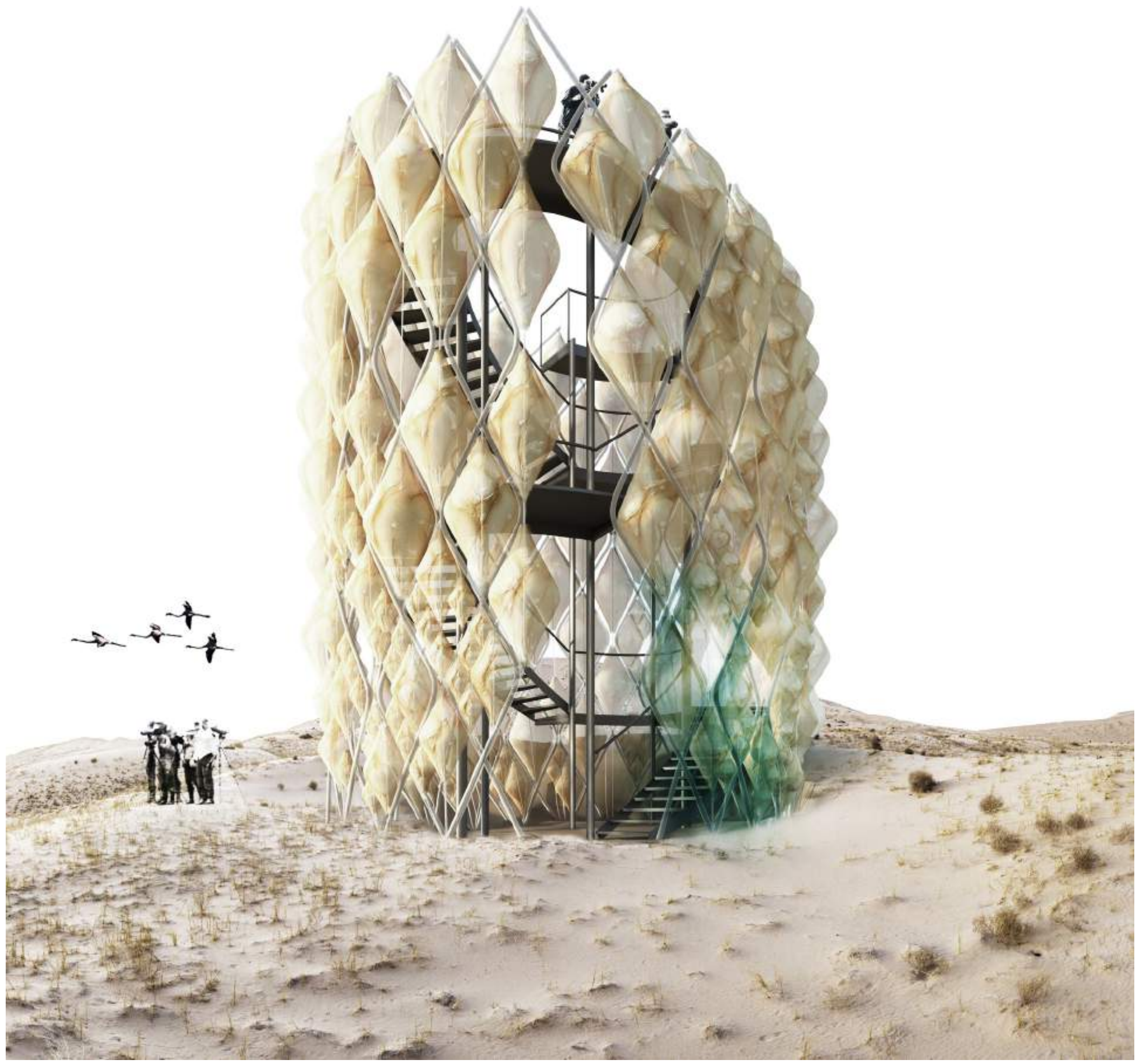
[35] Diagram showing the design composition

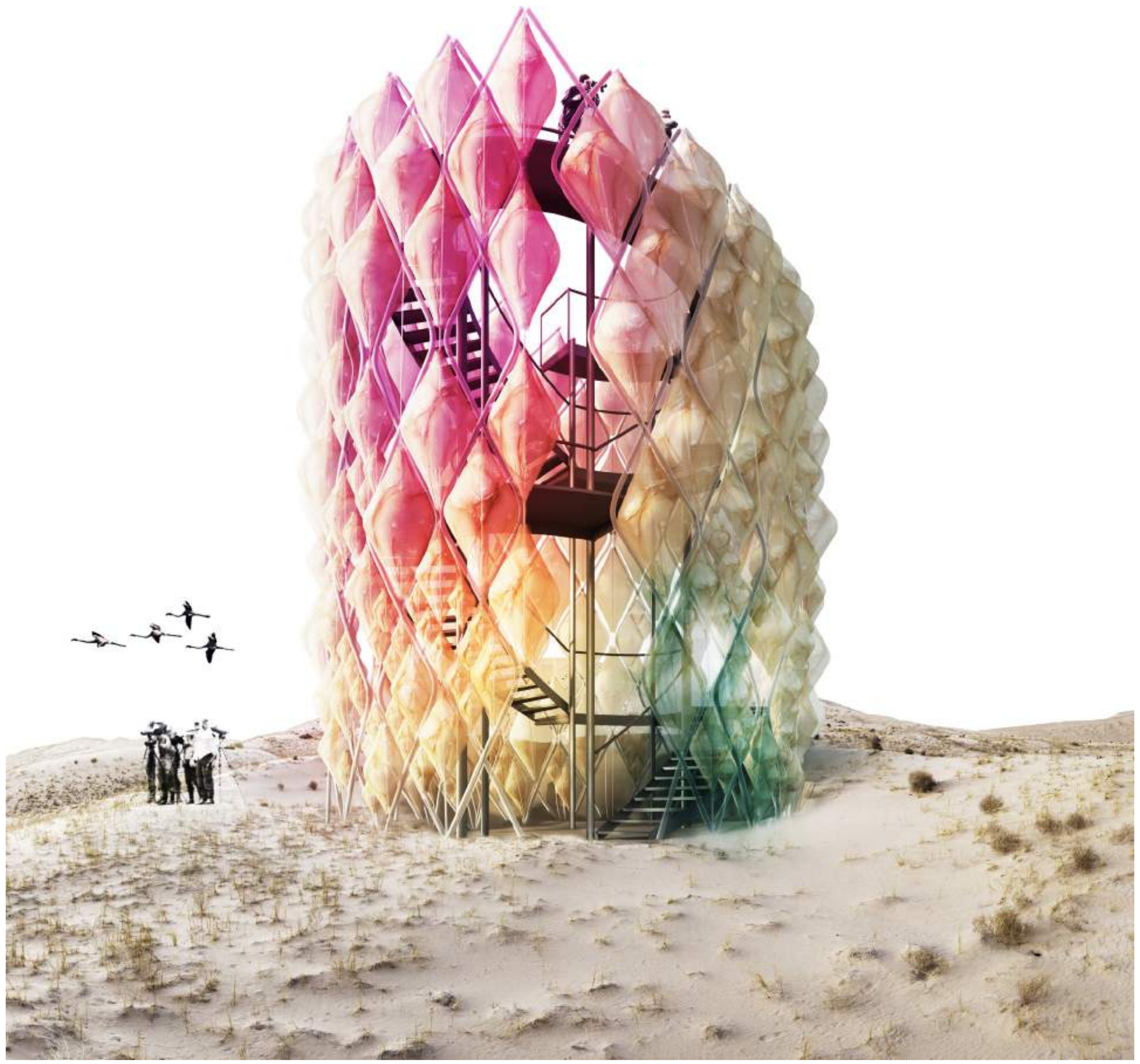
flamingo observation tower



[36] Isometric view showing the potential of microbial cellulose coloration both during the cultivation process as well as after growth by spreading the water with pigment through the system of PVC tubes | Mature stage - more than 1 year

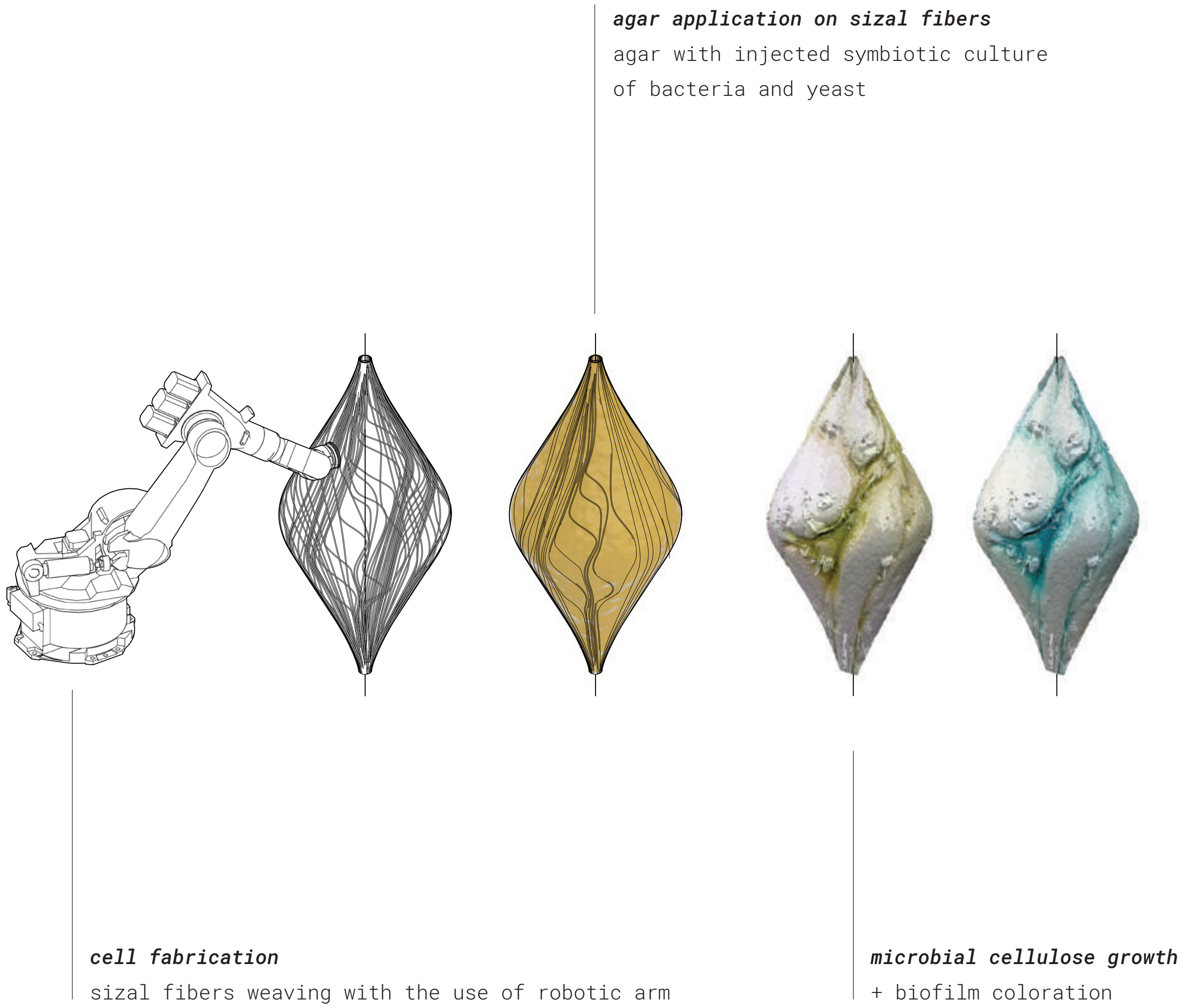
flamingo observation tower



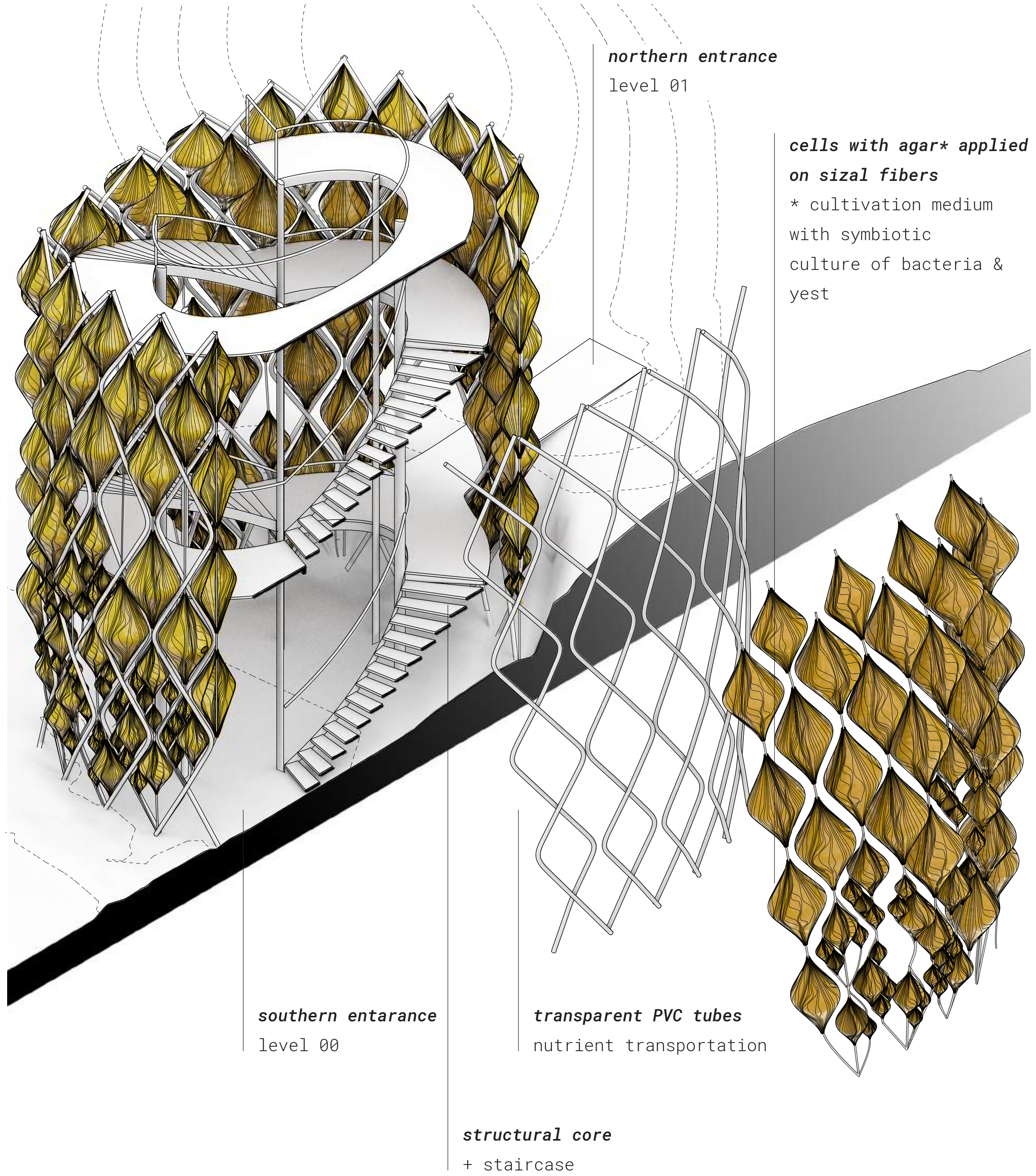


[37] Perspective of Flamingo Observation Tower

[38] Perspective of Flamingo Observation Tower showing the potential of coloration and constant change of the tower



