UNIVERSIDAD DE VALLADOLID

ESCUELA DE INGENIERIAS INDUSTRIALES

Grado en Ingeniería en Tecnologías Industriales

Aquaponics, a system that combines aquaculture with hydroponics in a symbiotic environment.

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Valladolid, 13 de Diciembre.

TFG REALIZADO EN PROGRAMA DE INTERCAMBIO

TÍTULO: Aquaponics, a system that combines aquaculture with hydroponics in a symbiotic environment.

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FECHA: 17/12/2019

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Resumen:

El equipo del proyecto, Hygrow, tiene como objetivo construir un prototipo funcional de una Acuaponía. Acuaponía es un sistema que combina la acuicultura con la hidroponía en un entorno simbiótico. El objetivo del proyecto es crear un paquete con toda la información necesaria para que el siguiente equipo pueda construir una acuaponía real en un container.

En primer lugar, se han realizado una detallada investigación sobre aspectos clave de un sistema acuapónico. Estos aspectos son la acuaponía en general, tipos de acuaponía, acuaponía de impresión 3D, hidroponía, acuicultura, parámetros, suministro de energía y un modelo de aislamiento del container. En segundo lugar, se ha diseñado y construido un prototipo completo de acuaponía, el cual contiene tres tipos de acuaponía, cultivo en aguas profundas, lecho de medios y película de nutrientes, y donde todo el control se ha realizado con Arduino y Raspberry pi.

Palabras clave:

Acuaponía, hidroponía, acuicultura, impresión 3D y construcción.

Aquaponics

A system that combines aquaculture with hydroponics in a symbiotic environment

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EPS-Project - Fall 2019

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Preface

This is the final report of the aquaponics project done by ten students of Novia Yrkeshögskolan that take part in the European Project Semester (EPS). The European Project Semester is offered in 18 different universities in Europe, including Novia University of Applied Sciences located in Vaasa, Finland. It is designed with engineering students in mind, but students with a business or management background are welcome as well. The EPS program is crafted to address the design requirements of the degree and prepare students with all the necessary skills to face the challenges of today's world economy. Classes are offered to students alongside their projects that help deepen their knowledge of project management. Students participating in EPS meet together as a group each day to build their engineering and management skills in class and then meet in teams of 2-10 students to work on their dedicated projects.

The ten students that made this research report about aquaponics define themselves as Hygrow. The students came up with this brand name because it perfectly summarizes the project. In the aquaponic system, the objective is to grow plants and fish in a closed loop of water (hydro).

The project was carried out in response to a project assignment from two teachers at Yrkeshögskolan Novia and the University of Vaasa. Their request was to build an aquaponic farm completely enclosed in a 20ft shipping container, to develop practical knowledge of circular and sustainable natural farming.

Hygrow wants to especially thank Mikael Ehrs and Rayko Toshev for their guidance and feedback. Next, we would like to thank Svenska Kulturfonden for sponsoring the Hygrow aquaponic system. Furthermore, we would like to thank our other sponsors: Vaasan Eläinkeskus, Yrkeshögskolan Novia, University of Vaasa, Konttivuokraus Oy, Fish shop R. Cederberg and Suomen Bio Kierto Tuote Oy. We would also like to thank the Building Coordinator at Technobotnia, Sebastian Ingberg, for helping us with getting a lot of resources. Furthermore, we would like to thank Physics Teacher Anders Skjal, for allowing us to use the laboratory. As well as Laboratory Engineer Hans Linden, for providing us with electronic equipment.

Vaasa, December 2019
Berta Alonso Martínez, Bouke Boumeester, Marina Casades Cornet, Miguel Fernandez Martina, Nino Koers, Simon Lex, Marleen van Loon, Stephanie Olumba, Pierre Trott and Lode Verheyen

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Reading guide

This project will be completed using phases. These phases are researching, designing, building and testing and results. Chapters found in this report are based on these phases.

