After failing in this direction of the research (creating inflatable structures for algae cultivation) I went a few steps back and started looking into different types of microalgae existing in nature. And it turned out that there are 7 kinds of algae according to their habitat, and Hydrophilus (aquatic) algae is just one of them. My attention was caught by Edaphic (terrestrial) and Aerial algae which obtain very similar properties in terms of photosynthesis comparing to aquatic algae, but do not need constant flow of water - although a certain humidity level must be maintained in order to stay alive. Another interesting feature of these forms of algae is that when environmental conditions are adverse, algae go into a form of hibernation until conditions are once again favorable.

So the decision was taken to 3D print algae medium (natural biodegradable hydrogel) with an embedded culture, using a robotic arm fitted with a pump extruder. There were no precedents in the field of architecture on such kind of work, but luckily 2 weeks before I changed the direction of my project a scientific paper on green bioprinting was published in the Engineering in Life Sciences journal. In this article it is said how researchers at the Institute of Food Technology and Bioprocess Engineering, Technische Universität Dresden, in Dresden, Germany have teamed with the Centre for Translational Bone, Joint and Soft Tissue Research, at the University Hospital and Faculty of Medicine of Technische Universität Dresden to do just that — 3D print algae-laden hydrogel scaffolds for possible medical applications and uses with 3D printed human tissue. In this research scientists managed to prove that it was possible to 3D print growing, living microalgae.

"The application of RP [rapid prototyping] methods for encapsulation of microalgae can be expected to open new and interesting possibilities for diverse applications,"[1]

So far, this is the only one known example of 3d printing algae and it was done for biotechnological and medical applications, when in my thesis I wanted to bring it to a larger scale, proving that this technology has the potential not only in medical field, but also in the field of architecture.

My research is based on a deductive scientific methodology, since it implies obtainment of general rules out of particular tests. Also there were no precedents in architectural field on 3d printing algae based gels, so I had to prove this statement.

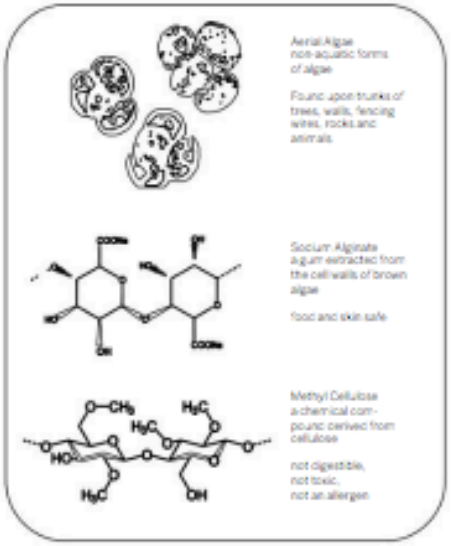
1 - Green bioprinting: Fabrication of photosynthetic algae-laden hydrogel scaffolds for biotechnological and medical applications (2015) – Engineering in Life Sciences, Eng. Life Sci. 2015, 15, 177–183

Research problem
Bio-inspiration highlights a sensitive observation of biological processes and their transfer into novel design methodologies for the creation of innovative architectural explorations. And in my thesis I would like to propose a bio solution to architectural problems, such as air purification, shading, and aesthetics.

Research question
Exploration of designing with a living material by means of new digital fabrication techniques.
My research begins with the question of how to design with a biomaterial that lives, grows and dies. The first steps for this research have precedents, especially the exploration of algae's potential use within the realm of architecture. But so far all the examples of realized projects, while not many, are very complex systems including a rigorous amount of technical detail. For my project, I would like to explore the possibilities of creating living systems by means of novel fabrication techniques (additive manufacturing and robotics) that allow to produce biodegradable objects combining natural hydrogels and microalgae.

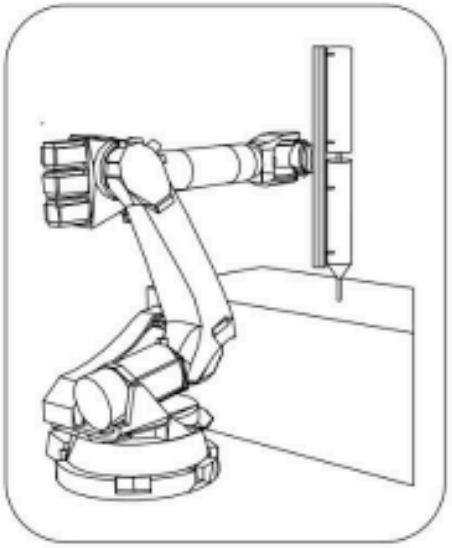
Hypothesis
With the emergence of 3d printing technology (additive manufacturing) and computation currently aiding design and architecture, combining these technologies with bio solutions such as algae and hydrogel could simplify the process of manufacturing artificial ecosystems that could be used as efficient CO2 capture systems, as well as biophotovoltaic systems for green energy generation.

Objectives
When work is done in a lab, perfect conditions are created for a living matter to thrive and grow, but when it comes to a scale of architecture those rules do not apply, because you simply cannot control all the conditions such as temperature, humidity and light intensity. The challenge faced was the practicality of living structures that I was going to create.
In my research I wanted to investigate
- Living matter as a design material - combination of empirical and practical design approaches.
- Durability and life span of printed structures
- Their response to existing conditions (such as temperature, humidity, etc)
- Environmental conditions that allow systems to grow
- To understand the limits of printing with alge based gels – how tall can the structure be, how complex, time of printing and complexity of fabrication
- Materiability that is not based on the "sandwich", but with the embedded variety of functions (natural intelligence).



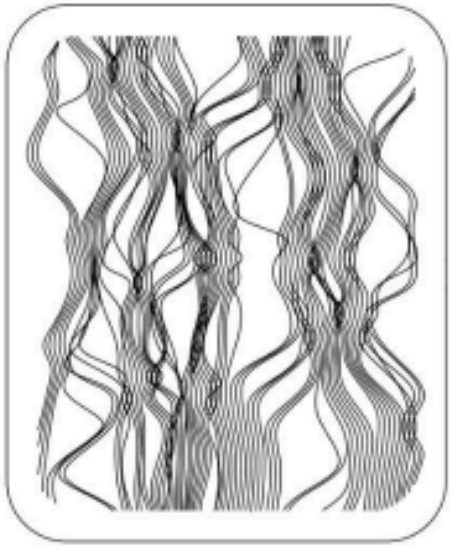
ALGAE BASED PASTE

Consists of 3 components:
- Methyl Cellulose (powder hydrogel)
- Sodium Alginate (gelling agent)
- Aerial algae (don't require constant water flow, hibernate when not exposed to a certain humidity level)



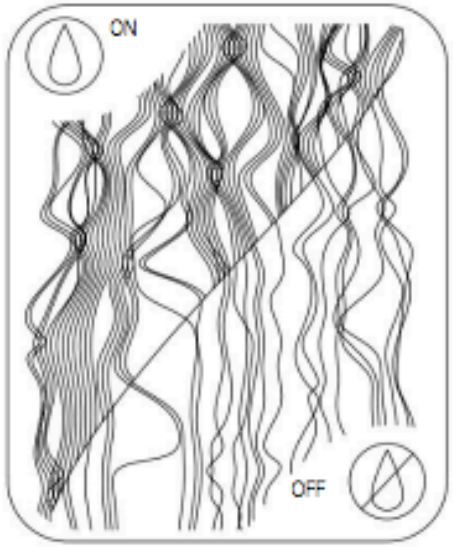
ROBOTIC FABRICATION

3D printing of algae based gel using a pneumatic extruder attached to a robotic arm



PATTERN

Generating different types of patterns regarding opacity of the screen, deformation of the material (shrinking), size of the final piece, etc. Taking into consideration humidity levels and sun exposure



CONTROL

Environmentally controlled system that can be switched on/off simply by exposure to water/sun.