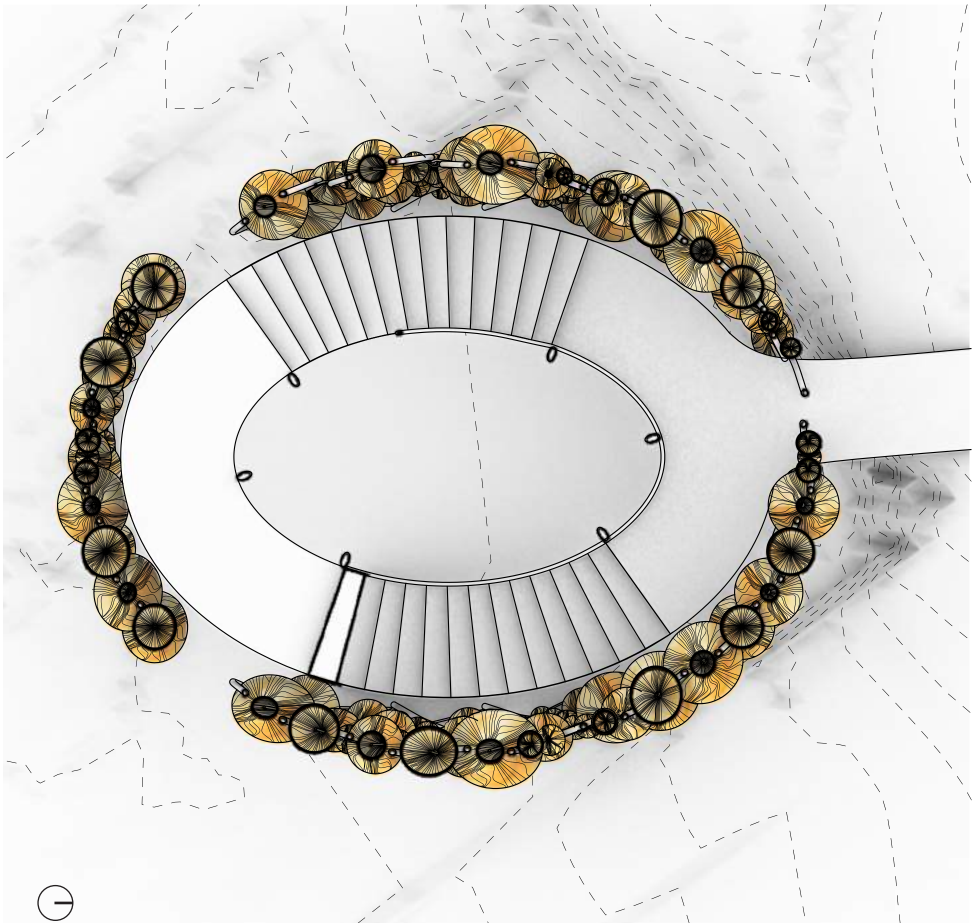
flamingo observation tower



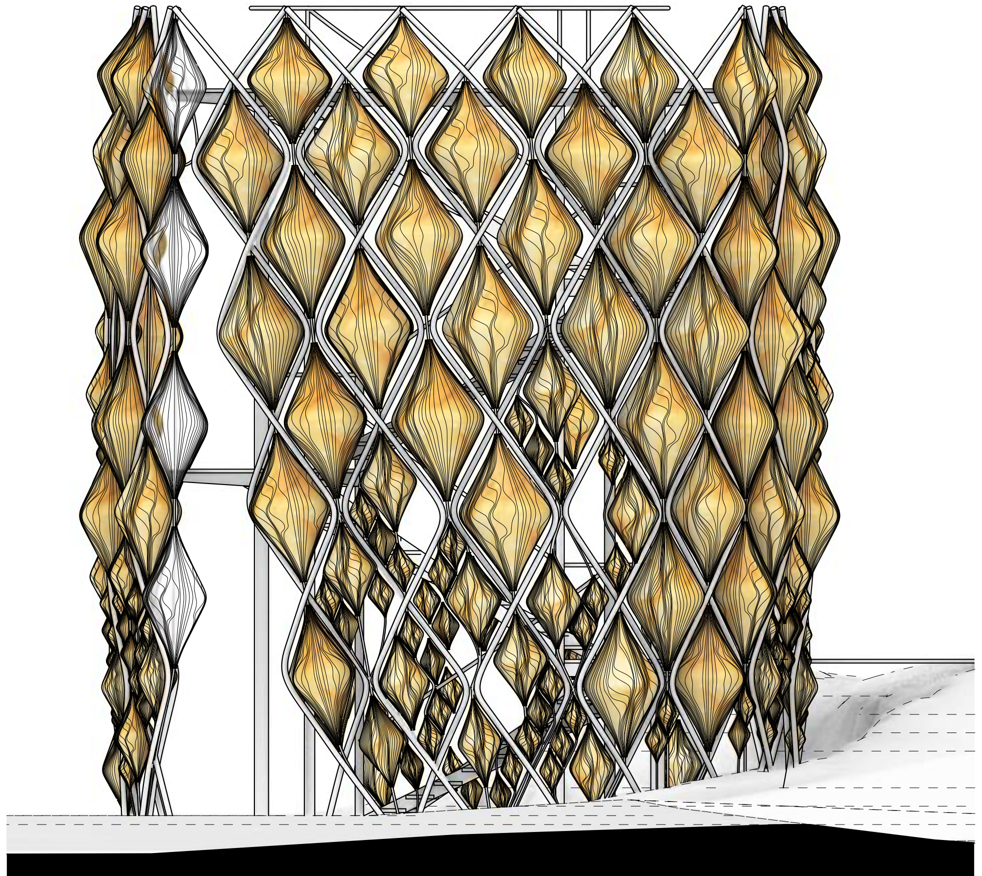
[39] Fabrication of cells and cellulose growth diagram

[40] Isometric view of section and exploaded 'feeding' system after fabrication | Initial stage - first few months

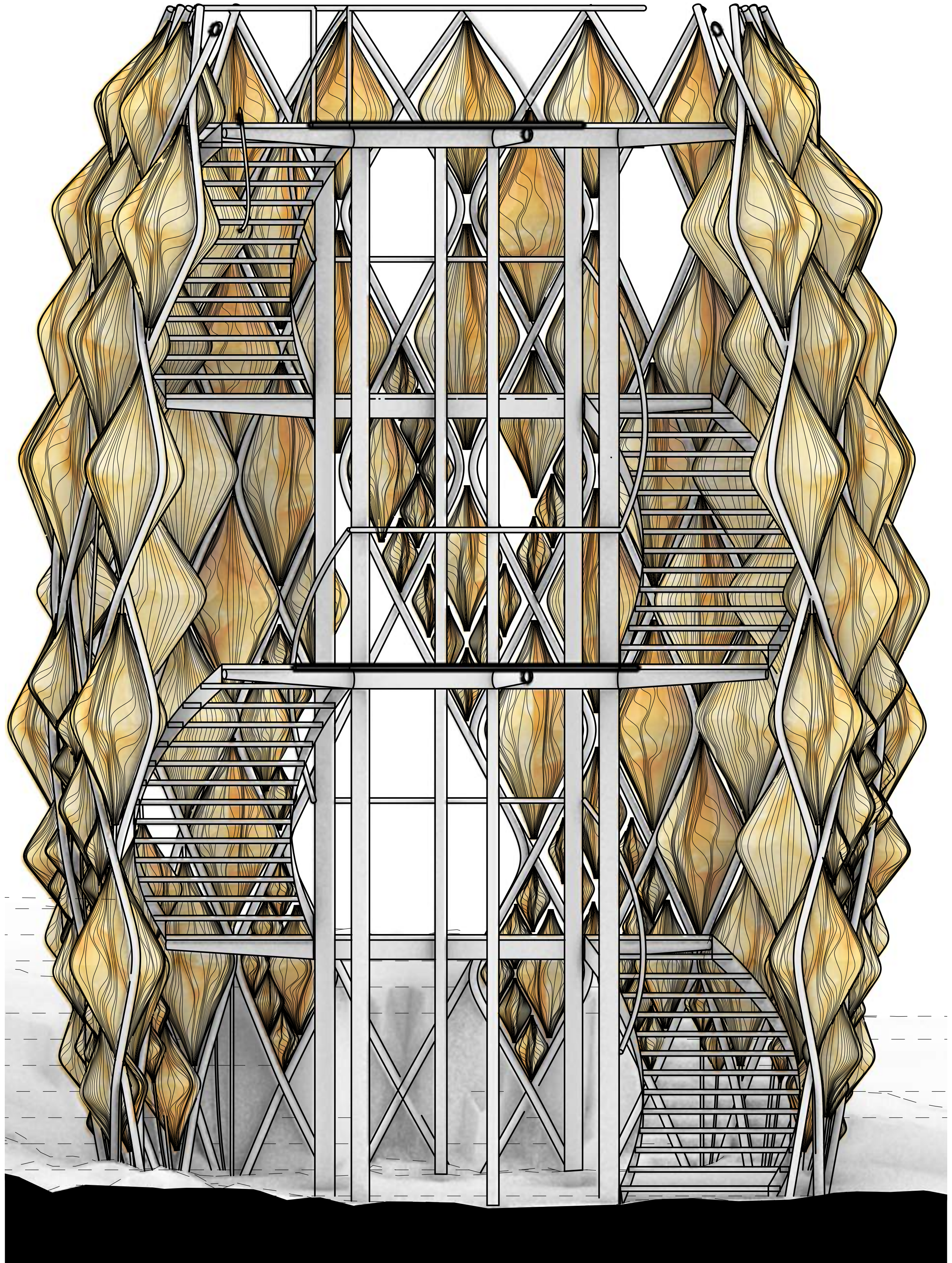
flamingo observation tower



[41] Plan | level 01



[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

[44] When the fabricated and the grown unite | Internal perspective of the tower

reflection

"A project ends well when it opens doors for you, when it makes you dream much more."

Killian Jornet

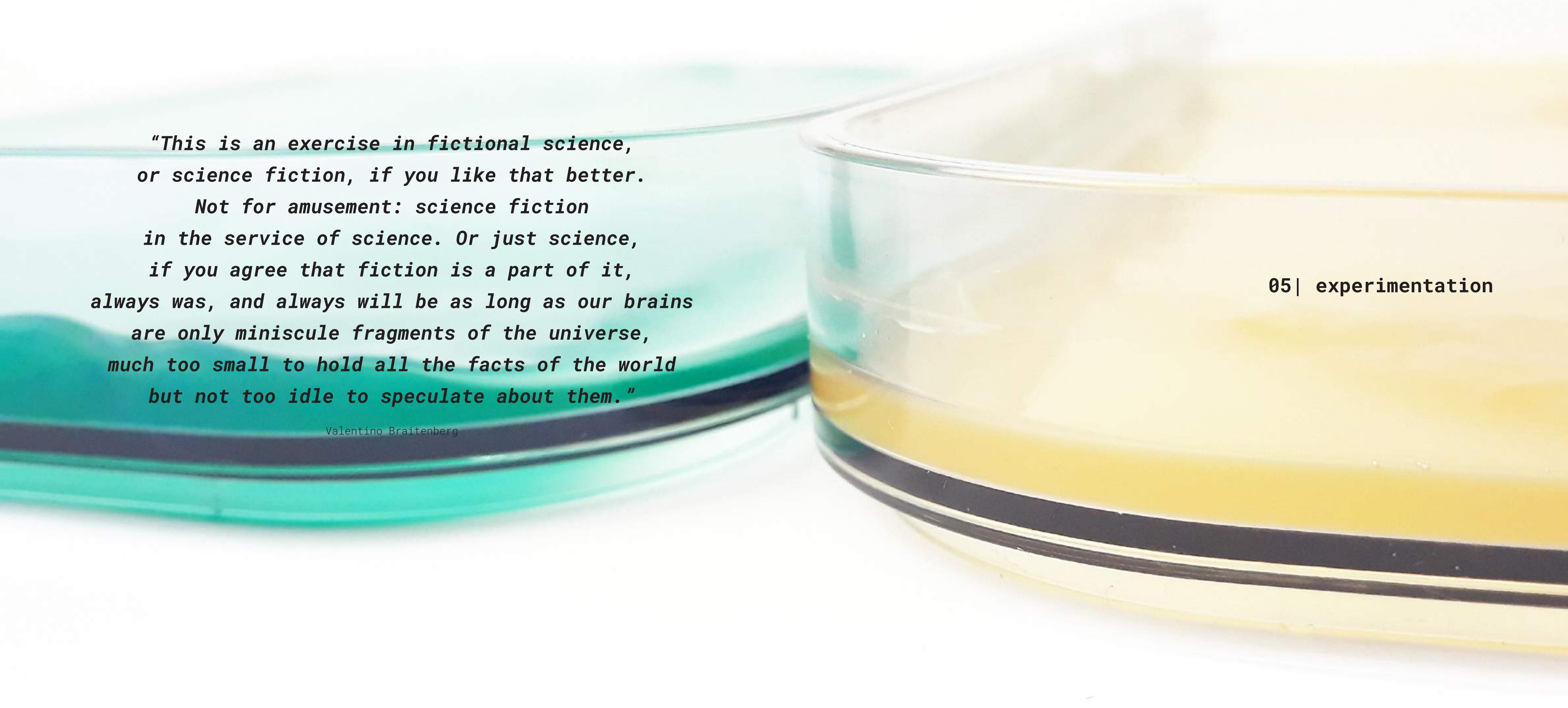
The main aim of this thesis was to explore and elucidate the potential of microbial cellulose in designing an environmentally responsive architecture with high level of integration between structure, shape, and material, across micro, meso and macro scales.

The very extensive research phase consisting of experimentation and prototyping parts and examinating 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 adress 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.



*“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

05| experimentation

[45] Cultivation of microbial cellulose during series of experiments #2 and #5

[46] Growing sample of microbial biofilm from the experiment #5.1

introduction

Experimentation | Aim

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 eluciadtion 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.

[47]

[48]

[49]

[47] First experiments in DIY Micro lab 01
[48] DIY Micro Lab 02 | Micro Lab 523 at Chalmers School of Architecture
[49] Experimentation in Micro lab at Department of Biology and Biological Engineering
[50] Experimentation in Micro lab at Department of Biology and Biological Engineering
[51] Experimentation in Micro lab at Department of Biology and Biological Engineering

micro lab

"Rags to Riches" Micro Lab

All the experiments were conducted in different lab spaces according to available options and needed conditions during the research time.

DIY Micro Lab 01

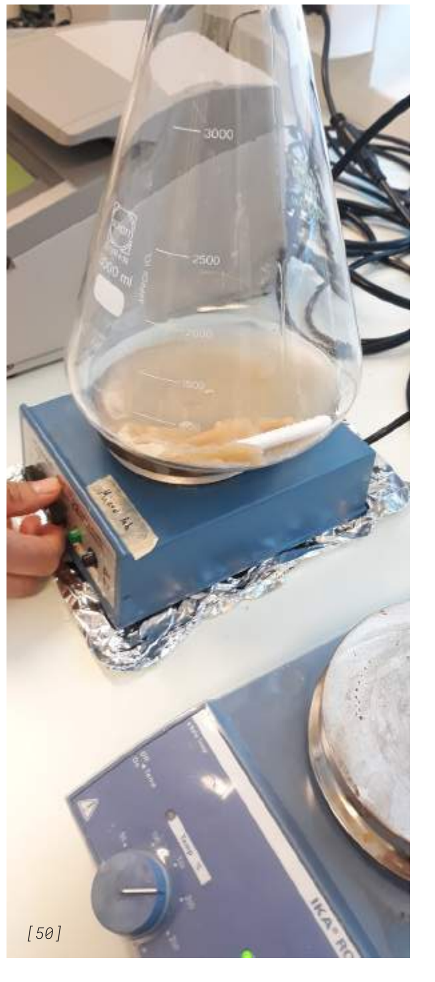
The initial experiments investigating the pure cellulose growth according the traditional method of symbiotic culture of bacteria and yeast cultivation were conducted in DIY Micro lab established by the author.