The report starts with an introduction to the project and the project goal. Next, chapter 2 is about the research that has been done. It is divided in aquaponics in general, the types of aquaponics, hydroponics, aquaculture, water treatment, parameters, design calculations, controlling aquaponics, aquaponics and 3D-printing, lightning, energy supply, housing and life cycle assessment.
Chapter 3 is the design chapter. This chapter is based on all the research that can be found in chapter 2. Therefore, the decision for the design of the setup can be found in this chapter. Followed by the decision for the plants, fish, lights, coding, energy supply and housing.
After the decisions were made, the building process could start. In chapter 4 the building process is explained per subject. After building everything was tested and logically results were obtained. This can be read in chapter 5.
In chapter 6 the previous findings are concluded and recommendations for the group in the next semester are written.
At last the bibliography with all the used references can be found in chapter 7 and the appendix in chapter 8.

Abstract

The main goal was to design and build an experimental setup where aquaculture is combined with hydroponics in a symbiotic environment in accordance with the wishes of the supervisors. Since this assignment is too complex for one person to do alone, a team of ten students was assigned to bring this project to a successful conclusion.

The Hygrow project team aimed to successfully complete the design and construction of a functional and attractive aquaponic setup to present to the stakeholders. This included making a hand-off package to show future students the exact procedures that were carried out to make an aquaponic system.

First research has been done. This chapter contains information about key aspects of an aquaponic system. These aspects are aquaponics in general, types of aquaponics, 3D printing aquaponics, hydroponics, aquaculture, parameters, energy supply and insulation. Sustainability and eco-friendliness were taken into account while doing research.

After the research, the designs were made. The type of aquaponic system was chosen, it contains deep water culture, nutrient film in towers and media bed in 3Dponics. Energy supply will be generated with renewable energy. The plants that are used are lettuce, swiss chard, spinach, mint, basil and parsley. The best fish to use in an aquaponic system in Finland are trout, perch, sturgeon or carp. In the system are perch that were caught from the sea and African Cichlid from the pet shop because it was impossible to catch more perch. Also shrimps or prawns could be used in the system. To light the plants, the best option is to use addressable LED lights. Next, a wind turbine would be the best option to power the system. And because the aquaponic setup needs to be build in a 20ft container, the insulation is designed.

After designing, the building process could start. First the three perch were caught together with local fishermen. After the team started to try and catch more perch themselves, it was decided to buy Malawi Cichlids from the pet shop. Next to the obtained fish, plants were seeded. This went wrong a couple of times due to lights that were not powerful enough. Next, the fish tanks were assembled together with the settling tank and the biofilter tank. After the fish were installed in this system, the deep water culture was added. Above the deep water culture the LED stips were installed. Then the setup was shown to future students that were visiting Technobotnia. After the visit, the team started with mounting all the electronics in a special box. Because, the DIY team finished the basic setup, they could start with building the tower system. Herefore, the water supply needed to be mounted. Also the fish feeder needed to be installed so the team did not have to feed them manually. Lastly the 3Dponics system was built and installed.

In the end, a lot of results were accomplished and the aquaponic setup was working on its own. It was a challenge to supply the water to the towers due to pump specifications that were not fit. After a waterpump and an air pump were connected, the water could be pumped two meters high.

For a long time, it was not possible to 3D print because the national post was on strike and the university run out of ABS. In the end the team managed to print 110 bioballs.
The plants could not grow properly due to poor lighting and some of the plants were infected with a parasite. In the end a few of the seeded plants could be added to the deep water culture system. Some plants that were bought from the plant shop were also put in the deep water culture and they managed to grow more roots in the water and develop more leaves.
It was very difficult to adapt the perch to artificial food. At some point they stopped eating but after putting them back with the african cichlids they started to eat the artificial food. Also an automatic fish feeder was installed.
The settling tank worked from the beginning. Although the water got cloudy sometimes and needed to be changed. Therefore, the water cloudiness should be monitored and changed every two weeks if necessary. The water evaporation is estimated to be 15 liters per week, therefore this needs to be regularly checked and filled.
There was not enough time to obtain results for the hydroponic systems. However, the deep water culture system is working well. When the aquaponic setup is installed in the 20ft container, it is recommended to use insulation material with 150mm thickness.

In the end, the project was successfully due to the project goal that was completed. Unfortunately the setup is not completely functioning yet. Therefore, the team recommends the next group to start with obtaining fish as soon as possible. This has been found very difficult and a critical part of the aquaponic setup. It is recommended to use carp because these fish are optimal to be grown in Finland.
The second crucial part of the aquaponic system are the plants. It is recommended to start seeding the plants in the beginning of the semester with the right light supply.
To filter the system, the settling tank and the biofilter tank with the bioballs are working great. It is recommended to buy extra bioballs but it is not necessary to buy more bacteria since there is still plenty left.