METHODS AND MATERIALS// ALGAE

Algae (singular alga) are a large and diverse group of photosynthetic, eukaryotic, plant-like organisms that use chlorophyll in capturing light energy, but lack characteristic plant structures such as leaves, roots, flowers, vascular tissue, and seeds.[1] Algae range from single-celled organisms to multi-cellular organisms. In my thesis I will focuse of the application of micro-algae in architecture.

Microalgae - are microscopic algae, typically found in freshwater and marine systems [2]. They are unicellular species which exist individually, or in chains or groups. Depending on the species, their sizes can range from a few micrometers (µm) to a few hundreds of micrometers.

Today microalgae are of great interest in the fields of biotechnology and architecture: they belong to one of the most promising sources of alternative energy because they convert sunlight into biomass more efficiently than higher plants.
This phenomena can be explained by the fact that they are unicellular organisms and each single cell is involved in the process of photosynthesis.
Simultaneously algae use the greenhouse gas carbon dioxide (CO_2) to grow photoautotrophically (using light as the energy source in the synthesis of food from inorganic matter). It is believed that micro algae produce approximately **half of the atmospheric oxygen**.

REACTION OF PHOTOSYNTHESIS

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

Moreover, algae are helpful in reducing pollutants, since they live on a high concentration of **carbon dioxide, nitrogen dioxide and sulfur dioxide**, released by automobiles, cement plants, breweries, fertilizer plants, steel plants, etc. These pollutants serve as nutrients for the algae, thus making this biomaterial very attractive for purposes of air purification and biofiltration (the removal of nutrients, heavy metals, and industrial pollutants from wastewater) [3].

1 - New World Encyclopedia, http://www.newworldencyclopedia.org/entry/Algae
2 - Thurman, H. V. (1997). Introductory Oceanography. New Jersey, USA
3 - Microalgae As Sources of High Added-Value Compounds, BIOTECHNOLOGY PROGRESS 27(3):597-613 - MAY 2011

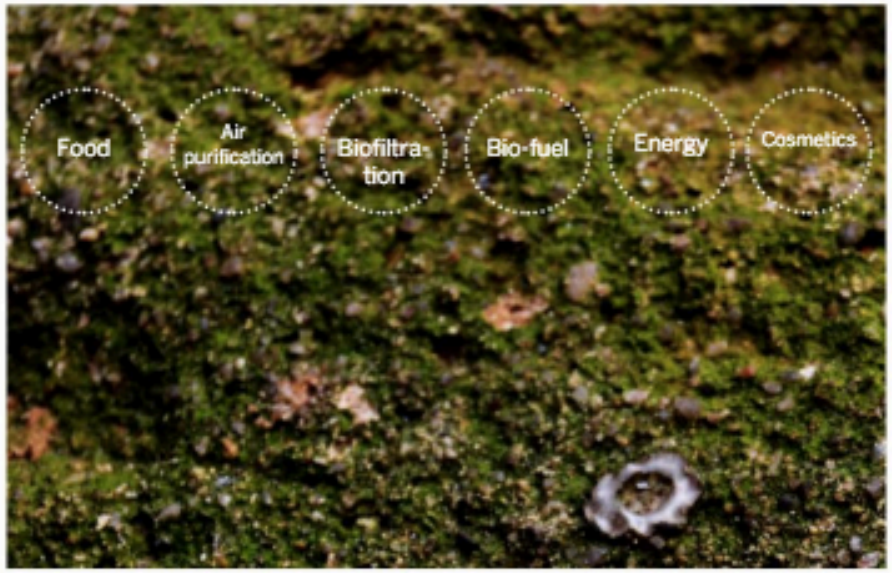
ALGAE CHALLENGES

After overviewing the previous experience of algae projects in architecture, it becomes clear that all of them are using aquitic forms of microalgae that are usually contained in systems of tubes, plastic bags, or panels (so-called bioreactors). Technologically bioreactors are highly complicated systems based on usage of aquatic algae, including water and air pumps, integrated systems of CO_2 supply, nutrient feeding systems, etc., which makes their manufacturing and maintanance a very challenging task . That's why all these systems that seem to be innovative and have an intelligent and progressive technology behind them are really difficult to realize on a big scale.

During the first two months of my thesis I worked with aquatic algae trying to create an algae curtain (membrane) that would be a delicate, flexible, and aesthetically pleasing version of a bioreactor, but I faced a variety of problems during its fabrication. The problems that I faced included welding plastic sheets in a precise way since I needed to create inflatables with complex patterns, leaking water, and air and water pumps having the capacity to maintain the system at a larger scale.

After failing in this direction of the research I went a few steps back and started looking into different types of microalgae existing in nature. And it turned that there are 7 kinds of algae according to their habitat, and Hydrophilus (aquatic) algae is just one of them. My attention was caught by Edaphic (terrestrial) and Aerial algae which obtain very similar properties in terms of photosynthesis comparing to aquatic algae, but do not need constant flow of water - although a certain humidity level must be maintained - in order to stay alive. Another interesting feature of these forms of algae is that when environmental conditions are adverse, algae go into a form of hibernation until conditions are once again favorable.

So the decision was taken to 3D print algae medium with an embedded culture, using a robotic arm fitted with a pump extruder.



ACCORDING TO THEIR HABITAT ALGAE ARE CLASSIFIED INTO SEVEN GROUPS:

1. Hydrophilus algae:
These are aquatic, free floating or completely submerged algae.

2. **Edaphic algae**:
Terestial algae are called Edaphic algae. They live upon or inside the surface of earth. Edaphic algae are classified into two types,
- Saprophytes E.g. Mesotaemium, Botryduium
- Crypyophytes E.g. Nostoc, Anabaena

3. **Aerial algae**:
These are aerial forms of algae. They are found upon trunks of trees, walls, fencing wire, rocks and animals. Aerial algae are classified into four types. They are,
- Epiphyllophytes E.g. Trentepohlia
- Epiphloephytes
- Epizoophytes E.g. Chaetophorales
- Lithophytes E.g. Sctonema, Vaucheria, Nostoc

4. Cryophytic algae:
Algae living on ice and snow are called cryophytes or cryophytic algae.
Eg. Chlamydomonas, Ankistrodesmus and Mesotaenium.