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.



[50]

[51]

list of experiments

[52] Cultivation of microbial cellulose during series of experiments #2 and #5

[53]

[54]

[55]

[56]

[53] Ingredients for #1.1 sample
[54] Close-up of #1.1 sample of microbial biofilm growing for 5 days
[55] Top view of #1.1 sample
[56] Top view of #1.1 sample of microbial biofilm grown for 14 days
[57] Dry #1.1 sample of microbial biofilm grown for 14 days and dried for 5 days

experiment #1.1 | primary biofilm growth
deep vessel | 14 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
- 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.

[57]

[58]

[59]

[60]

[58] Front view of #1.1 sample
[59] Front view of #1.1 sample of microbial biofilm grown for 30 days
[60] Top view of #1.1 sample
[61] Top view of #1.1 sample of microbial biofilm grown for 30 days
[62] Dry #1.1 sample of microbial biofilm grown for 30 days and dried for 10 days

[61]

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 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 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.

[62]

[63]

[64]

[63] Ingredients for half of #2.1 sample
[64] Front view of #2.1 sample of microbial biofilm grown for 14 days
[65] Top view of #2.1 sample of microbial biofilm grown for 14 days

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

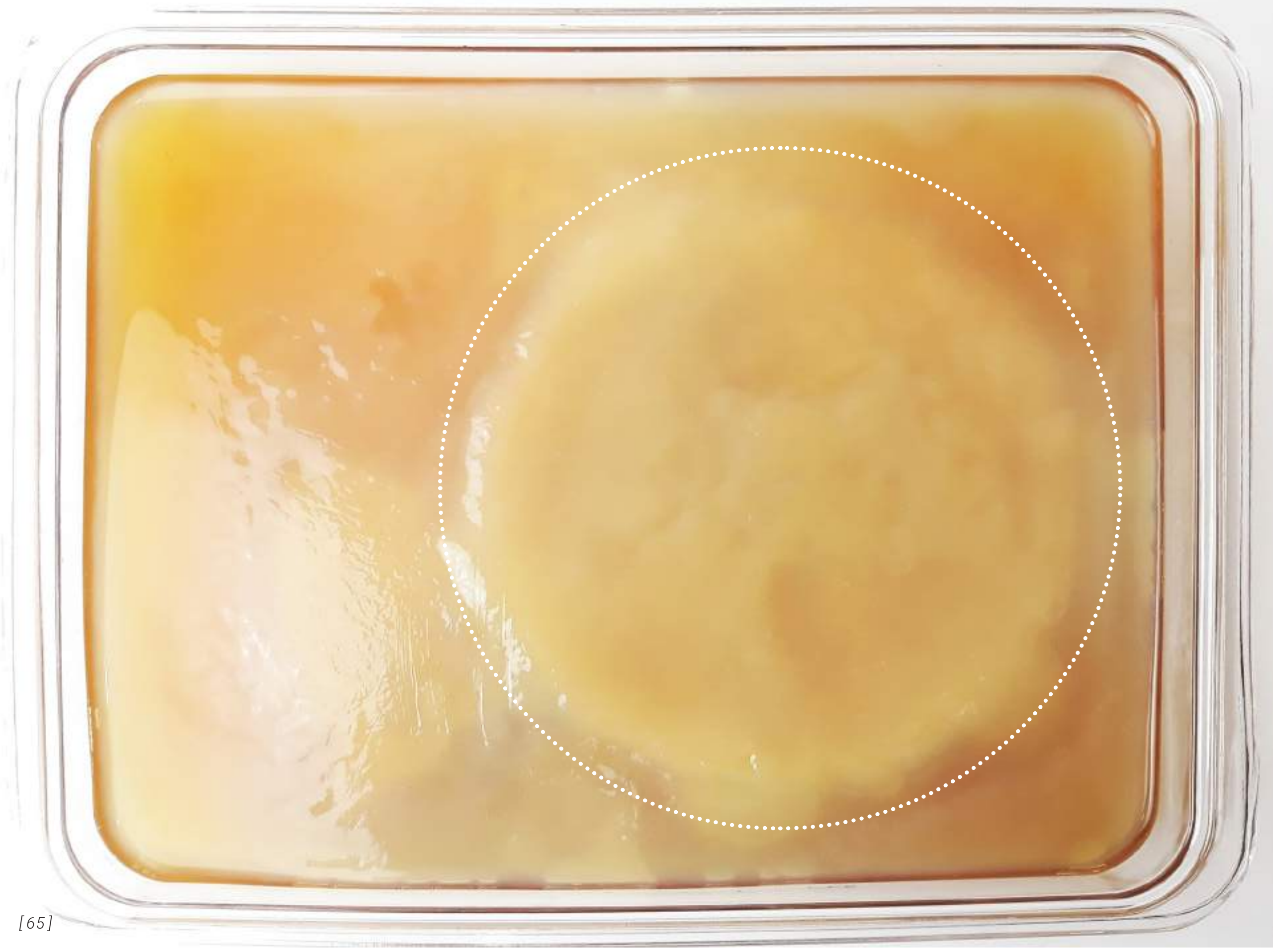
Result

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 thiner 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.



[65]

[66] Top view of #2.2 sample of microbial biofilm grown for 14 days, before coloration

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.

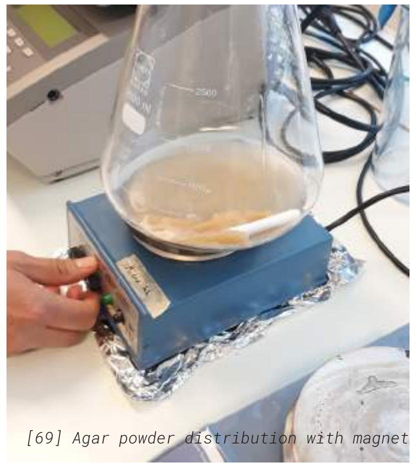
- sample thickness before drying: 3-10 mm

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 coloration with the use of added colours (page XX).

[67] Close-up of #2.2 sample of microbial biofilm

[68] Agar powder


[69] Agar powder distribution with magnet


[70] Solid physical state of agar

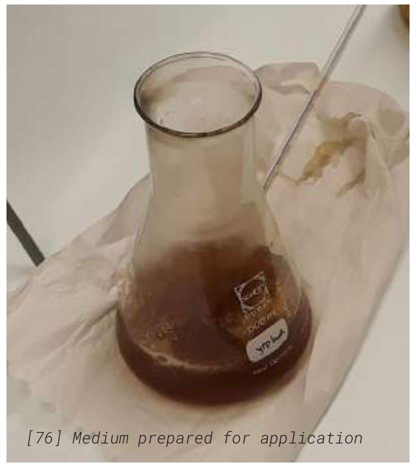

[71] Sample tubes in centrifuge

[72] Concentrated culture on the bottom


[73] Concentrated culture in sample tubes

[74] Mixing a sample tube with microbes


[75] Preparing medium with tea and agar


[76] Medium prepared for application

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 reserch phase, where the liquid medium used so far was not appropriate. The experiment examinates 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 decresed to 45°C - addition of concentrated symbiotic culture (10 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 40°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.

[77] Samples of agar with culture applied on cotton gauze located on a plastic and foam forms

[78] Samples of agar with culture applied on cotton gauze

[79] Samples of agar with culture in petri dish

experiment #3.2 agar plate + cotton gauze | medium shift

solid medium + natural fibers

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.

Ingredients

- agar medium from the experiment #3.1
- cotton gauze

Growth conditions

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

[80] Application of agar on foam mold

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 yest - 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.

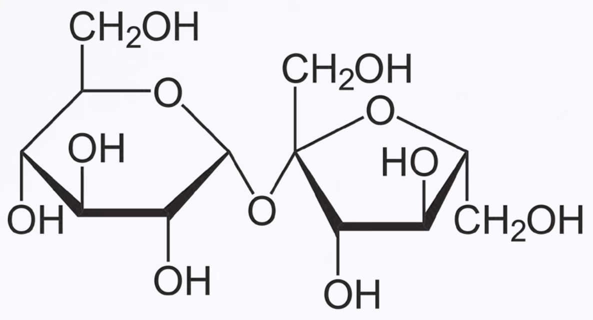
Series #3 Medium shift: general conclusions

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.

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.



[81] Skeletal formula of sucrose ($C_{12}H_{22}O_{11}$)

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.

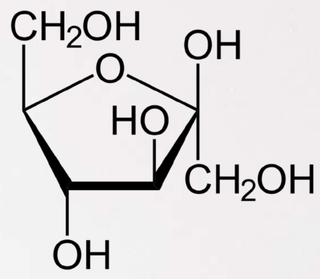
Nutrition manipulation: carbon source

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 ($C_6H_{12}O_6$) 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 partucular 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.

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.



[83] Skeletal formula of fructose ($C_6H_{12}O_6$)

[82] Samples of microbial cellulose growing during the series of experiments #4

[84]

[85]

[86]

[87]

[88]

[89]

[84] Ingredients for #4.1a red apple sample
[85] Front view of #4.1a red apple sample
[86] Top view of #4.1a red apple sample
[87] Top view of #4.1a red apple sample of microbial biofilm grown for 5 days
[88] Front view of #4.1a red apple sample of microbial biofilm grown for 14 days
[89] Top view of #4.1a red apple sample of microbial biofilm grown for 14 days
[90] Drying #4.1a red apple sample of microbial biofilm grown for 14 days

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.

[90]

[91]

[92]

[93]


[94]


95]


[96]

[91] Ingredients for #4.1b red apple sample
[92] Front view of #4.1b red apple sample of microbial biofilm grown for 14 days
[93] Front view of #4.1b red apple sample
[94] Top view of #4.1b red apple sample
[95] Close-up of #4.1b red apple sample of microbial biofilm grown for 14 days
[96] Top view of #4.1b red apple sample of microbial biofilm grown for 14 days
[97] Drying #4.1b red apple sample of microbial biofilm grown for 14 days

experiment #4.1b red apple | 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 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 thiner biofilm grown on the surface.


[97]

[98]

[99]

[100]


[101]


[102]


[103]

[98] Ingredients for #4.2a green apple sample
[99] Front view of #4.2a green apple sample of microbial biofilm grown for 14 days
[100] Front view of #4.2a green apple sample
[101] Top view of #4.2a green apple sample
[102] Close-up of #4.2a green apple sample of microbial biofilm grown for 14 days
[103] Top view of #4.2a green apple sample of microbial biofilm grown for 14 days
[104] Drying #4.2a green apple sample of microbial biofilm grown for 14 days

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.


[104]

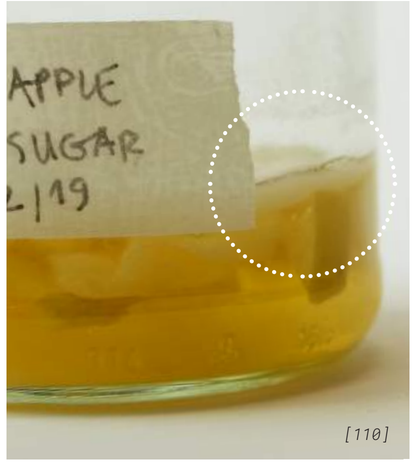
[105]


[106]

[107]

[108]


[109]


[110]

[105] Ingredients for #4.2b green apple sample
[106] Front view of #4.2b green apple sample of microbial biofilm grown for 14 days
[107] Front view of #4.2b green apple sample
[108] Top view of #4.2b green apple sample
[109] Top view of #4.2b green apple sample of microbial biofilm grown for 14 days
[110] Close-up of #4.2b green apple sample of microbial biofilm grown for 14 days
[111] Drying #4.2b green apple sample of microbial biofilm grown for 14 days

experiment #4.2b green apple | 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 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 thiner biofilm in the second phase


[111]

[112]

[113]

[114

[115]

[112] Ingredients for #4.3a pear sample
[113] Top view of #4.3a pear sample
[114] Front view of #4.3a pear sample
[115] Front view of #4.3a pear sample of microbial biofilm grown for 14 days
[116] Top view of #4.3a pear sample of microbial biofilm grown for 14 days
[117] Drying #4.3a pear sample of microbial biofilm grown for 14 days

[116]

experiment #4.3a pear | 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 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 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.

[117]

[118]


[119]

[120]

[121]


[122]


[123]

[118] Ingredients for #4.3b pear sample
[119] Top view of #4.3b pear sample
[120] Front view of #4.3b pear sample
[121] Front view of #4.3b pear sample of microbial biofilm grown for 14 days
[122] Top view of #4.3b pear sample of microbial biofilm grown for 14 days
[123] Close-up of #4.3b pear sample of microbial biofilm grown for 14 days
[124] Drying #4.3b pear sample of microbial biofilm grown for 14 days

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 thiner biofilm in the second phase of experiment - #4.3b.


[124]

[125]

[126]

[127]

[128]

[129]

[130]

[125] Ingredients for #4.4a mango sample
[126] Top view of #4.4a mango sample
[127] Front view of #4.4a mango sample
[128] Front view of #4.4a mango sample of microbial biofilm grown for 14 days
[129] Top view of #4.4a mango sample of microbial biofilm grown for 14 days
[130] Close-up of #4.4a mango sample of microbial biofilm grown for 14 days
[131] Drying #4.4a mango sample of microbial biofilm grown for 14 days

experiment #4.4a mango | 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 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.

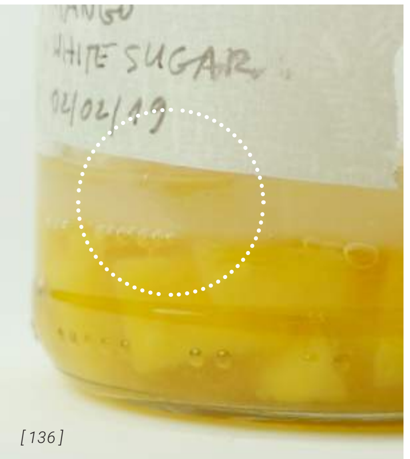
[131]

[132]

[133]

[134]

[135]



[136]

[132] Ingredients for #4.4b mango sample
[133] Front view of #4.4b mango sample of microbial biofilm grown for 14 days
[134] Front view of #4.4b mango sample
[135] Top view of #4.4b mango sample
[136] Close-up of #4.4b mango sample of microbial biofilm grown for 14 days
[137] Top view of #4.4b mango sample of microbial biofilm grown for 14 days
[138] Drying #4.4b mango sample of microbial biofilm grown for 14 days

[137]

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.

[138]

[139]

[140]

[141]

[142]

[143]

[144]

[139] Ingredients for #4.5a kiwi sample
[140] Top view of #4.5a kiwi sample
[141] Front view of #4.5a kiwi sample
[142] Front view of #4.5a kiwi sample of microbial biofilm grown for 14 days
[143] Top view of #4.5a kiwi sample of microbial biofilm grown for 14 days
[144] Close-up of #4.5a kiwi sample of microbial biofilm grown for 14 days
[145] Drying #4.5a kiwi of microbial biofilm grown for 14 days

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.

[145]

[146]


[147]

[148]


[149]


[150]


[151]

[146] Ingredients for #4.5b kiwi sample
[147] Top view of #4.5b kiwi sample
[148] Front view of #4.5b kiwi sample
[149] Front view of #4.5b kiwi sample of microbial biofilm grown for 14 days
[150] Top view of #4.5b kiwi sample of microbial biofilm grown for 14 days
[151] Close-up of #4.5b kiwi sample of microbial biofilm grown for 14 days
[152] Drying #4.5b kiwi sample of microbial biofilm grown for 14 days

experiment #4.5b kiwi | 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 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 - contrariwise 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.