Finally for the setup in the 20ft container it is recommended to implement the deep water culture and the vertical towers. The deep water culture is easy to build and maintain and it works good. Next, the vertical towers are preferred because compared to the 3Dponics it is easy to clean and a higher density of plants can be grown.
It is important to start building the system as soon as possible because an aquaponic setup can not be built in a couple of weeks.

Lastly, it is recommended to not overuse 3D printing. For many parts it is time consuming and mostly also has higher costs than buying the products from a shop.

Abbreviations

Abbreviation	**Explanation**
3D	Tridimensional
ABS	Acrylonitrile Butadiene Styrene
AC	Alternating current
CPU	Central processing unit
CSP	Concentrated solar power
CSS	Cascading Style Sheets
DC	Direct current
DIY	Do-It-Yourself
DNA	Deoxyribonucleic acid
DO	Dissolved Oxygen
DWC	Deep Water Culture
EC	Electrical conductivity
EPS	European project semester / expanded polystyrene
Etc	Etcetera
FCR	Food conversion rate
GUI	Graphical User Interface
GWP_{100}	Greenhouse Warming Potential over a timescale of 100 years
HDPE	High-Density Polyethylene
HID	High-intensity discharge
HMI	Human-machine interface
HPS	High-Pressure Sodium
HTML	HyperText Markup Language
IR	Infrared radiation

ISO	International Organization for Standardization
IoT	Internet of Things
ISS	International Space Station
LED	Light-emitted diode
LCA	Life Cycle Assessment
Li-ion	Lithium-ion
Li-ion polymer	Lithium-ion polymer
MBBR	Moving bed bioreactor
MBC	Media Bed Culture
MH	Metal Halide
NFT	Nutrient Film Technique
PETT	Polyethylene terephthalate
PAR	Photosynthetically active radiation
pH	Power of hydrogen
PLA	Polylactic acid
ppm	parts per million
PVA	Polyvinyl alcohol
PVC	Polyvinyl chloride
RAS	Recirculation Aquaculture System
TAN	Total Ammonia Nitrogen
TSR	Tip speed ratio
UML	Unified Modeling Language
UV	Ultraviolet

Table of Contents

1 Introduction

This introduction contains information about the necessity of this project, the goal of the project, the goal of this project team, the deliverables, and the different fields of study that can be found within this report.

Most information which is given in this report is a brief summary or conclusion of everything which has been done, so a lot of references will be made to other reports which can be found in the “hand-off package”.

1.1 Motivation

As a project for the European Project Semester (EPS), an aquaponic system will be made. Aquaponics is a system in which aquaculture (raising aquatic animals) is combined with hydroponics (cultivating plants in water) in a symbiotic environment. The study of aquaponics is becoming more important for its benefits. With this type of farming, less water, land and labour is used in comparison with traditional agriculture, producing is free of pesticides and herbicides. Producing can be done even in the hardest environments (Nelson and Pade, n.d.-b) (Theaquaponicsource.com, n.d.). To achieve such a goal, one has to make an experimental setup. This paper is the documentation of how such a goal is achieved.

1.2 Goal

The goal is divided into two different parts. On the one hand the main goal and on the other hand the project goal.

Main Goal:
The main goal is to design and build an experimental setup where aquaculture is combined with hydroponics in a symbiotic environment in accordance with the wishes of the supervisors. Since this assignment is too complex for one person to do alone, a team of ten students is assigned to bring this project to a successful conclusion.

Project goal:
The project goal is to successfully complete the design and construction of a functional and attractive aquaponic setup to present to the stakeholders. This includes making a hand-off package to show students the exact procedures carried out to make an aquaponic system.

Fields of Study:
As each team member has a different educational backgrounds and different knowledge of several topics, the fields of study found in this report are categorized as shown in Figure 1.