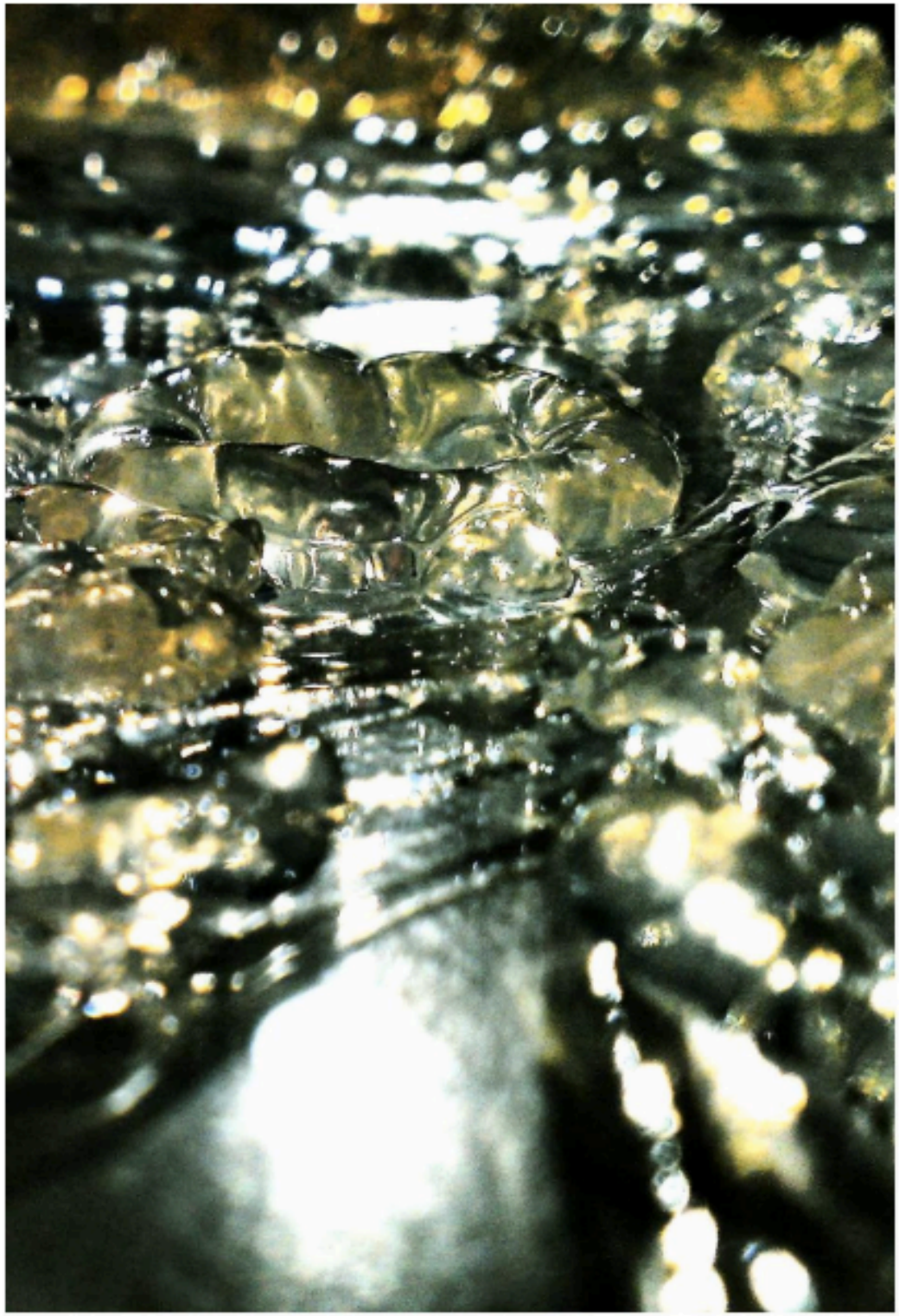
5. **Symbionts or Endophytes**:
Algae growing in symbiotic association with other plants are called symbionts. There are three types. They are,
- Symbiotic with fungi E.g. Chroococcus, Nostoc, Chlorella and palmella
- Lives inside the pteridophyte Azolla. Eg. Anabaena azollae.
- Found in the corolloid roots of Cycas. Eg. Anabaena cicadae.

6. Endozoic algae:
Algae living inside the body of animals are called Endozoic algae.
- Inside fresh water sponges
- Inside Hydra

7. Parasites
Algae live as parasites on other plants. Eg.Cephaleuros virescens.

A GENERALIZED SET OF CONDITIONS FOR CULTURING MICRO-ALGAE

Parameters	Range	Optima
Temperature (C)	16-27	18-24
Salinity (g.l-1)	12-40	20-24
Light intensity (lux)	1,000-10,000	2,500-5,000
Photoperiod (light: dark, hours)	(depends on volume and density)	16:8 (minimum) 24:0 (maximum)
pH	7-9	8.2-8.7



METHODS AND MATERIALS// GROWTH MEDIUMS

For the past decade, additive manufacturing of hydrogels has become a rapidly evolving technique to produce nano-featured biocompatible tissue scaffolds for tissue engineering purposes.[1]
In my research I was aiming to use these materials for microalgae cultivation.
To maintain the algae alive, 2 types of medium were tested:
1) Agar medium;
2) Methylcellulose (powder hydrogel) with sodium alginate.

1) Agar medium
Agar is a jelly-like substance, obtained from algae. Agar is derived from the polysaccharide agarose, which forms the supporting structure in the cell walls of certain species of algae, and which is released on boiling. Agar is indigestible for many organisms so that microbial growth does not affect the gel used and it remains stable.

2)* Methylcellulose + Sodium Alginate

Methylcellulose is a chemical compound derived from cellulose. It is a hydrophilic white powder in pure form and dissolves in cold water, forming a clear viscous solution or gel. Like cellulose, it is not digestible, not toxic, and not an allergen.

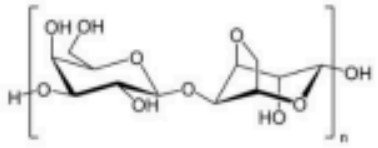
Sodium Alginate is a gum, extracted from the cell walls of brown algae, through binding with water it forms a viscous gum. The chemical compound sodium alginate is the sodium salt of alginic acid, also called algin or alginate. Sodium alginate has a wide use across a wide variety of industries including food, textile printing and pharmaceutical. Alginate is both food and skin safe.

The first showed good algae growth rate, but some constraints were identified – such as extrusion temperature and algae insertion, which can be only done after having completed the printing of the medium. The second medium, on the contrary, forms a homogeneous mass that can be extruded at room temperature, having added the algae to the mix prior to printing.