[152]

[153]

[154]

[155]

[156]

[157]

[153] Ingredients for #4.6a purple grape sample
[154] Front view of #4.6a purple grape sample of microbial biofilm grown for 14 days
[155] Front view of #4.6a purple grape sample
[156] Top view of #4.6a purple grape sample
[157] Close-up of #4.6a purple grape sample of microbial biofilm grown for 14 days
[158] Top view of #4.6a purple grape sample of microbial biofilm grown for 14 days
[159] Drying #4.6a purple grape of microbial biofilm grown for 14 days

[158]

experiment #4.6a purple 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 a purple grape. What is more, the experiment explores also the potential of natural coloration with the use of pigments which occure 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

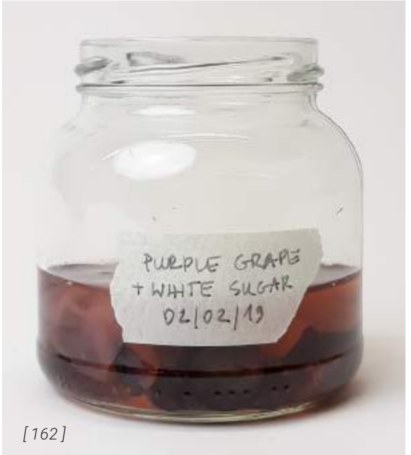
During the first 7 days of the experiment #4.6a, the significant growth of biofilm was observed. Therefore, purple grape was also used during the second part of the experiment - #4.5b.

Moreover, pigments naturally occuring 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.

[159]

[160]

[161]



[162]

[163]

[164]

[165]

[160] Ingredients for #4.6b purple grape sample
[161] Top view of #4.6b purple grape sample
[162] Front view of #4.6b purple grape sample
[163] Front view of #4.6b purple grape sample of microbial biofilm grown for 14 days
[164] Top view of #4.6b purple grape sample of microbial biofilm grown for 14 days
[165] Close-up of #4.6b purple grape sample of microbial biofilm grown for 14 days
[166] Drying #4.6b purple grape sample of microbial biofilm grown for 14 days

experiment #4.6b purple grape | 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 purple grape and added sucrose. It explores also the potential of natural coloration with the use of pigments which occure 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
- 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 occuring 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.

[166]

[167]

[168]

[169]


[170]


[171]


[172]

[167] Ingredients for #4.7 green grape sample
[168] Front view of #4.7 green grape sample of microbial biofilm grown for 14 days
[169] Front view of #4.7 green grape sample
[170] Top view of #4.7 green grape sample
[171] Close-up of #4.7 green grape sample of microbial biofilm grown for 14 days
[172] Top view of #4.7 green grape sample of microbial biofilm grown for 14 days
[173] Drying #4.7 green grape sample of microbial biofilm grown for 14 days

experiment #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.

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

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

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.


[173]

[174]

[175]

[176]


[177]


[178]

[174] Ingredients for #4.8 pomegranate sample
[175] Front view of #4.8 pomegranate sample of microbial biofilm grown for 14 days
[176] Front view of #4.8 pomegranate sample
[177] Top view of #4.8 pomegranate sample
[178] Close-up of #4.8 pomegranate sample of microbial biofilm grown for 14 days
[179] Top view of #4.8 pomegranate sample of microbial biofilm grown for 14 days
[180] Drying #4.8 pomegranate sample of microbial biofilm grown for 14 days


[179]

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 occure 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

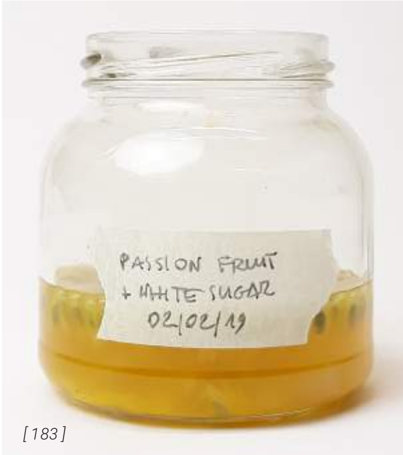
Conclusions

Pigments naturally occuring 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.

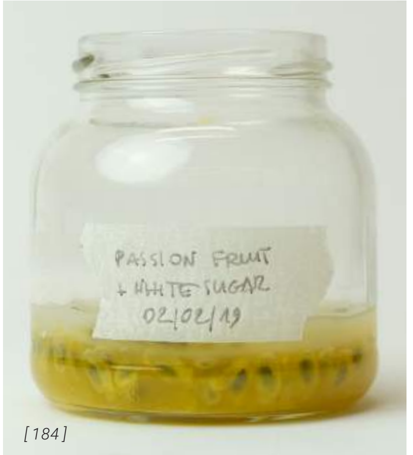

[180]

[181]


[182]



[183]



[184]


[185]


[186]

[181] Ingredients for #4.9 passion fruit sample
[182] Top view of #4.9 passion fruit sample [183] Front view of #4.9 passion fruit sample
[184] Front view of #4.9 passion fruit sample of microbial biofilm grown for 14 days
[185] Top view of #4.9 passion fruit sample of microbial biofilm grown for 14 days
[186] Close-up of #4.9 passion fruit sample of microbial biofilm grown for 14 days
[187] Drying #4.9 passion fruit sample of microbial biofilm grown for 14 days

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
- 10 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.


[187]

[188]


[189]

[190]

[191]


[192]


[193]

[188] Ingredients for #4.10 blueberry sample
[189] Top view of #4.10 blueberry sample
[190] Front view of #4.10 blueberry sample
[191] Front view of #4.10 blueberry sample of microbial biofilm grown for 14 days
[192] Top view of #4.10 blueberry sample of microbial biofilm grown for 14 days
[193] Close-up of #4.10 blueberry sample of microbial biofilm grown for 14 days
[194] Drying #4.10 blueberry sample of microbial biofilm grown for 14 days

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 occure 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

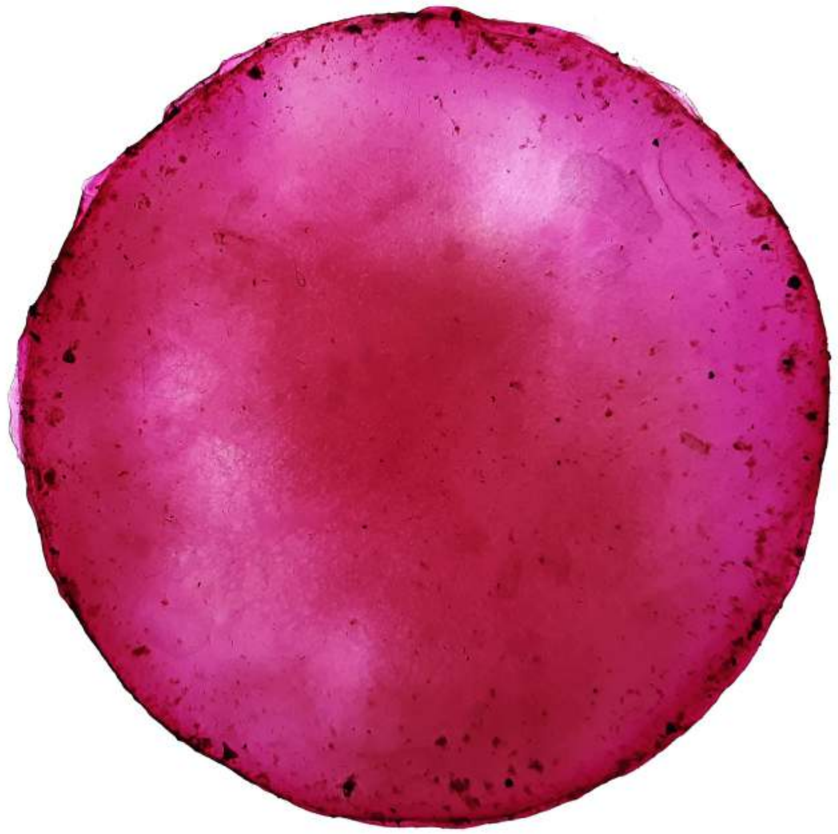
Exceptionally consistent, thick and flexible sample of biofilm, with a strong purple colour and blueberry seeds embedded on the edges, has grown on the surface of cultivation medium.

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

Conclusions

The intense pigments naturally occuring 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.


[194]

[195]


[196]

[197]


[198]


[199]

[195] Ingredients for #4.10 blueberry sample
[196] Front view of #4.10 blueberry sample of microbial biofilm grown for 14 days
[197] Front view of #4.10 blueberry sample
[198] Close-up of #4.10 blueberry sample of microbial biofilm grown for 14 days
[199] Top view of #4.10 blueberry sample of microbial biofilm grown for 14 days
[200] Drying #4.10 blueberry sample of microbial biofilm grown for 14 days

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 occure 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

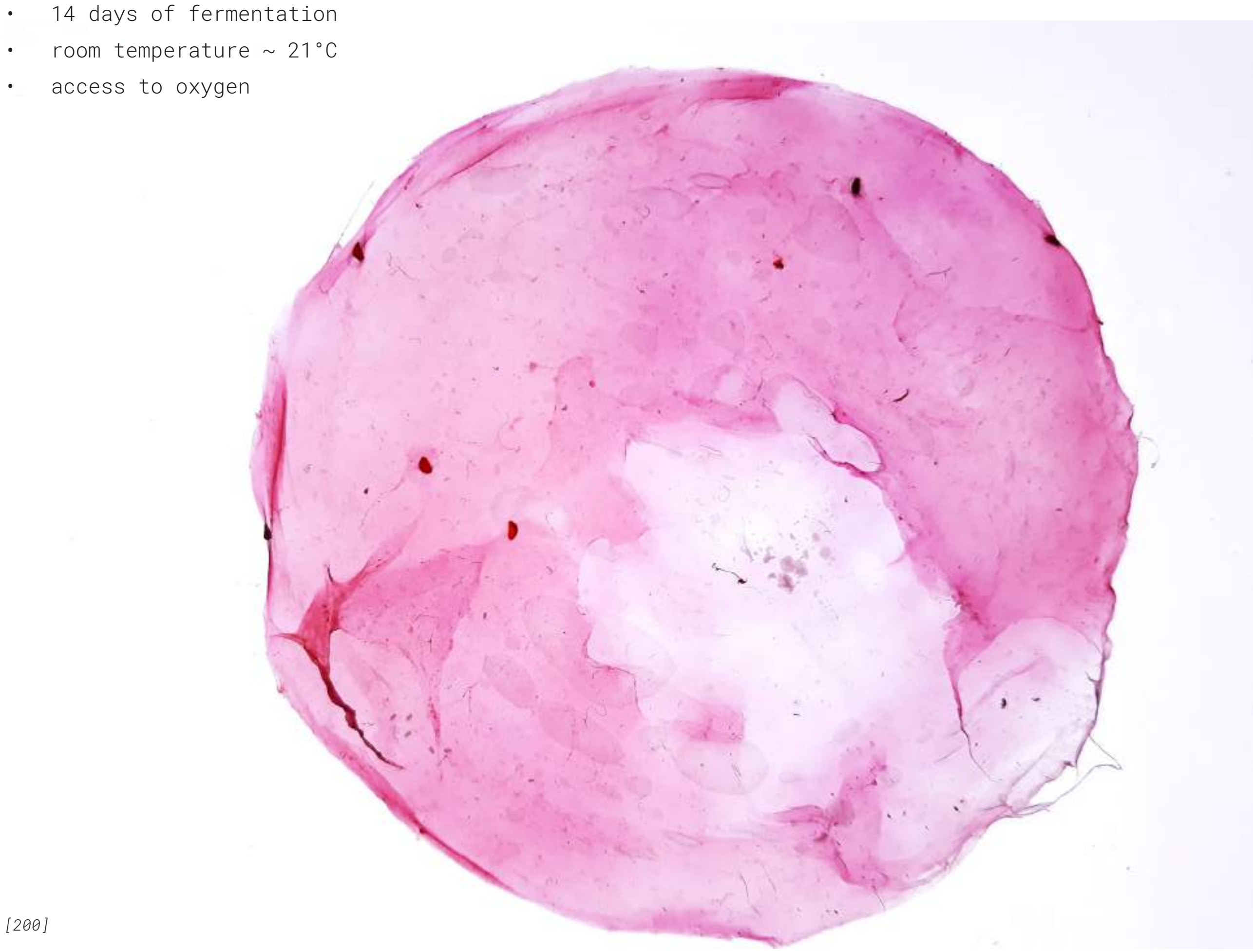
Result

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

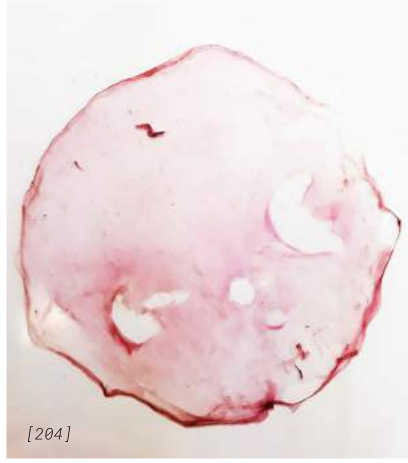
An intense pigments naturally occuring in lingonberries influenced the colour of the grown biofilm. What is more, the process of drying did not influence the coloration level of a biofilm.


[200]

[201]

[202]

[203]



[204]

[205]

[201] Top view of #4.12 blackberry 5 ml sample of biofilm grown for 14 days
[202] Drying #4.12 blackberry 5 ml sample of biofilm grown for 14 days days
[203] Tree samples of #4.12 blackberry experiment
[204] Drying #4.12 blackberry 15 ml sample of biofilm grown for 14 days days
[205] Close-up of #4.12 blackberry 45 ml biofilm grown for 14 days
[206] Top view of #4.12 blackberry 45 ml sample of biofilm grown for 14 days
[207] Drying #4.12 blackberry 45 ml sample of microbial biofilm grown for 14 days

[206]

experiment #4.12 blackberry | 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 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 occure 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 occuring in blackberries influenced the colour of the grown bio-

[207]

[208]

[209]

[210]

[211]

[212]

[208] Ingredients for #4.13 carrot sample
[209] Top view of #4.13 carrot sample
[210] Front view of #4.13 carrot sample of microbial biofilm grown for 14 days
[211] Close-up of #4.13 carrot sample of microbial biofilm grown for 14 days
[212] Top view of #4.13 carrot sample of microbial biofilm grown for 14 days
[213] Drying #4.13 carrot sample of microbial biofilm grown for 14 days

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.

Ingredients

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

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.

[213]

[214]

[214] Ingredients for #4.14 tomato sample
[215] Front view of #4.14 tomato sample of microbial biofilm grown for 14 days
[216] Top view of #4.14 tomato sample
[217] Top view of #4.14 tomato sample of microbial biofilm grown for 14 days
[218] Drying #4.14 tomato sample of microbial biofilm grown for 14 days

[215]

[216]

[217]

experiment #4.14 tomato | 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 tomato and added sucrose. It explores also the potential of natural coloration with the use of pigments which occure 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 ~ 21°C
- 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 occuring in tomatoes did not influence the colour of the grown biofilm.