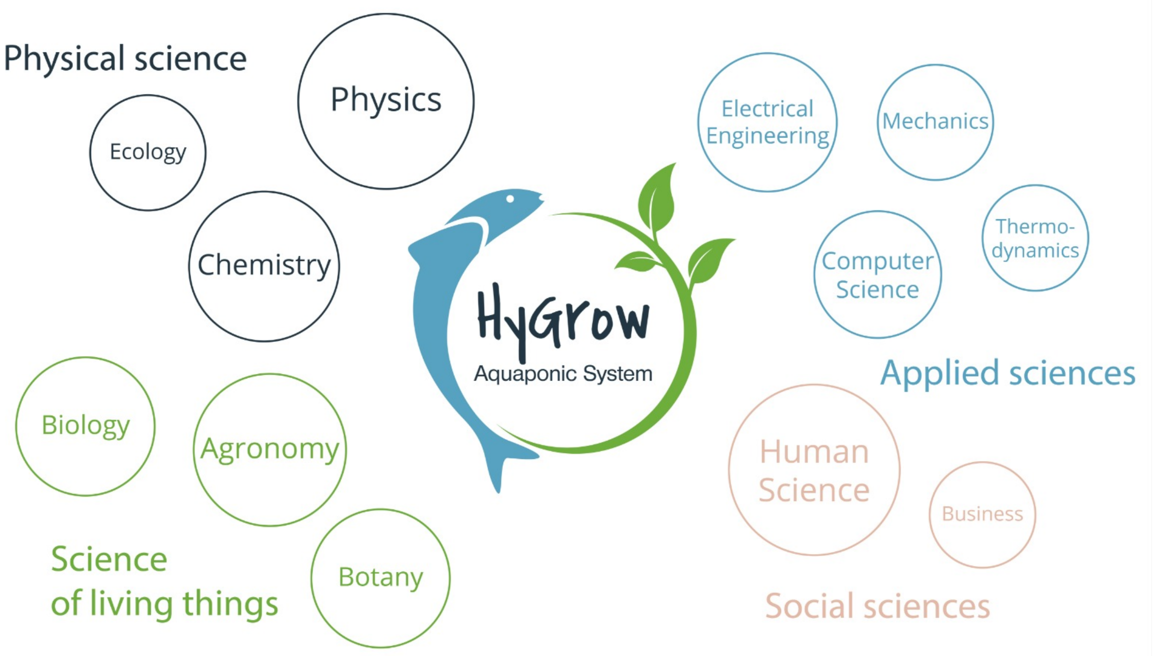


Figure 1 Categorized fields of study

Physical science: this can be defined as Ecology, Chemistry and Physics. This field of science related to the physical environment around the aquaponic.

Science of living things: this is split into Biology Agronomy and Botany. This field of science represents the living components of our aquaponic.

Applied sciences: this consists of Mechanics, Electrical Engineering, Computer Science and Thermo-dynamics. This field of study is more technical than the others. They are related to external- man-made components that will help maintain the aquaponic system.

Social sciences: this is split into Human Science and Business. This field of science involves human influence, interaction with and utilization of the aquaponic.

These fields of sciences represent each group members' strengths and areas of knowledge. They are important as they cover all studies relating to this aquaponic system and its design.

2 Research

This chapter contains research types of aquaponics, 3D printing aquaponics, hydroponics, aquaculture, parameters, energy supply and insulation. Sustainability and eco-friendly were taken into account while doing research. This chapter will be used in the design part as information to support decisions that are made.

2.1 Aquaponics in general

Below, the general process and concept of aquaponics are discussed. Additional information or extensive research can be found in the handoff package/02. aquaponics research/ 02. aquaponics research

2.1.1 General process overview

Aquaponics can be categorised as a sustainable agricultural production system, a system which closely resembles a natural ecosystem and tries to close its nutrient cycle. It is a symbiosis of a recirculation aquaculture system (RAS) and a hydroponics system, where these two technologies are combined into one closed-loop system. In Figure 2 the aquaponic system is explained in more detail.

The fish get fed and excrete waste nitrogen in the form of ammonia, that gets dissolved in the water to ammonium. A pump drives the circulation of the water in the system. The water exits the fish tank and goes to the hydroponic stage. Here, bacteria convert the ammonium to nitrite and then to nitrate. Nitrate is the type of nitrogen which the plants use in photosynthesis for foliage development. After the water has passed the hydroponic stage, it is mostly purified of nutrients. So the fish receive freshwater through natural filtration. A separate biofilter tank can be added to improve the filtration. *(Goddek et al., 2015) (Junge, König, Villarroel, Komives, & Jijakli, 2017) (Rakocy, Masser, & Losordo, 2016)*