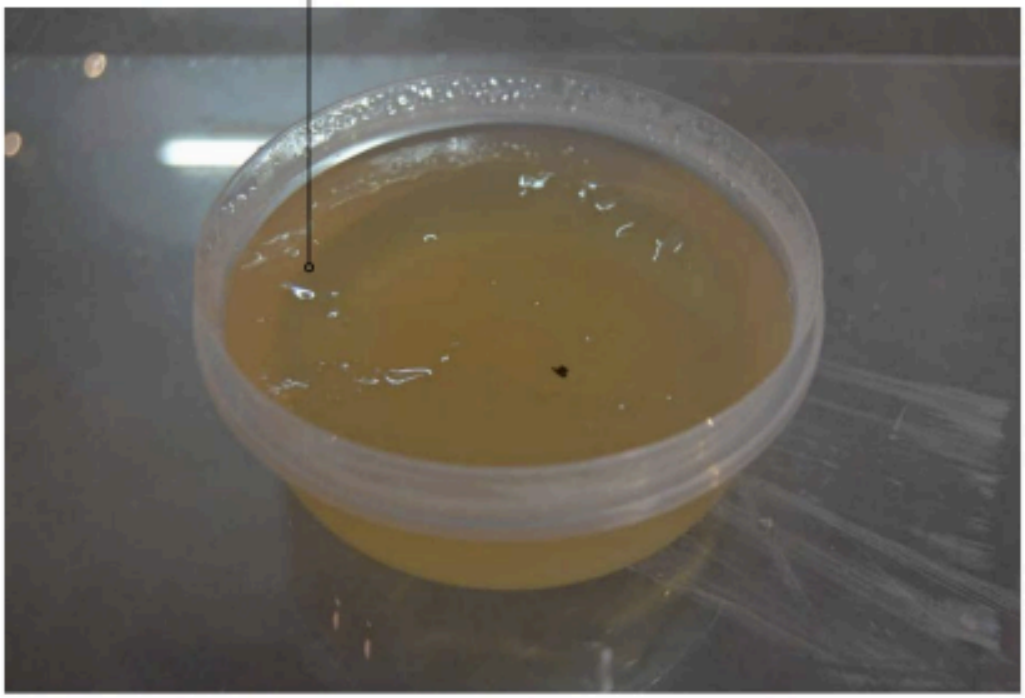
*The medium #2 eventually was chosen for extrusion with a robotic arm.

1 - Melchels FPW, Domingos MAN, Klein TJ - "Additive manufacturing of tissues and organs"- Progr Polym Sci 2011

// GROWTH MEDIUMS// AGAR + NUTRIENTS



Agar Agar



// GROWTH MEDIUMS// AGAR + NUTRIENTS

Agar Agar + Water + Nutrients → (heat 100 C / boiling) → Mixture → (cool down 37 C) → Print at t=37 C → Inject algae culture

Algae Culture Agar Composition

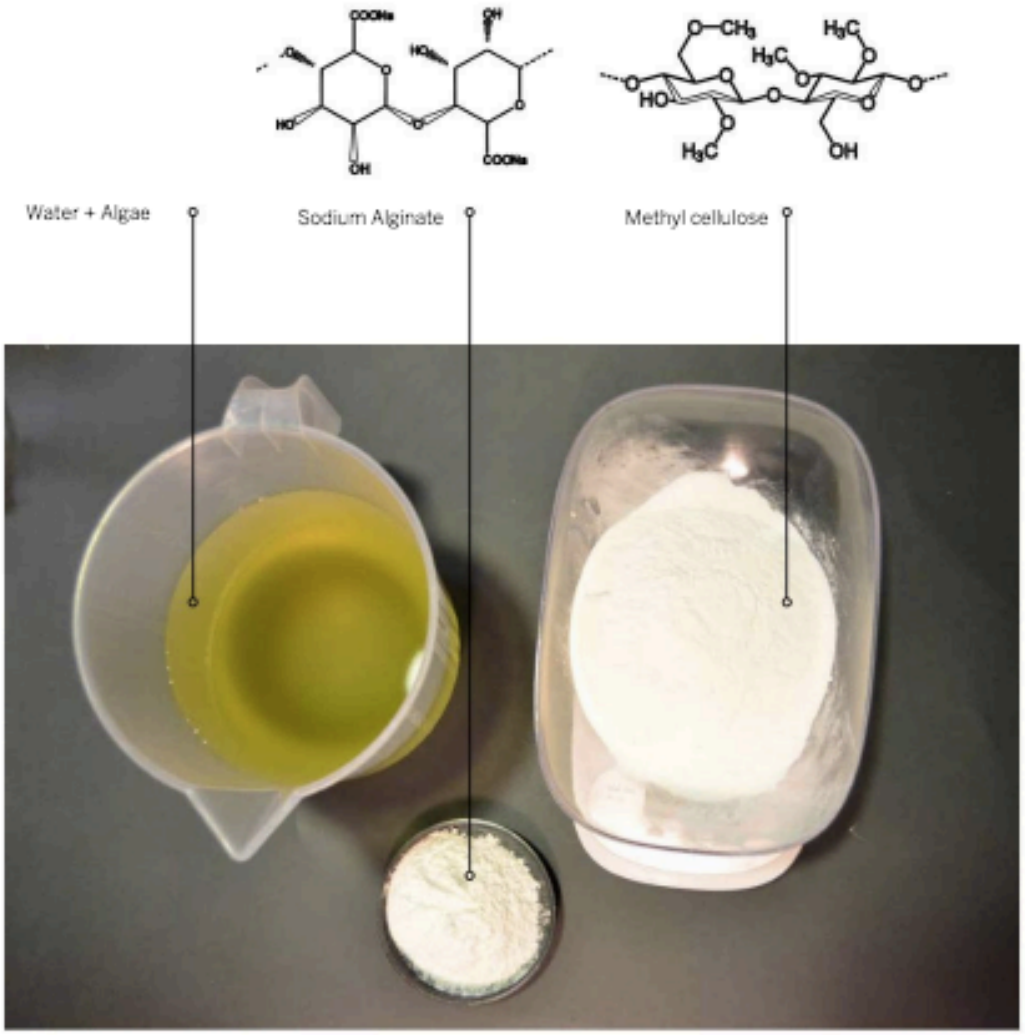
Ingredients	Gms / Litre
Sodium nitrate	1.000
Dipotassium phosphate	0.250
Magnesium sulphate	0.513
Ammonium chloride	0.050
Calcium chloride	0.058
Ferric chloride	0.003
Agar	15.000
Final pH (at 25°C)	7.0ffl0.2

Conclusions//

+ Good growth rate of algae
+ Aesthetically pleasing appearance

- Needs boiling for preparation
- Extrusion can be done at t=37 C, which means that the extruder has to be equipped with a system for temperature control
- Algae is put into the medium after deposition (medium preparation t=100 C, algae do not withstand high temperatures and even 37 C can cause a thermal shock)

// GROWTH MEDIUMS// METHYL CELLULOSE + SODIUM ALGINATE



// GROWTH MEDIUMS// METHYL CELLULOSE + SODIUM ALGINATE

An alginate/methylcellulose blend was used as printing material.
Thirty milligrams per milliliter alginic acid sodium salt was dissolved in water containing algae culture in it. This provides algae with necessary nutrients and ph in order for them to grow.
Methylcellulose powder was added to the solution in a methylcellulose:alginate ratio of 3:1 based on the dry mass of the compounds. The mixture was thoroughly stirred to obtain a homogenous plotting paste and incubated for 2 h at room temperature to allow swelling of the methylcellulose.
After plotting, the prints were transferred into a 100mMCaCl2 solution and incubated for 10 min in order to crosslink the alginate component of the scaffolds. The entire fabrication process was conducted at room temperature.