[218]

[219]

[220]

[221]


[222]

[219] Ingredients for #4.15 beetroot sample
[220] Front view of #4.15 beetroot sample of microbial biofilm grown for 14 days
[221] Front view of #4.15 beetroot sample
[222] Top view of #4.15 beetroot sample
[223] Top view of #4.15 beetroot sample of microbial biofilm grown for 14 days
[224] Drying #4.15 beetroot sample of microbial biofilm grown for 14 days


[223]

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 occure 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

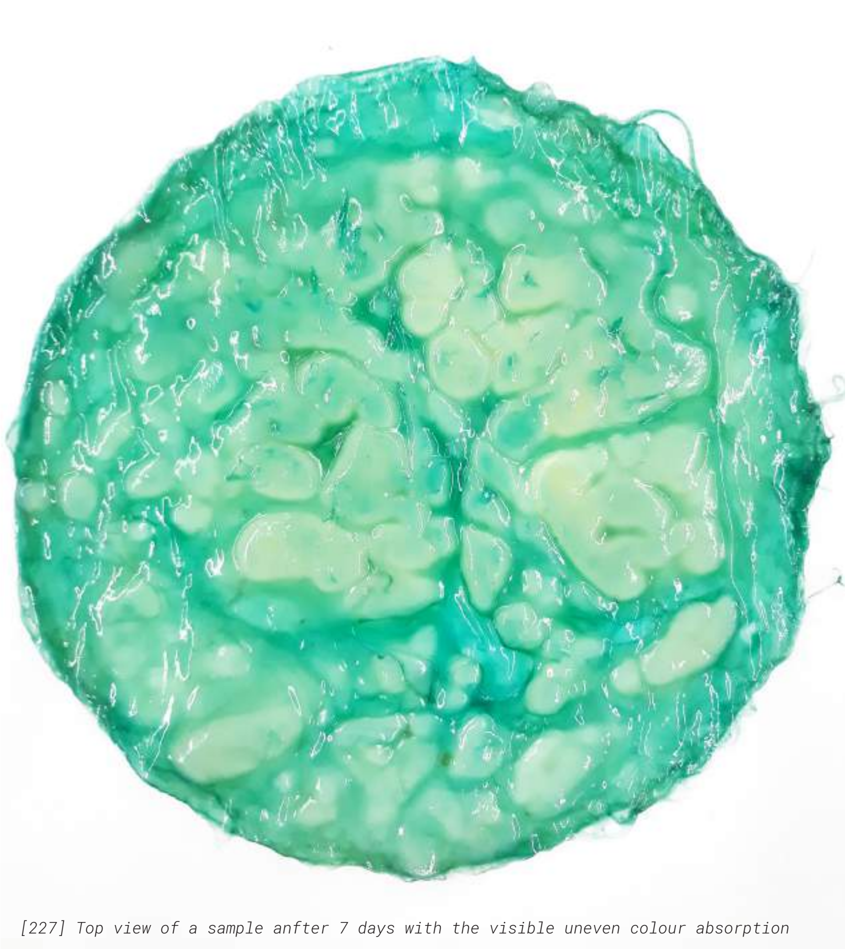
Conclusions

An intense pigments naturally occuring in beetroots influenced the colour of the grown biofilm.


[224]

[225] Color distribution on biofilm

[226] Top view of coloured sample



[227] Top view of a sample anfter 7 days with the visible uneven colour absorption

[228] Close-up of #5.1 micro:brain coloured sample

experiment #5.1 micro:brain | 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 examinated. During the experiment #5.1 sample from experiment #2.2 was used.

Ingredients

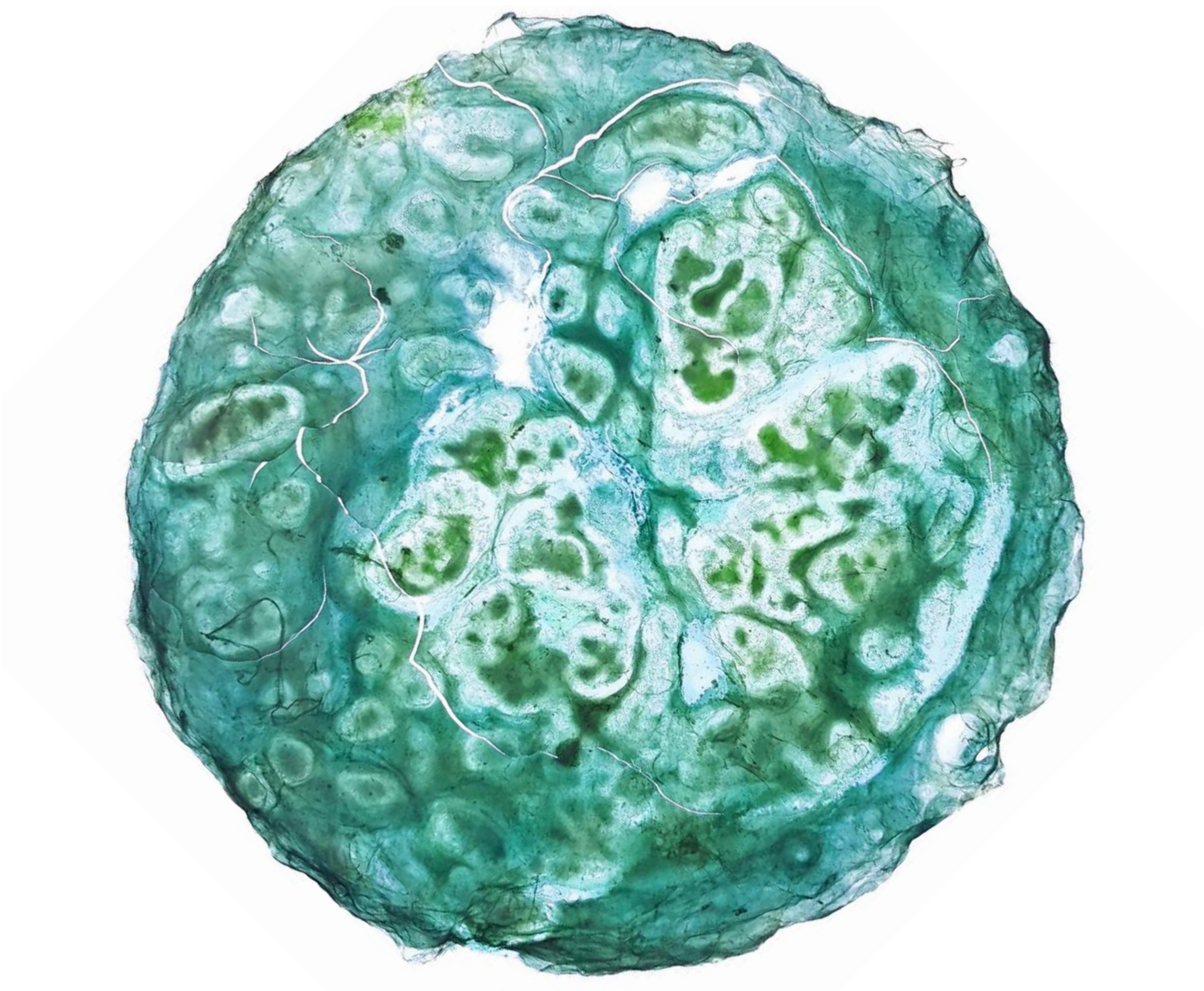
- biofilm sample from experiment #2.2
- few drops of a blue dye

Result

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

Conclusions

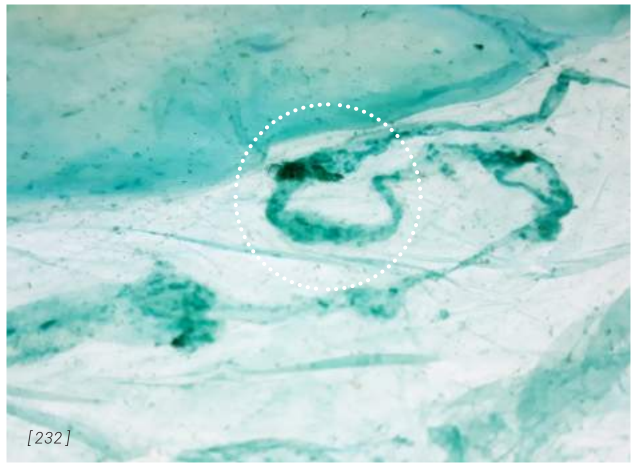
The experiment shows that there is an enormous potential of biofilm coloration with the use of added colours which are absorbed unevenly by different part of microbial cellulose resultng in creation of various patterns, unique for each sample.



[229] Dried sample of microbial biofilm #5.1

[230]

[231]



[232]

[233]

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

Ingredients

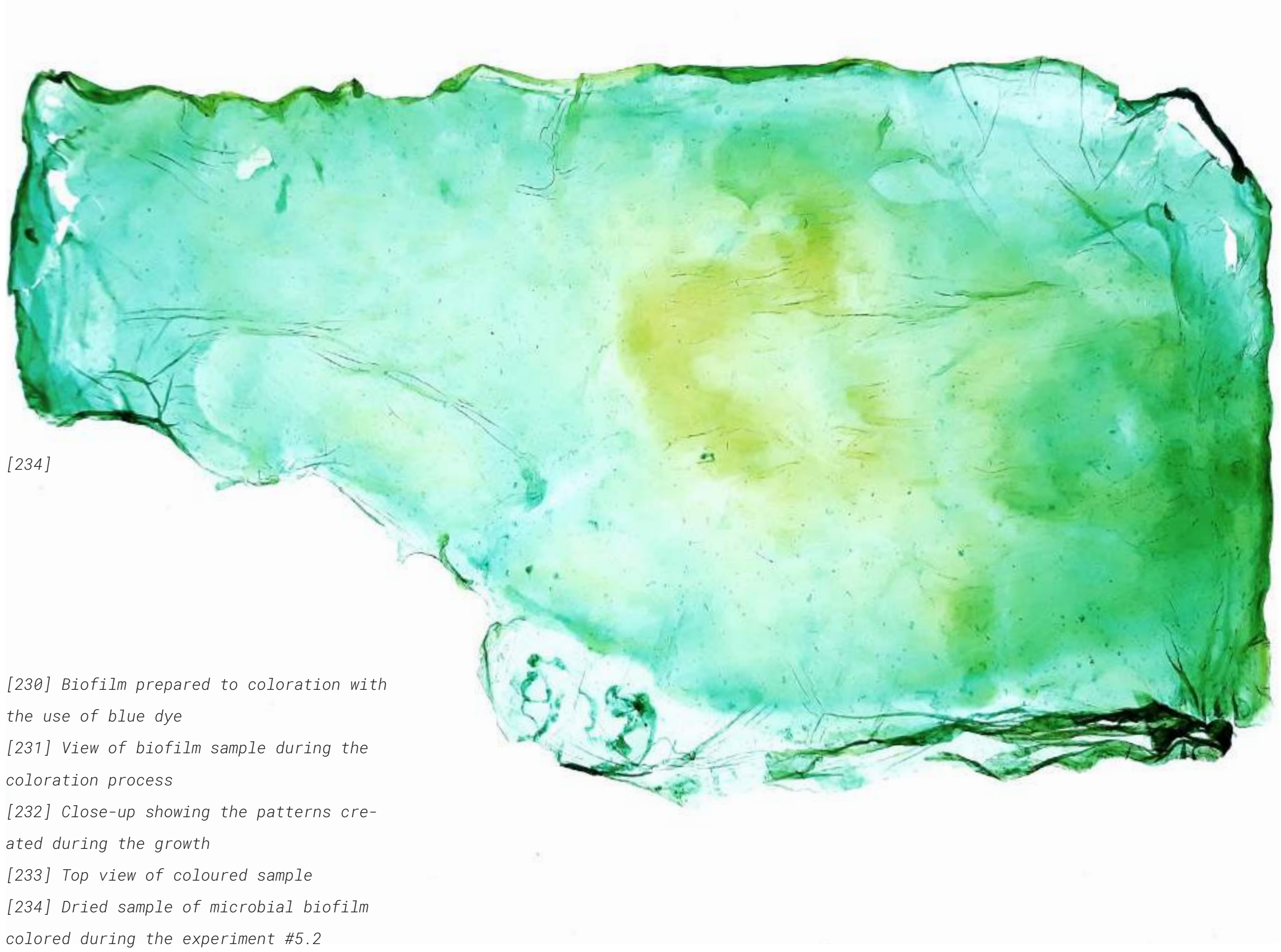
- biofilm sample from series of experiments #1
- few drops of a blue dye

Result

As in the experiment #5.1 color distrubuted on the surface was unevenly absored by the biofilm. Thiner 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 resultng in creation of various patterns, unique for each sample.



[234]

[230] Biofilm prepared to coloration with the use of blue dye
[231] View of biofilm sample during the coloration process
[232] Close-up showing the patterns created during the growth
[233] Top view of coloured sample
[234] Dried sample of microbial biofilm colored during the experiment #5.2

[235]

[236]

[237]

[235] Ingredients for the experiment
[236] Dried sample of microbial cellulose shown in the spatial context
[237] Sample during the coloration
[238] Colored and dried sample of microbial biofilm showing the variety of patterns in one 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 examinated. 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

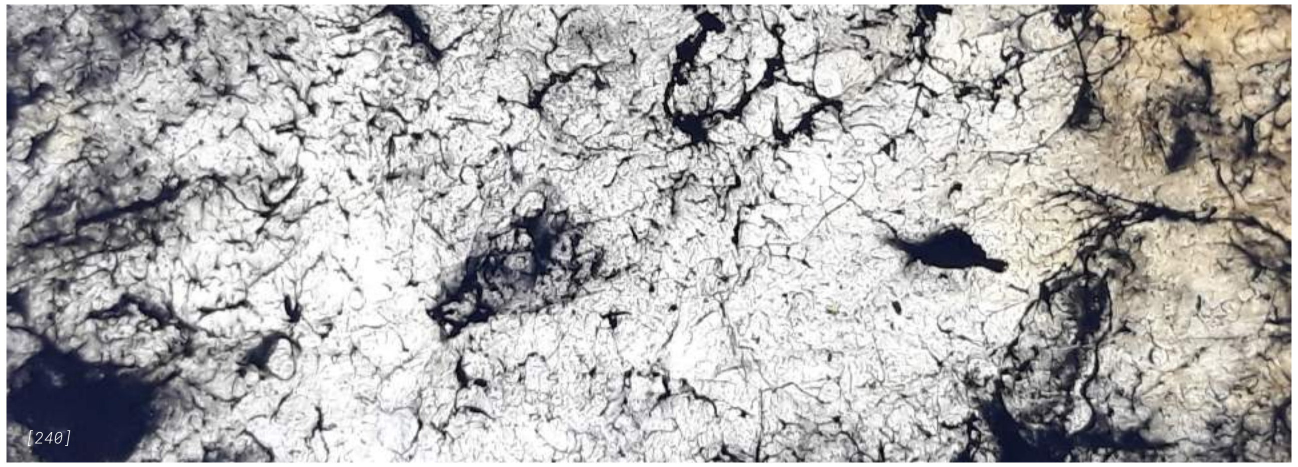
Unlike in the experiment #5.1 and #5.2, the blue dye distrubuted on the surface is evenly absored by the biofilm. What is more, after drying process, sample didn,t change the colour and remained blue.

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 resultng in creation of various patterns, unique for each sample.

[238]

[239]



[240]

[239] Sample during the coloration
[240] Close-up of the colored and dried sample of microbial biofilm showing the variety of patterns in one sample
[241] Top view of coloured sample
[242] Dried samples of microbial biofilm: colored (left) and without coloration (right)

[241]

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 examinated. 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 distrubuted on the surface was unevenly absored by the biofilm - thiner parts absorbed more colour while the thick ones remained less coloured. After the drying process an uneven distrubution 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 part of microbial cellulose resultng in creation of various patterns, unique for each sample.

[242]

[243]

[244]

[243] Ingredients for the experiment
[244] Sample during the coloration
[245] Close-up of colored sample
[246] Colored and dried sample of microbial biofilm

[245]

experiment #5.5 | 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 examinated. 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 distrubuted on the surface was unevenly absored by the biofilm - thiner parts absorbed more colour while the thick ones remained less coloured. After the drying process an uneven distrubution 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 resultng in creation of various patterns, unique for each sample.