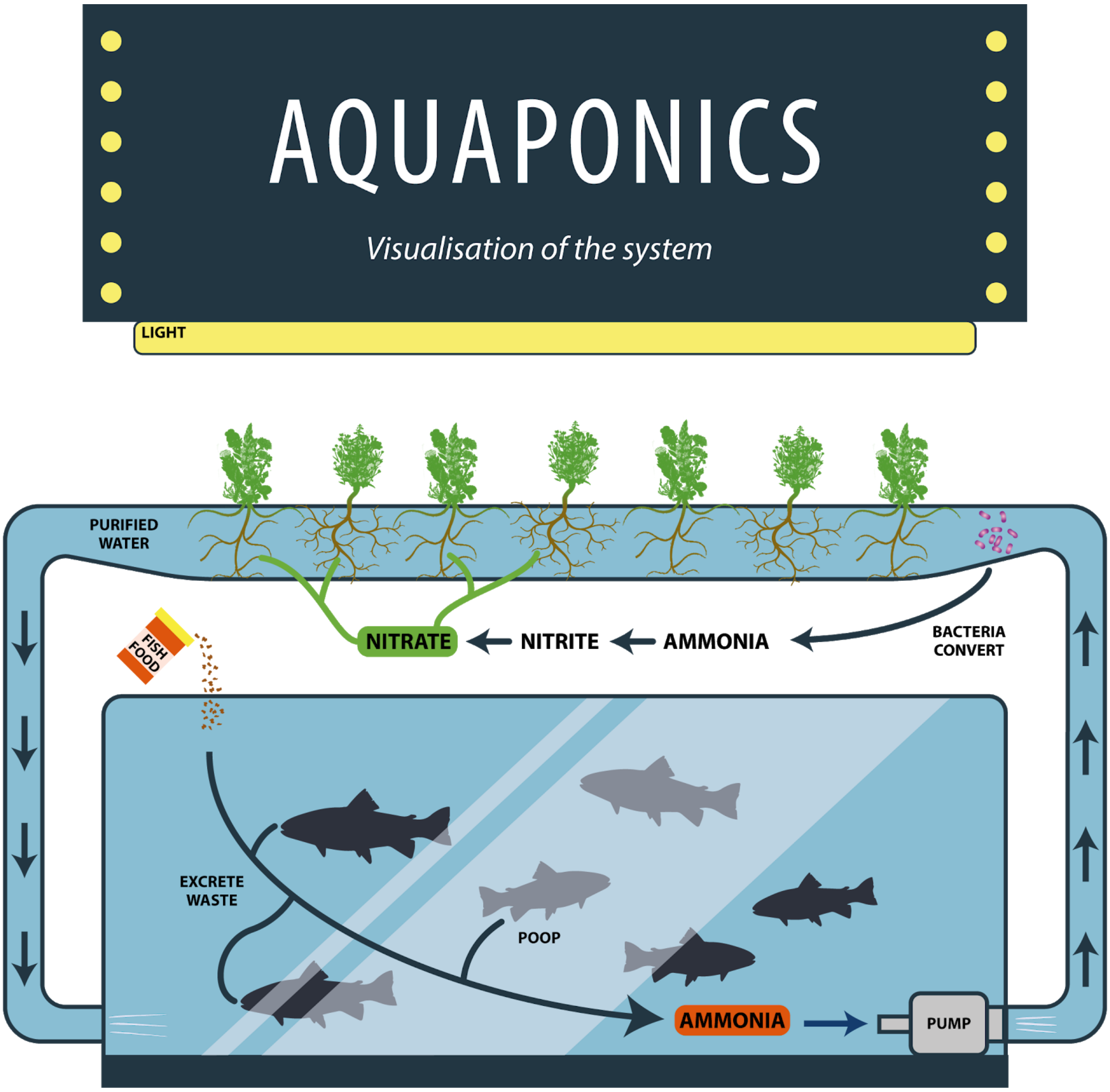


Figure 2 Visualisation of an aquaponic system.

2.2 Types of aquaponics

Aquaponics is a form of agriculture that combines breeding fish in tanks with soilless plant culture, also known as hydroponics. An aquaponic can be built in different ways. Therefore, the different types are introduced and discussed in this chapter.