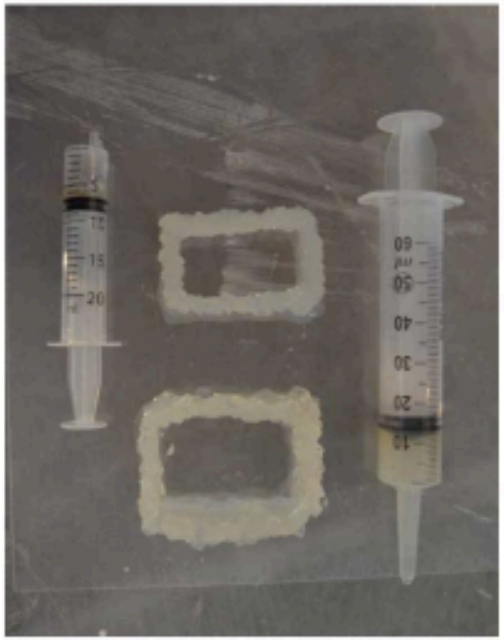
Conclusions //

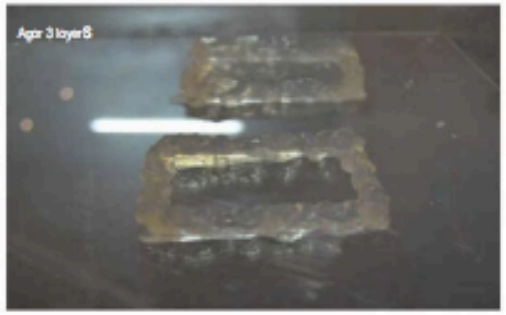
- Needs extra treatment after printing (crosslinking + nutrients)
- Material preparation is time consuming (approximately 3 hours)

+ Homogeneous mass that can be extruded at a room temperature
+ Algae is put into the printing paste prior printing

Material tests with a syringe

Firstly, materials had to be tested on their printability. So a regular syringe was used for that purpose.
For this experiment 2 syringes with different volumes and tip diameters were used as well as 2 types of gel: methylcellulose/sodium alginate and agar based mixtures. The objective was to study how many layers can be constructed before the srtucture collapses and what conditions are required for printing.



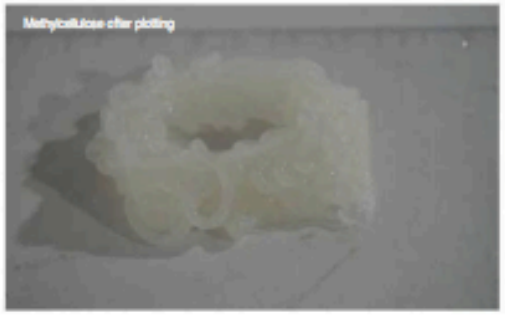


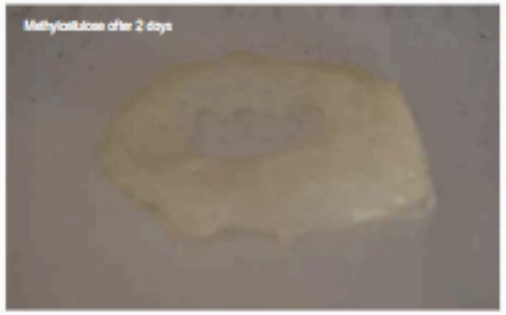
Methyl cellulose

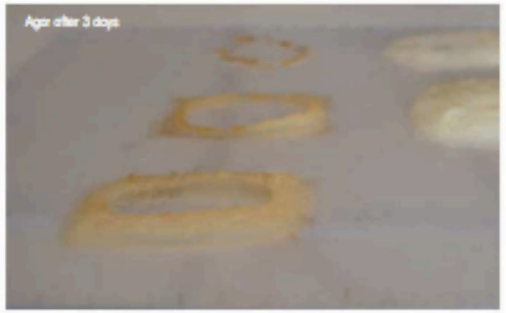
Material has high viscosity, thus higher extruding pressure is needed, thereby allowing printing more layers than with agar. Also, the heating is not required for the process of extrusion. After drying the structure deflates up to 90% forming a flat rigid piece. The rigidity depends on the initial amount of layers - the piece is more rigid when it has more layers in it.