[246]

[247]

[248]

[249]

[247] Ingredients for the experiment
[248] Close-up of colored sample of biofilm showing the transition of colour saturation
[249] Top view of #5.6 sample of biofilm
[250] Dried sample of self-healed biofilm showing the transition of colour saturation

experiment #5.6 | coloration
red 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 examinated. During the experiment #5.4 sample from series of experiments #1 was used.

Ingredients

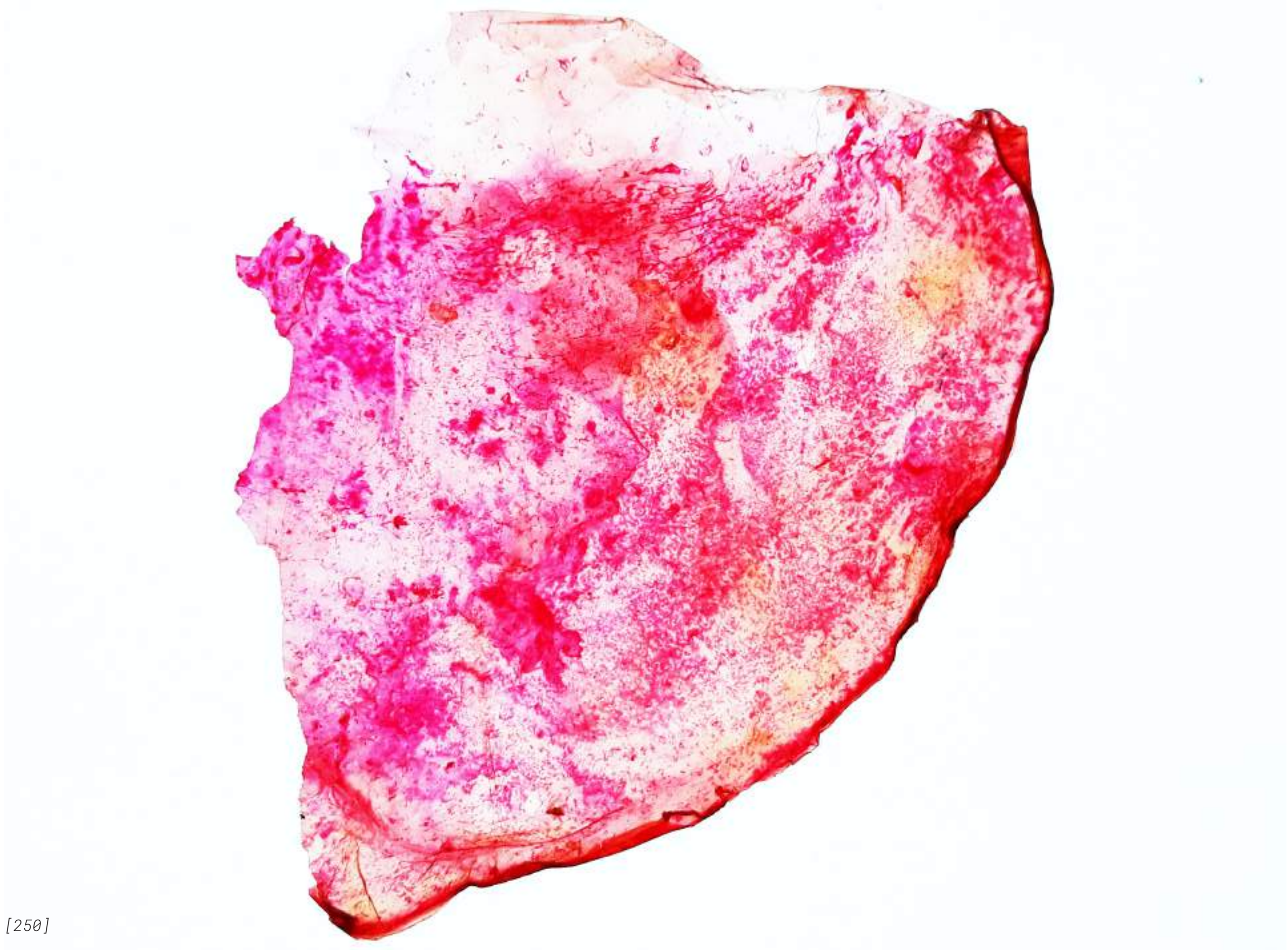
- biofilm sample from series of experiments #1
- few drops of a red dye

Result

The red dye distrubuted on the surface was unevenly absored by the biofilm - thiner parts absorbed more colour while the thick ones remained less coloured. After the drying process an uneven distrubution 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 part of microbial cellulose resultng in creation of various patterns, unique for each sample.



[250]

[251]

[252]

[253]

[251] Cut pieces of microbial cellulose
[252] Biofilm pieces located in the cultivation medium
[253] Close-up of #6.1 sample of self-healed pieces of biofilm
[254] Top view of #6.1 sample of self-healed pieces of biofilm
[255] Dried #6.1 sample of self-healed pieces of biofilm shown with the sunlight in the background indicating the translucency of the material
[256] Dried #6.1 sample of self-healed pieces of biofilm with the visible cutting marks

[254]

experiment #6.1 | self-healing

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 examinated 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.

[255]

[256]

[257] Biofilm pieces located in the cultivation medium

[258] Top view of #6.2 sample of self-healed pieces of biofilm

[259] Close-up of #6.2 sample of self-healed pieces of biofilm which derive from coloration experimetns #5.5 and #5.6

experiment #6.2 flamingo | self-healing

experiments #5.5 + #5.6

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 experimetns #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.

[260] Dried sample #6.2 of self-healed pieces of biofilm showing the potential of self-healing abilities of microbial cellulose

[261] Top view of sample #2 of biofilm cultivated without the access to sunlight

[262] Top view of sample #1 of biofilm cultivated with the access to sunlight

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 examinated 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 grown 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.

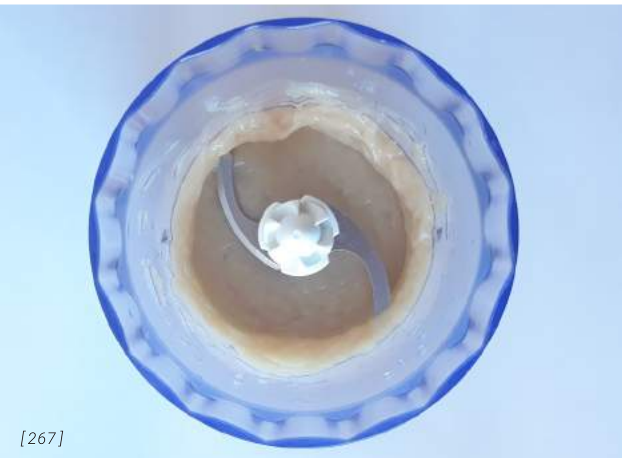
[263] Comparison of two samples #1 (cultivated with the access to sunlight) and #2 (cultivated without the access to sunlight)


[264]


[265]


[267]


[268]


[267]

[264] Sample of microbial cellulose before blending
[265] Blended microbial cellulose in blender
[266] Top view of the sample of microbial cellulose before blending
[267] Top view of mixed microbial cellulose in blender
[268] Mixed microbial cellulose in syringe before extrusion
[269] Unevenly extruded microbial cellulose with the use of syringe

experiment #8.1 | 3D extrusion

3D extrusion

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.

[269]

06| prototyping

“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

[270] Prototyping | Composite of microbial cellulose and other natural fibers shown in the spatial context

list of prototypes

[271] Prototype #4.2 translucency

introduction

Prototyping | Aim

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 build 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 thinkering, 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) examinating 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.

[272]

[273]

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

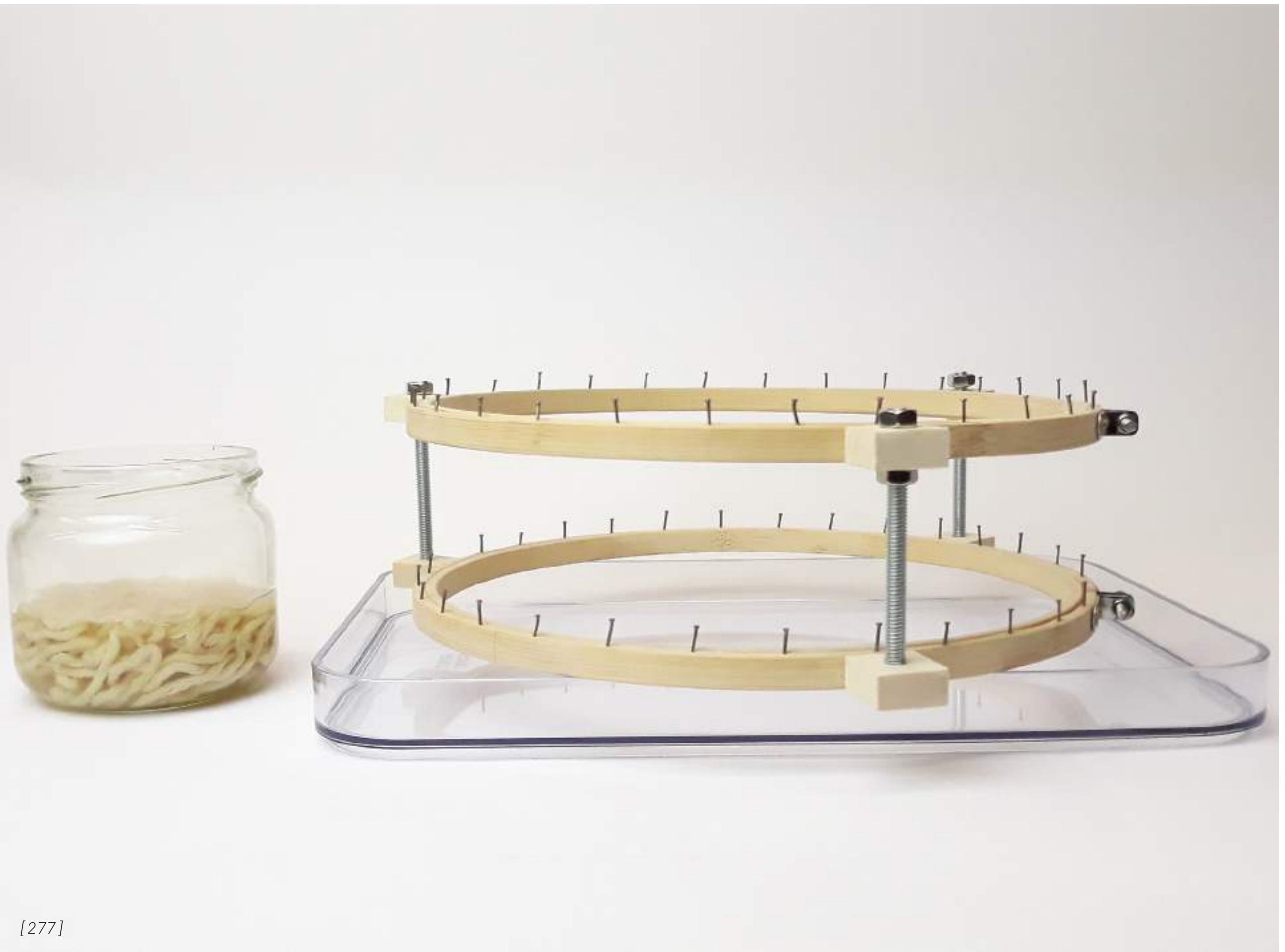
Prototype shows the potential of formation biocomposites of microbial cellulose and other natural fibers which are 100% biodegradable. Therefore, microbial cellulose has a huge advantage over the composites built of the materials which are not biodegradable, i.e carbon fiber composites which cannot be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

[274]

[275]

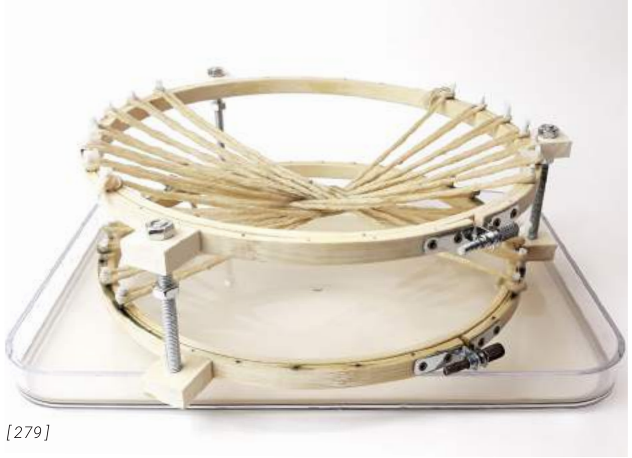
[272] Top view of microbial cellulose growing on the surface of fibers located in the cultivation medium
[273] Front view of microbial cellulose growing on the surface of fibers
[274] Top view of microbial cellulose grown on the surface of fibers
[275] Sample of microbial cellulose grown on the surface of fibers
[276] Dried sample of microbial cellulose grown on the surface of fibers

[276]



[277]

[278]



[279]

[277] Elements prepared for the prototype #1.2
[278] Close-up of fibers woven on the 3D structure
[279] Fibers woven on the 3D structure
[280] Close-up of fibers woven on the 3D structure and a very thinbiofilm layer which started growing on the surface of fibers from the center of structure

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 offibers stiffness.

Conclusions

Prototype #1.2 shows that to acheive 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 examinating the distance of fibers have to be conducted.

[280]

[281]

[282]

[283]

[281] Elements prepared for the prototype #1.3

[282] Top view of different fibers located in the cultivation medium

[283] Close-up of the microbial cellulose growing of the fibers located in the cultivation medium

[284] Dried prototype #1.3 showing microbial cellulose grown on the surface of different fibers

prototype #1.3 | various 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.

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.