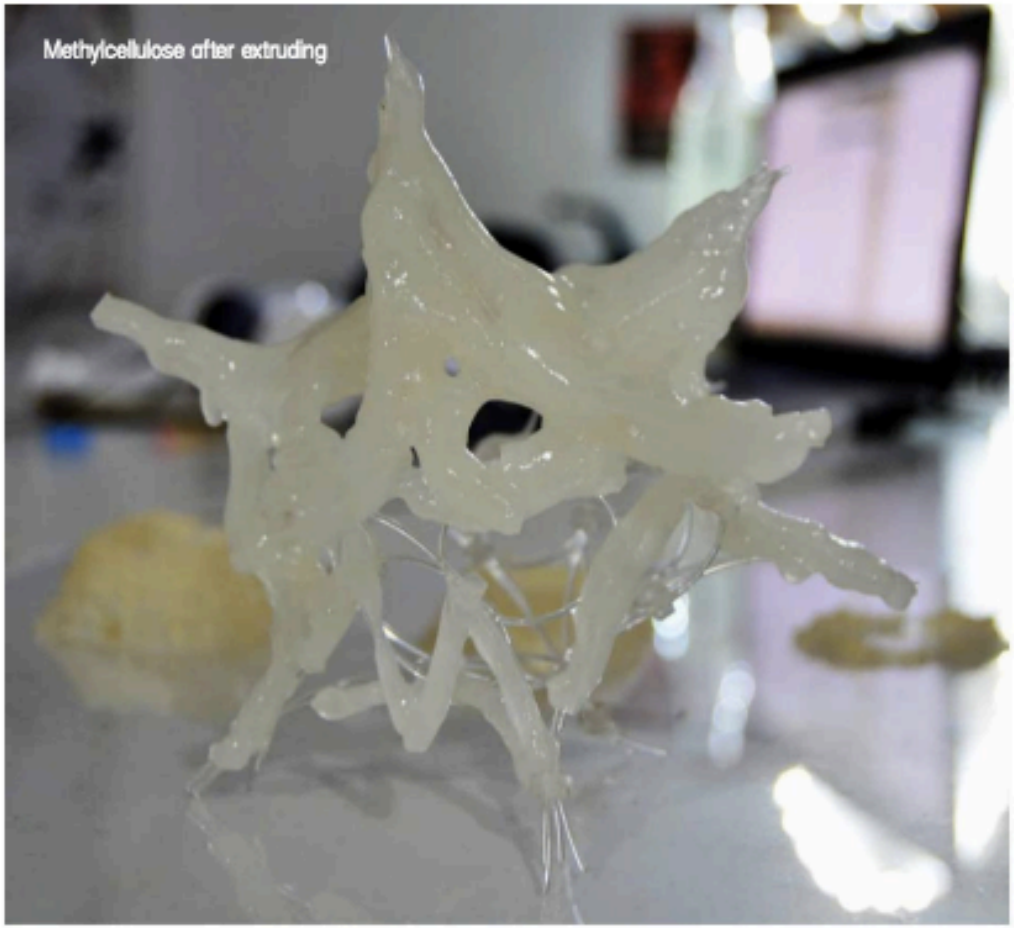
Agar

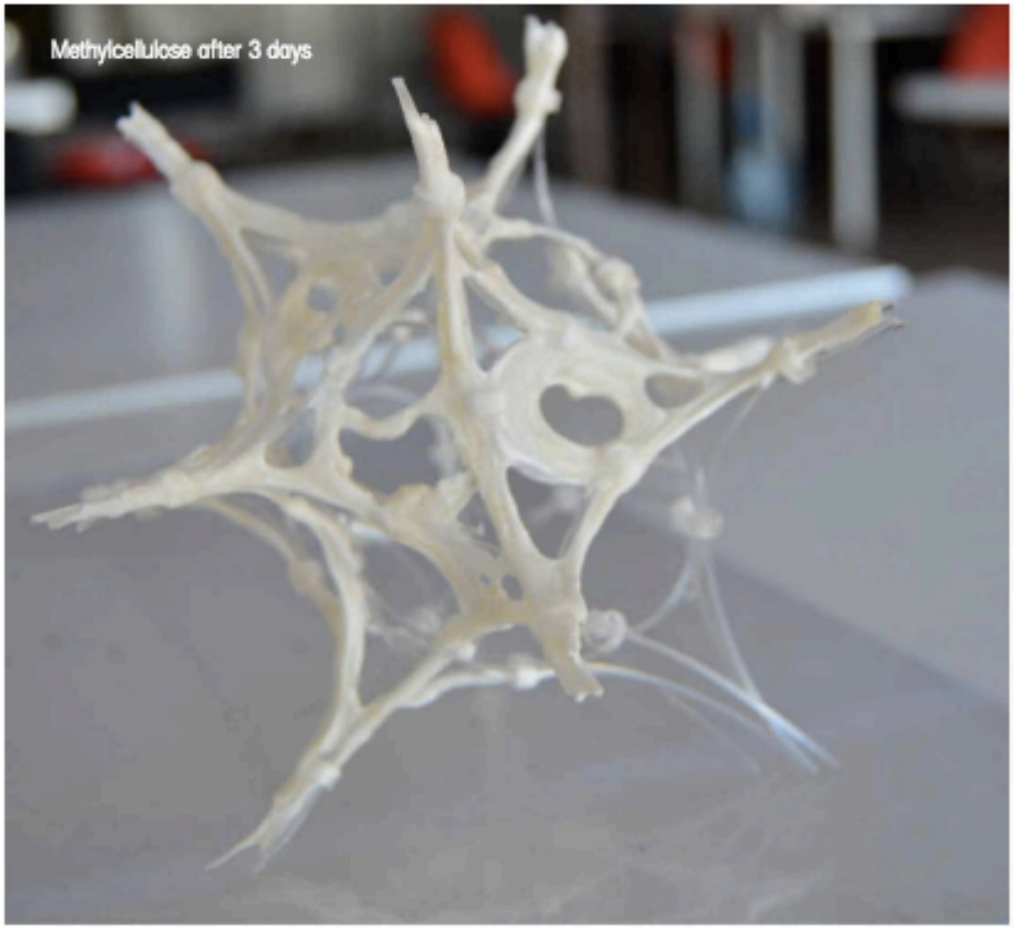
Material has fine homogeneous texture which benefits extrusion, but the optimum printing temperature for agar medium is 37 degrees Celcius, otherwise material cools down and solidifies which causes crumbling while printing, which in its turn prevents different layers from bonding with each other

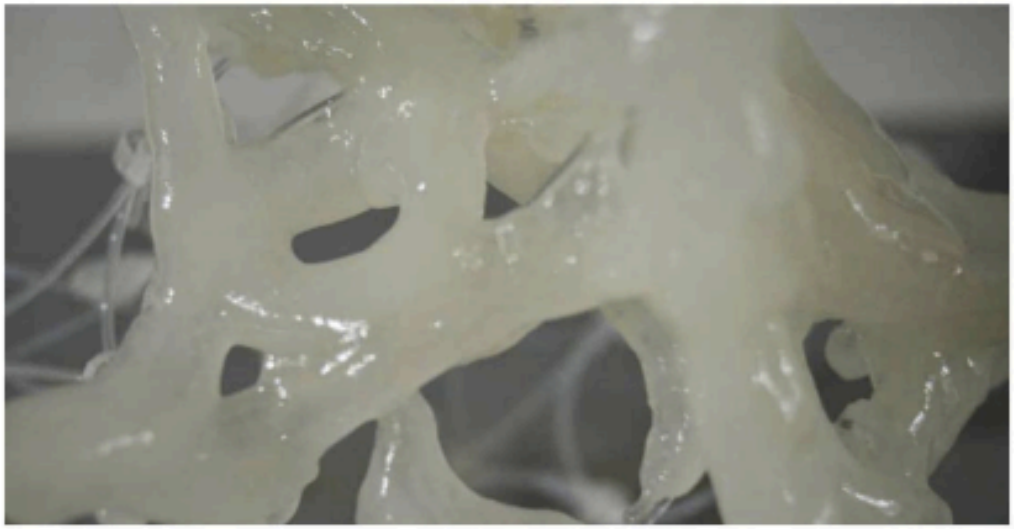


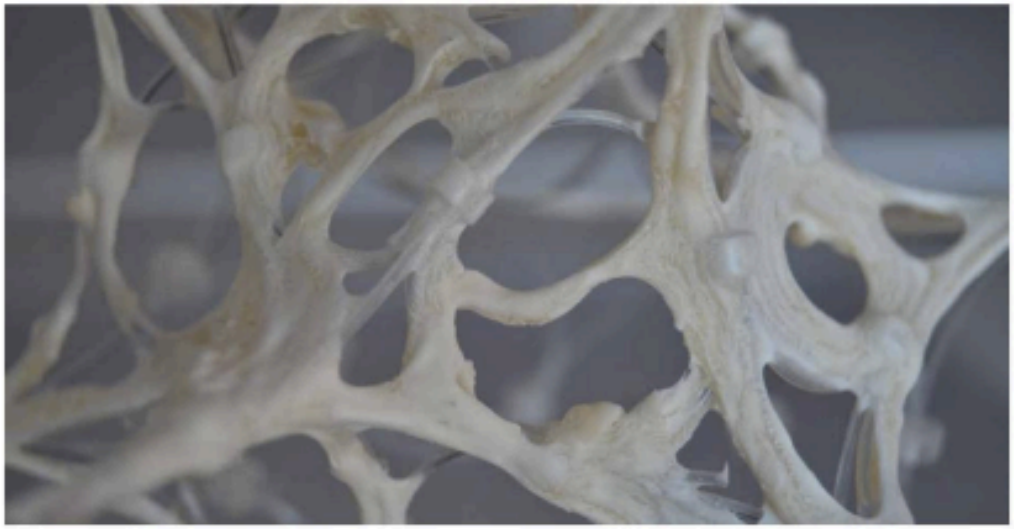





Methylcellulose after extruding


Methylcellulose after 3 days





MATERIAL TESTS// GROWING ALGAE

Simultaneously with testinng extrusion capabilities of growth mediums for algae cultivation, I was testing the growth of algae culture *Chlorella Vulgaris* in different kinds of water in order to explore the needs and requirements of the material I was working with.

Cultivating algae culture in

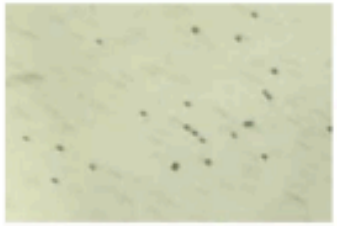
- Distilled water (negative growth results)

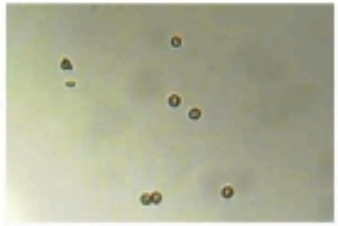
Distilled water has the ph 0, which is not suitable for algae. In this case all the nutrients had to be added to the water to maintain the culture alive.

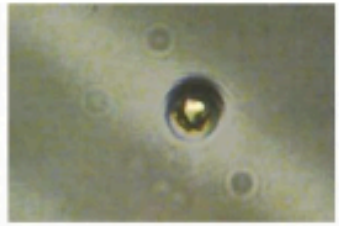
- Tap water (positive growth results)
- Rain water (positive growth results)

Rain water provides nutrients such as nitrogen and phosphorus required for algae growth.

An air pump was used to circulate algae solution and to provide ample "dirty" air including CO2.