[284]

[285]

[286]

[287]

[288]

[285] View of the cotton gauze located in the cultivation medium
[286] Top view of microbial cellulose growing on the surface of cotton gauze
[27] Top view of the sample of biofilm removed from cultivation medium
[288] Close-up of the microbial cellulose grown of the cotton gauze
[289] Dried prototype #1.5 showing microbial cellulose grown on the surface of cotton gauze

prototype #1.4 | cotton gauze

composites of bacterial cellulose + natural fibers

Biocomposites of microbial cellulose

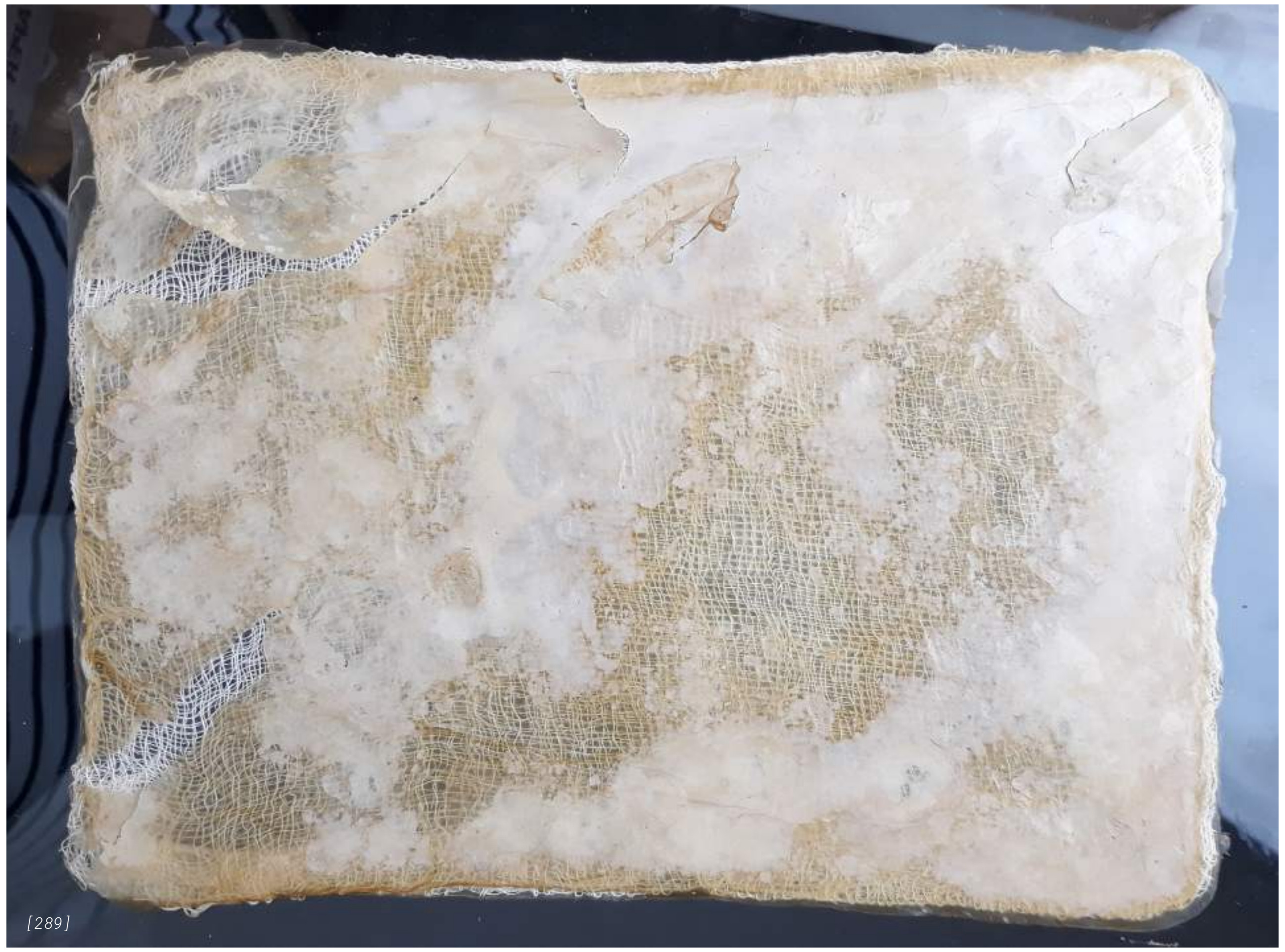
The following prototype investigates the tendency of microbial cellulose to grow on other natural fibers.

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

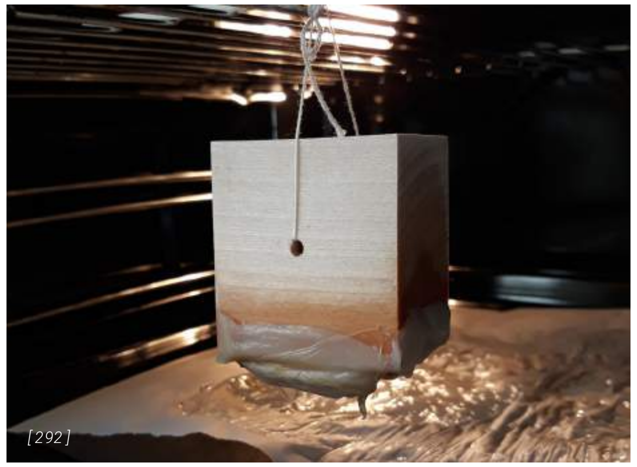
Like the previous prototypes from the series #1, prototype #1.4 shows the potential of formation the biocomposites of microbial cellulose and other natural fibers which are 100% biodegradable. Therefore, microbial cellulose has a huge advantage over the composites built of the materials which are not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



[289]

[290]

[291]



[292]

[290] View of microbial cellulose grown on the surface of wooden cube located in the cultivation medium
[291] Close-up of the microbial cellulose grown of the wooden surface
[292] View of microbial cellulose on wooden cube during the drying process in the oven in the temperature of 70°C
[293] Dried samples of microbial cellulose grown on the wooden surface

prototype #2.1 | growth on wooden scaffolding

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.

[293]

prototype #3.1 | biofilm + wooden molds
3D elements

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.

[294]

prototype #3.2 | biofilm + wooden molds + cotton gauze
3D elements

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.

[295]

[294] Close-up of the microbial cellulose elements after drying process in the oven
[295] Dried composite of microbial cellulose and cotton gauze formed with the use of wooden molds

[296]

[297]

[298]

[296] Close-up of the dried prototype #4.1 showing the spatial qualities of composites of microbial cellulose and other natural fibers
[297] Prototype #4.1 before drying process
[298] Close-up of the dried prototype #4.1 showing the translucency of the composites of microbial cellulose and other natural fibers
[299] Dried prototype #4.1 showing the transition of translucency of microbial cellulose composites

prototype #4.1 | translucency
microbial cellulose + natural fibers

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. Is depicts the hierarchy of fibre structure as well as the transition of levels of translucency achieved within one continuous surface.

[299]


[300]


[301]


[302]


[303]

[300] Top view of dried prototype #4.2
[301] Dried prototype #4.2 showing the transition of translucency of microbial cellulose composites
[302] View of dried prototype #4.2
[303] Close-up of the prototype #4.2 before drying
[304] Close-up of the dried prototype #4.2 showing the translucency of the composites of microbial cellulose and other natural fibers
[305] Distribution of fibers during the preparation of the prototype #4.2

prototype #4.2 | translucency
microbial cellulose + natural fibers

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. In some parts the thicker layer of biofilm creates less translucent skin with pockets of air inbetween, while other parts are almost transparent.


[304]


[305]

[306]

[307]

[308]

[309]

[306] Preparation of molds for the prototype #4.3
[307] Top view of the prototype #4.3 before drying
[308] View of the prototype #4.3 during the drying process in the oven in the temperature of 70°C
[309] Top view of dried parts of the prototype #4.3
[310] Top view of the dried prototype #4.3

prototype #4.3 | translucency
microbial cellulose + natural fibers

Translucency

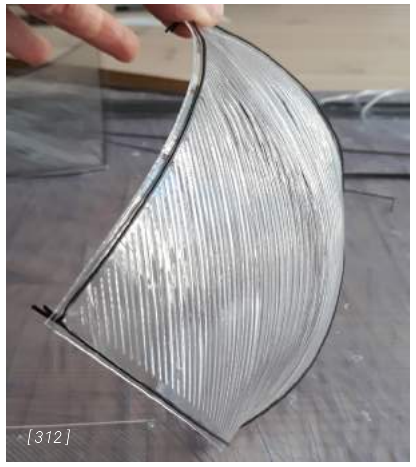
The aim of the prototype was to explore translucency of microbial cellulose - an important biofilm property chosen during the experimentation phase as the one worth further exploration.

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 inbetween the biofilm layers.

[310]


[311]


[312]


[313]


[314]


[315]


[316]


[317]

[311] Laser cut plastic elements formed with the use of wire
[312] Laser cut plastic elements formed with the use of wire
[313] Close-up of the wet latex applied on the plastic elements
[314] Latex applied on the plastic elements
[315] Close-up of the dried latex applied on the plastic elements showing the materiality achieved in the prototype #5.1
[316] Dried element of the prototype #5.1
[317] Dried elements of the prototype #5.1
[318] Dried elements of the prototype #5.1
[319] Dried element of the prototype #5.1
[320] Close-up of the dried latex applied on the plastic elements showing the materiality achieved in the prototype #5.1

prototype #5.1 | latex: material substitute
latex + plastic | elements: cells

Material substitute

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.

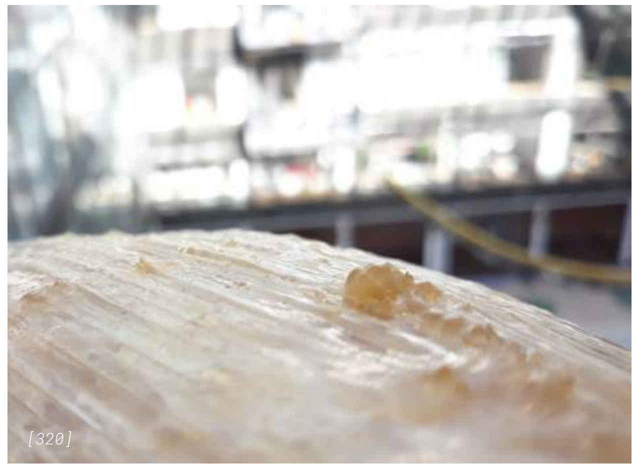
Liquid latex was chosen as an apropriate material which materiality,after drying process, reminds of dry biofilm explored in the project.

Conclusions

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.*


[318]


[319]


[320]

[321]


[322]


[323]

[321] Assembly of the prototype #5.2
[322] Dried elements of the prototype #5.2
[323] Dried element of the prototype #5.2 showing the translucency of material
[324] Prototype #5.2 showing the system consisiting of the elements - cells - and transparent tubes

prototype #5.2 | latex: material substitute
latex + plastic | system of cells

Material substitute

The aim of the prototype was the continuation of the development of system applied through a large-scale application.

Conclusions

Prototype #5.2 led directly to conducting the experiments #3 examinating 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.


[324]

[325]

[326]

[325] Preparation for the prototype #5.3
[326] Dried sample of latex applied on the fibers
[327] Close-up of the sample showing the materiality achieved during the prototyping phase #5.3
[328] Samples of the prototype #5.3 showing the the appearance of wet and dried latex applied on natural fibers
[329] Close-up of the highlighted sample showing the materiality achieved during the prototyping phase #5.3
[330] Close-up of the sample showing the materiality achieved during the prototyping phase #5.3
[331] Close-up of the highlighted sample showing the materiality achieved during the prototyping phase #5.3
[332] Close-up of the highlighted sample showing spatial qualities of the prototype #5.3

[327]

[328]

[329]

prototype #5.3 | latex: material substitute
latex + plastic + fibers | system of cells

Material substitute

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

Conclusions

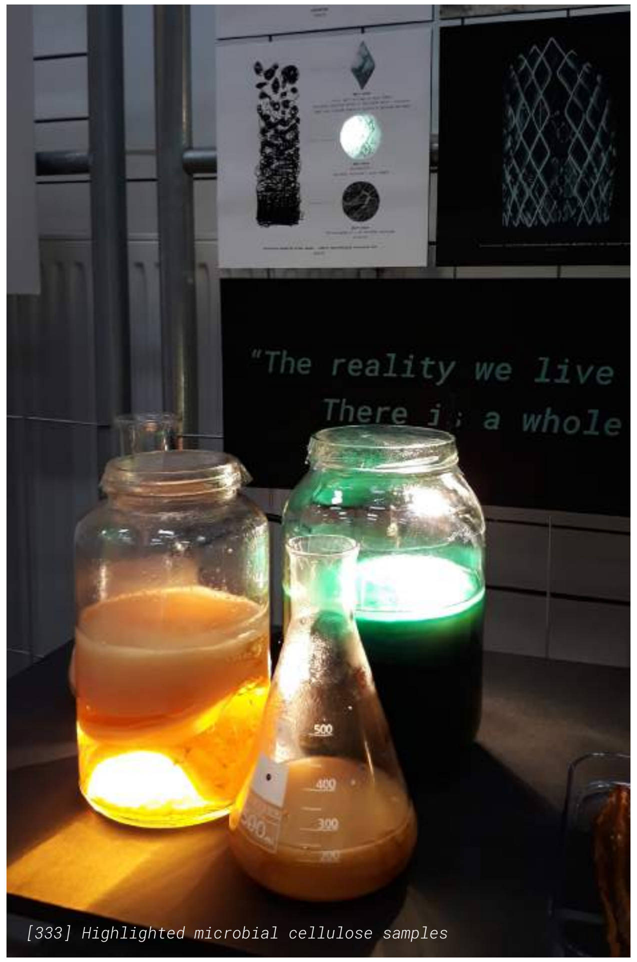
Prototype #5.3 led directly to finalization of the *system* of woven elements (cells) with agar layer applied on the top.

[330]

[331]

[332]

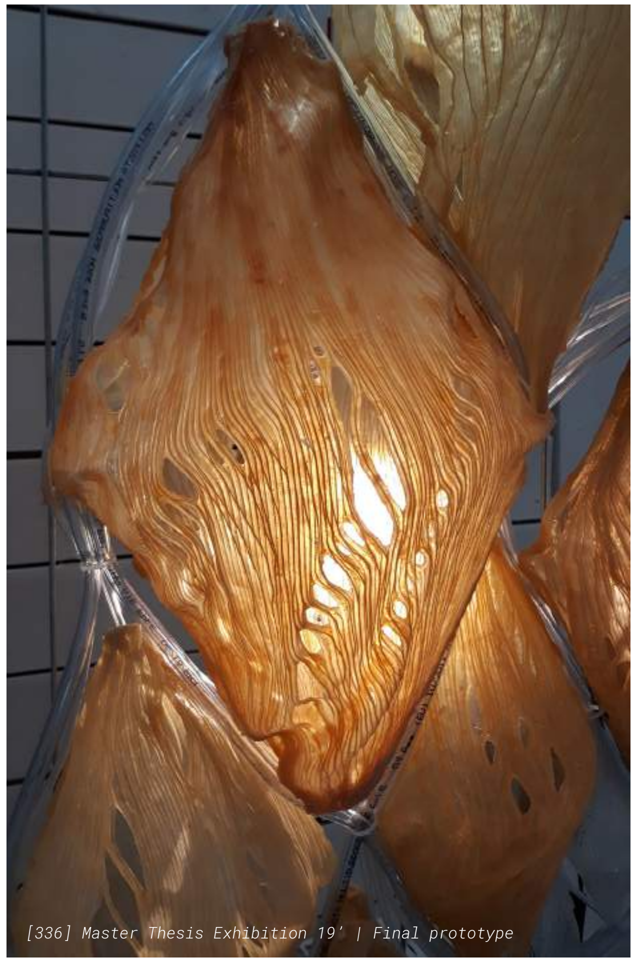
07| appendix



[333] Highlighted microbial cellulose samples

[334] Master Thesis Exhibition 19'

[335] Master Thesis Exhibition 19' / Growing Microbial Cellulose

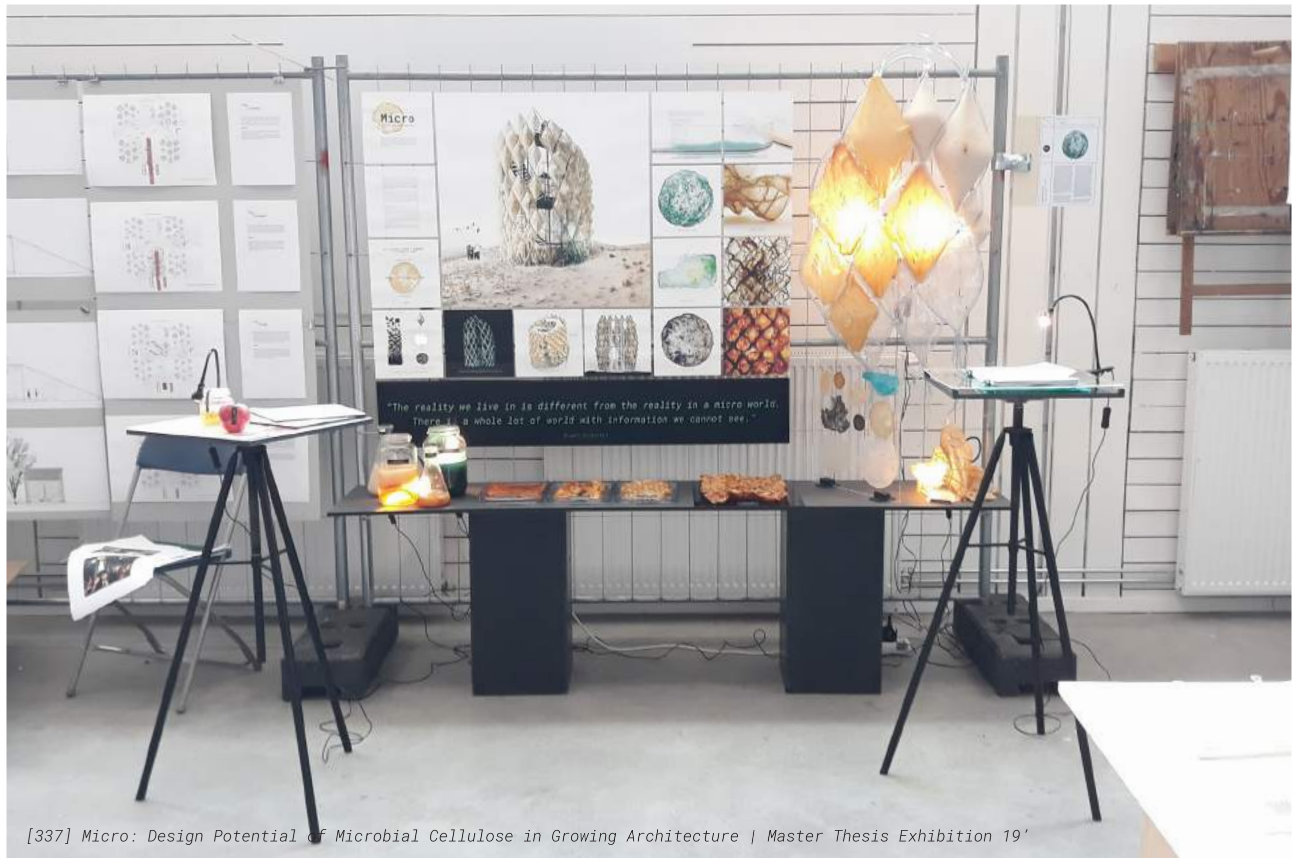


[336] Master Thesis Exhibition 19' | Final prototype

Master's Thesis Exhibition 19'

"One of the great beauties of architecture is that each time, it is like life starting all over again."

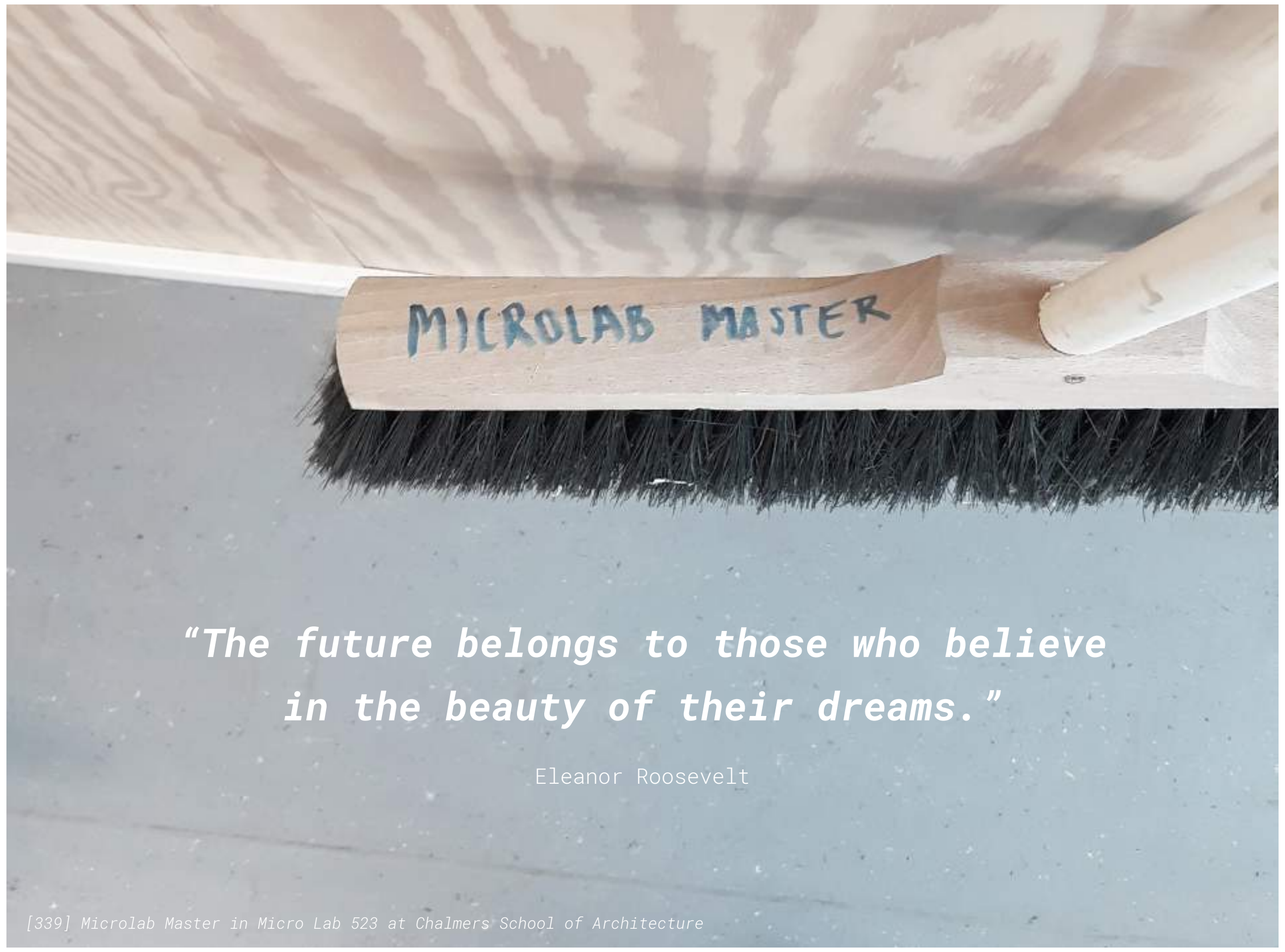
Renzo Piano



[337] Micro: Design Potential of Microbial Cellulose in Growing Architecture | Master Thesis Exhibition 19'

[The Master's Thesis Open Seminars and Exhibition took place at Chalmers School of Architecture during the days 03-05 of June 2019.]

[338] Micro Lab 523 at Chalmers School of Architecture



[339] Microlab Master in Micro Lab 523 at Chalmers School of Architecture

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
- Kjellgren Kaminsky | Göteborg, Sweden | 2018
- JSK Architects | Wroclaw, Poland | 2016 - 2017
- Atelier Starzak Strebicki | Poznan, Poland | 2014
- Office of Innovations in Architecture, Technology and Art at Department of Architecture | Wroclaw University of Technology | Wroclaw, Poland | 2013

Contact

Karolina Bloch
karolinabloch92@gmail.com
+48 505876022

bibliography

Literature

Camere, S., Karana, E. (2018). Fabricating materials from living organisms: an emerging design practice. Journal of Cleaner Production. Retrieved from https://www.sciencedirect.com/science/article/pii/S0959652618307388?via%3Dihub

Derme T., Mitterberger D., Di Tanna U. (2016). Growth-based fabrication techniques for bacterial cellulose: Three-dimensional grown membranes and scaffolding design for biological polymers , Proceedings of ACADIA 2016, Ann Arbor, MI, p 488-495

Gama, M., Gatenholm, P., Klemm, D. (2013). Bacterial NanoCellulose. Boca Raton: CRC Press, https://doi-org.proxy.lib.chalmers.se/10.1201/b12936

Glieder, A., Kubicek, C. P., Mattanovich, D., Wiltschi, B., & Sauer, M. (2016). Synthetic Biology. [electronic resource]. Cham : Springer International Publishing : Imprint: Springer, 2016. Retrieved from http://proxy.lib.chalmers.se/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat06296a&AN=clc.b2212453&site=eds-live&scope=site

Gruber, P. (2011). Biomimetics in architecture : architecture of life and buildings. Springer Verlag. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=cat06296a&AN=clc.b1474556&site=eds-live&scope=site

Kretzer, M. (Ed.) & Hovestadt, L. (Ed.) (2014). ALIVE. Advancements in adaptive architecture. Berlin, Basel: Birkhäuser. Retrieved 15 March 2019, from https://www-degruyter-com.proxy.lib.chalmers.se/view/product/429987

Kushner, M. (2015). The Future of Architecture in 100 Buildings. Simon & Schuster/ TED; Later prt. edition March 10, 2015.

National Research Council. (2009). A New Biology for the 21st Century. Washington, DC: The National Academies Press. https://doi.org/10.17226/12764.

Oxman, N., Laucks, J., Kayser, M., Uribe, C. D. G., Duro-Royo, J. (2013). Editorial: eCAADe (Education and research in Computer Aided Architectural Design in Europe). Retrieved from http://neri.media.mit.edu/assets/pdf/278.pdf

Oxman, N., Duro-Royo, J., Mogas-Soldevila, L. (2014). 3D Printing and Additive Manufacturing. Published in Volume: 1 Issue 3: September 19, 2014 Retrieved from :http://doi.org/10.1089/3dp.2014.0014

Oxman, N., Ortiz, C., Gramazio, F., & Kohler, M. (2015). Editorial: Material ecology. Computer-Aided Design, 60, 1–2. https://doi.org/10.1016/j.cad.2014.05.009

Solanki, S. (2018). Why Materials Matter: Responsible Design for a Better World. England: Prestel Publishing.

Venter, C. and Cohen, D. (2004). The Century of Biology. New Perspectives Quarterly, 21: 73-77. doi.org/10.1111/j.1540-5842.2004.00701.x

Talks

TED lecture. (2015) Neri Oxman. Design at the intersection of technology and biology. Retrieved from www.ted.com/talks/neri_oxman_design_at_the_intersection_of_technology_and_biology/discussion?utm_(2018-11-05)

Reference projects

Aquahoja: Programmable Water-Based Biocomposites for Digital Design and Fabrication across Scales | Mediated Matter research group at the MIT Media Lab | 2018

Microbial Cellulose [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

Silk Pavilion | Mediated Matter research group at the MIT Media Lab | 2013

Vibrant Tissue: Augmented Microbial Cellulose | MAA 02 | Master in Advanced Architecture | DvPS: Development Project Studio | The Institute for Advanced Architecture of Catalonia | IAAC | Catalina Puello | tutor: Marcos Cruz | 2018

Xylinum Cones | Jannis Hülsen, Stefan Schwabe | 2013

Xylinum Stool | Jannis Hülsen | 2011

Images

Unless otherwise indicated, images and diagrams are made by the author.

[01] Keating, S. (2013). Silk Pavilion | MIT Media Lab. Retrieved from: https://www.archdaily.com/384271/silk-pavilion-mit-media-lab (19-04-10)

[02] Kayser, M. (2013). Primary structure | MIT Media Lab. Retrieved from: https://www.archdaily.com/384271/silk-pavilion-mit-media-lab (19-04-10)

[03] Keating, S. (2013). Biological printer - Silkworm | MIT Media Lab. Retrieved from: https://www.archdaily.com/384271/silk-pavilion-mit-media-lab (19-04-10)

[04] Keating, S. (2013). Silk Pavilion | MIT Media Lab. Retrieved from: https://www.archdaily.com/384271/silk-pavilion-mit-media-lab (19-04-10)

[05] MIT Media Lab (2018). Aquahoja. Retrieved from: https://www.archdaily.com/894979/neri-oxman-and-mit-develop-programmable-biocomposites-for-digital-fabrication (19-05-01)

[06] MIT Media Lab (2018). Aquahoja research prioject. Retrieved from: https://www.archdaily.com/894979/neri-oxman-and-mit-develop-programmable-biocomposites-for-digital-fabrication (19-05-01)

[07] MIT Media Lab (2018). Aquahoja research prioject. Retrieved from: https://www.archdaily.com/894979/neri-oxman-and-mit-develop-programmable-biocomposites-for-digital-fabrication (19-05-01)

[08] MIT Media Lab (2018). Artifacts. Retrieved from: https://www.archdaily.com/894979/neri-oxman-and-mit-develop-programmable-biocomposites-for-digital-fabrication (19-05-01)

[09] Hülsen, J. (2011). Close-up of a chair prototype | Microbial cellulose grown on a wooden scaffolding. Retrieved from: http://jannishuelsen.com/?/work/xyliumstool (18-10-10)

[10] Hülsen, J. (2011). Chair prototype | Microbial cellulose grown on a wooden scaffolding. Retrieved from: http://jannishuelsen.com/?/work/xyliumstool (18-10-10)

[11] Hülsen, J. (2011). Diagram of microbial cellulose bio-manufacturing. Retrieved from: http://jannishuelsen.com/?/work/xyliumstool (18-10-10)

[12] Hülsen, J. (2011). Microbial cellulose bio-manufacturing. Retrieved from: http://jannishuelsen.com/?/work/xyliumstool (18-10-10)

[13] Hülsen, J., Schwabe S. (2013). Dried microbial cellulose element. Retrieved from: http://www.jannishuelsen.com/?/work/Xylinumcones (18-10-10)

[14] Hülsen, J., Schwabe S. (2013). Assembly of the dried microbial cellulose elements. Retrieved from: http://www.jannishuelsen.com/?/work/Xylinumcones (18-10-10)

[15] Hülsen, J., Schwabe S. (2013). Microbial cellulose growth in molds. Retrieved from: http://www.jannishuelsen.com/?/work/Xylinumcones (18-10-10)

bibliography

[16] ecoLogicStudio (2016). Three-dimensional prototype made of microbial cellulose. Retrieved from: http://www.ecologicstudio.com/v2/lab/project.php?idcat=53&idsubcat=71&idproj=171 (18-10-15)

[17] ecoLogicStudio (2016). Experimentation exploring the growth of microbial cellulose. Retrieved from: http://www.ecologicstudio.com/v2/lab/project.php?idcat=53&idsubcat=71&idproj=171 (18-10-15)

[18] ecoLogicStudio (2016). Microbial cellulose samples produced with the use of various fruits and vegetables. Retrieved from: http://www.ecologicstudio.com/v2/lab/project.php?idcat=53&idsubcat=71&idproj=171 (18-10-15)

[19] Puello, C. (2018). Fabrication of prototype with the use of robotic arm. Retrieved from: http://www.iaacblog.com/projects/vibrant-tissue_-augmented-microbial-cellulose-2/ (19-01-05)

[20] Puello, C. (2018). Prototype of a chair. Retrieved from: http://www.iaacblog.com/projects/vibrant-tissue_-augmented-microbial-cellulose-2/ (19-01-05)

[21] Puello, C. (2018). Samples of microbial cellulose. Retrieved from: http://www.iaacblog.com/projects/vibrant-tissue_-augmented-microbial-cellulose-2/ (19-01-05)

[22] Puello, C. (2018). Microbial cellulose growth with the use of various fruits. Retrieved from: http://www.iaacblog.com/projects/vibrant-tissue_-augmented-microbial-cellulose-2/ (19-01-05)

[26] Zienkiewicz, M. (2016). Scanning electron microscope image of bacteria Acetobacter xylinum. Retrieved from https://seedworld.com/push-harness-helpful-microbes (19-02-04)

[27] The Morgellons Research Foundation (2017). SEM micrograph of the wet structure of microbial cellulose. Retrieved from http://enacademic.com/dic.nsf/enwiki/1081507 (19-02-04)

[29] Bee Breeders Architecture Competition Organisers (2018). Existing observatory place. Retrieved from https://flamingotower.beebreeders.com/ (19-03-17)

[30] Bee Breeders Architecture Competition Organisers (2018). Al Wathba Wetland Reserve in Abu Dhabi. Retrieved from https://flamingotower.beebreeders.com/ (19-03-17)