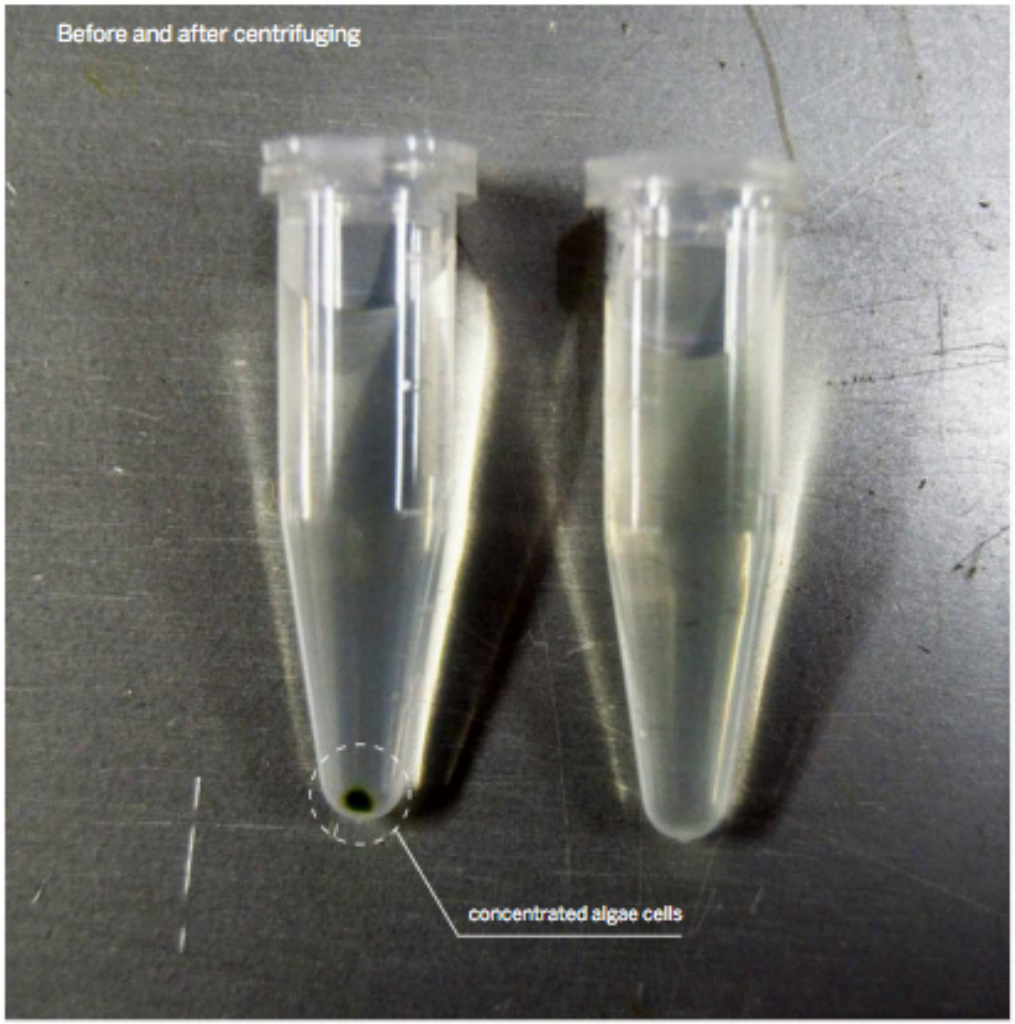


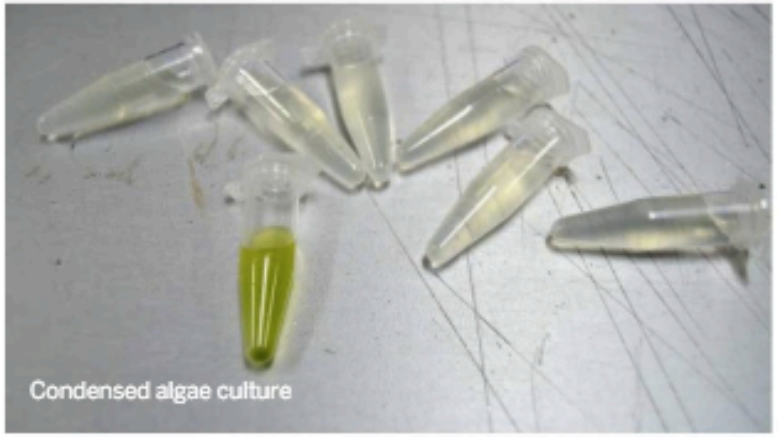




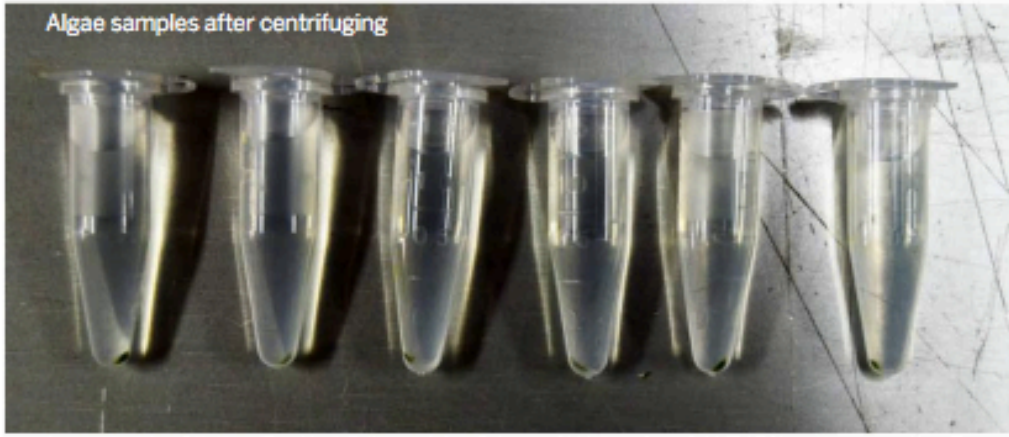
Algae cells under the microscope

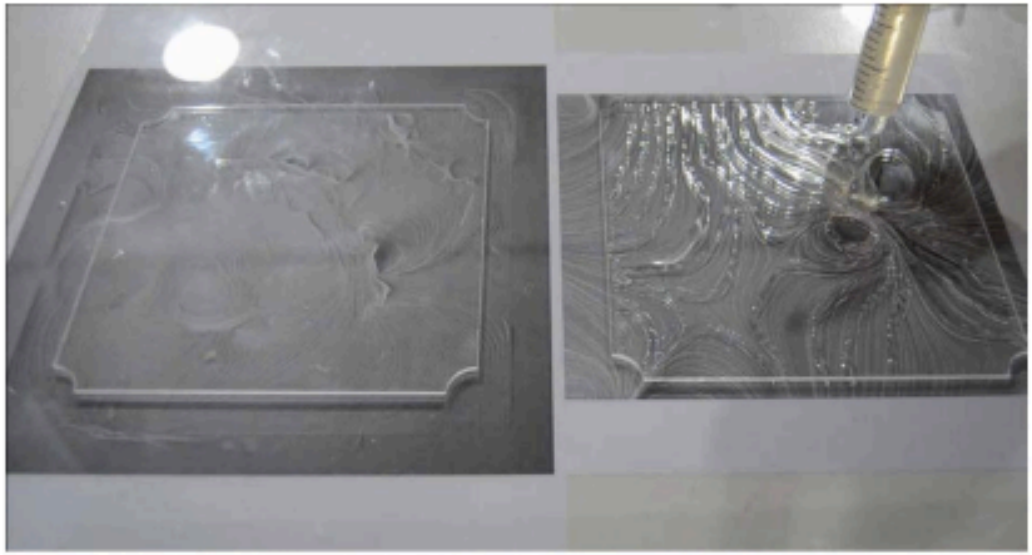
In order not to damage algae cells, centrifuging samples should be done at a speed of 4000 rpm for 5 min at 4°C

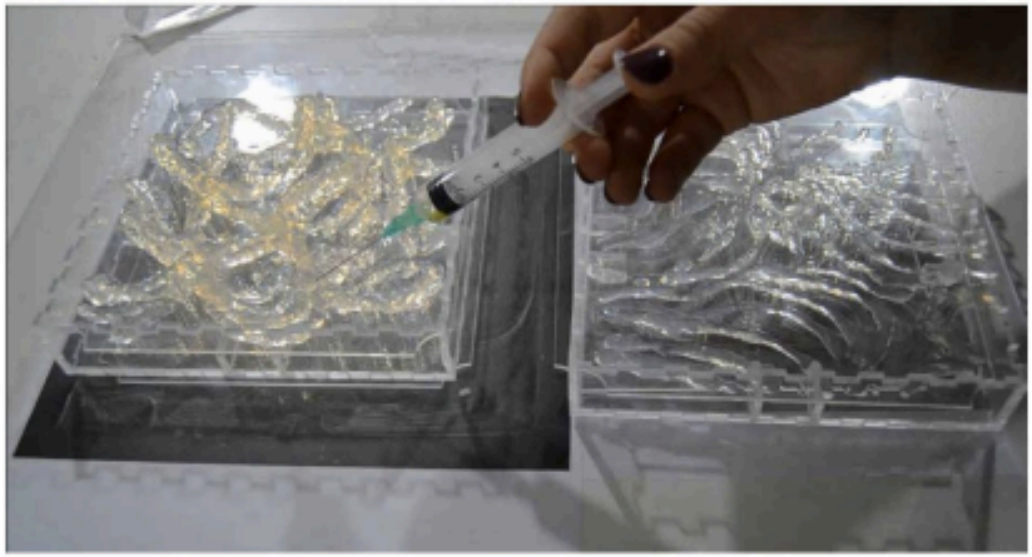


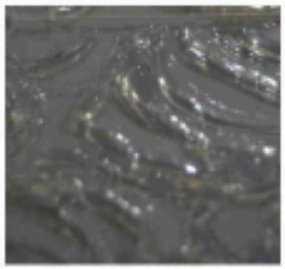


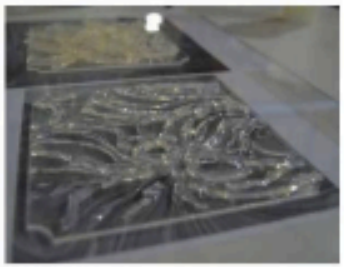
8 hours of centrifuging in order to fill one container with condensed algae culture











MATERIAL TESTS// TESTING ALGAE GROWTH IN GELS

Testing algae growth rate within gel substances was crucial for further development of the research, because it was very important to understand if microalgae could survive and reproduce in the environment different from their natural habitat.

To conduct this experiment 2 different types of the growth medium were prepared:
1) agar based medium
2) methylcellulose/sodium alginate mixture

Both of them are are compatible with algae cells. As well as the translucent nature of gel materials is beneficial for light transmittance.

Growth mediums were extruded with a syringe onto methacrylate plates which eventually were placed in transparent boxes to provide algae culture with extensive sunlight.

Syringes with different tip diameter were used to see if algae growth rate depends on the amount of the growth medium, its thickness and quality.

After exrtuding the medium onto plates, condensed algae culture was injected via syringe.
Afterwards boxes were kept in the reach of sunlight and sprayed with water every 3 days to keep the gel moisturized.

Observation of the boxes lasted for more than a month.
This test showed positive results on algae growth and demonstrated that microalgae culture can be embedded in 3d scaffolds with predesigned geometry by the additive technique. The alginate matrix has proven its suitability for cultivation of the embedded algae—as indicated by cell growth.

Algae clusters // Day 10

MATERIAL TESTS// TESTING ALGAE GROWTH

Algae growth cycle

Algae culture was injected into 4 different growth mediums and was put into plexi glass boxes in order to prevent gels from drying out.
Water was sprayed onto patterns every 3 days to maintain humidity levels.
Pictures were taken on the 1st, 10th, 20th and 40th days of the experiment.

Day 1 - Algae culture was inserted into the growth mediums with a syringe. Color of the patterns is white (methylcellulose) or translucent (agar);

Day 10 - immense algae growth observed in agar mediums; moderate growth observed in methylcellulose mediums;

Day 20 - agar medium aquired yellow tint which means that nutrients were depleting by that moment, which caused the death of algae culture;

Day 40 - yellow color is observed in agar mediums which meant that algae reached the end of its life cycle because of the nutrients' depletion - thereby algae had no ability to reproduce.

Conclusions
As it can be seen, the test showed positive results, which proved the statement that algae could grow in gel substances with nutrients added to the mixture. The fact the algae were able to reproduce in biodegradable polymers, thus forming a synthetic ecosystem, is truly fascinating, since this synergy doesn't occur in nature.
Also this experiment raises the inevitable question of a life cycle of living organisms. Unlike traditional architectural materials, bio materials operate within a different set of variable states. When working with bio materials, the dimension of time, variation, and decay become new material-defining properties.

Day 1

Day 10

Day 20

Day 40