2.2.1 Main types

There are different types of aquaponics system designs. Most of these designs are evolutions and/or combinations of the three basic setups for aquaponics: Nutrient Film Technique (NFT), Media Bed, and Deep Water Culture (DWC). These designs do not differ on the aquaculture side, but on how the crops are grown.

Nutrient film technique
Nutrient Film Technique or NFT is a hydroponic irrigation technique. In an NFT system, a very shallow stream of water containing all the dissolved nutrients required for plant growth is recirculated past the bare roots of plants in a watertight channel. The main goal with this system is to provide a constant film of water, hence the name 'nutrient film', so that the plants their roots can develop into thick mats at the bottom of the channel. The upper surface of the roots should be moist and in contact with the air, as can be seen in Figure 3. *(Aquaponicsexposed.com, n.d.) (Aquaponics.fandom.com, n.d.) (Aquaponics.com, n.d.)*

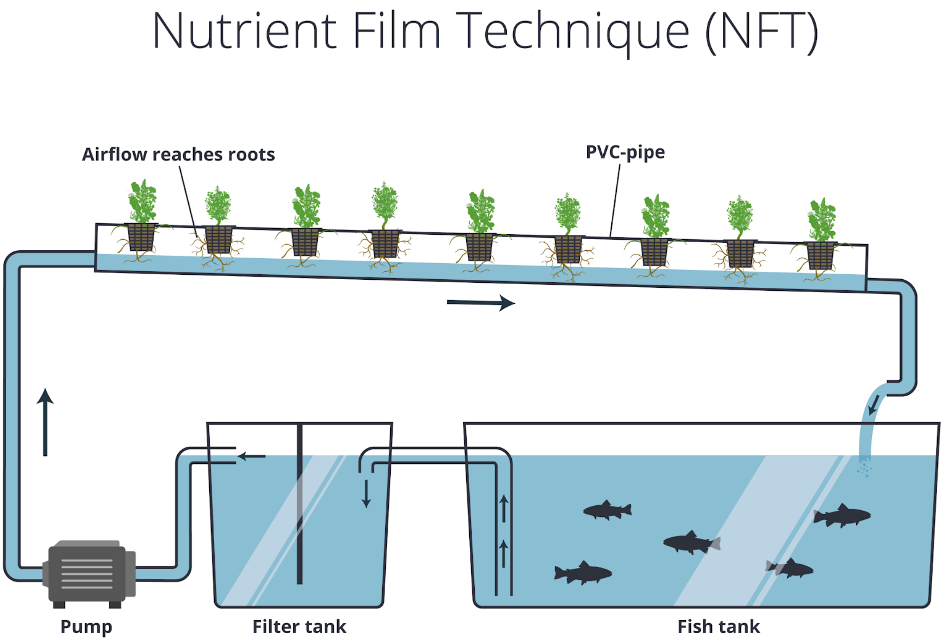


Figure 3 Nutrient Film Technique (NFT).

Strengths:

The main advantage of this system is that roots get an abundant supply of oxygen, water and nutrients. Therefore, these setups yield high-quality production over an extended period of cropping. By their design, NFT setups are popular in the commercial industry because of their space efficiency, easy access and lower labour costs. Setting up this style of system is beginner-friendly. Furthermore, they offer the possibility of future expansion. This system works with a constant flow of water, which prevents clogging and the growth of algae and funguses. It is easy to check on how the roots are growing since looking inside the channels to look for obvious problems that may impact the health and growth of the plants. *(Aquaponics Exposed, n.d.) (Aquaponics.fandom.com, n.d.) (Aquaponics.com, n.d.)*

Weaknesses:

Some other form of filtration must be integrated into the system. This design is best suited for leafy greens but not for large fruiting plants. The roots are not as well isolated from the temperature fluctuations. The flow rate must be constant for the plants to grow. This aquaponics installation has little to no buffering against interruptions, so a power outage, for instance, could ruin the culture. Routine maintenance is really important to prevent a water pump failure or clogging of the pipes and channels.
(Aquaponics Exposed, n.d.) (Aquaponics.fandom.com, n.d.) (Aquaponics.com, n.d.)

Media bed

The media bed is a type of aquaponics in which the plants are grown in containers filled with rock media, generally gravel or expanded clay to support the roots of the plants. The bed is constantly flooded and drained with the nutrient-rich water coming from the fish tanks. The media bed setup can be seen in Figure 4. *(Aquaponics.com, n.d.)*

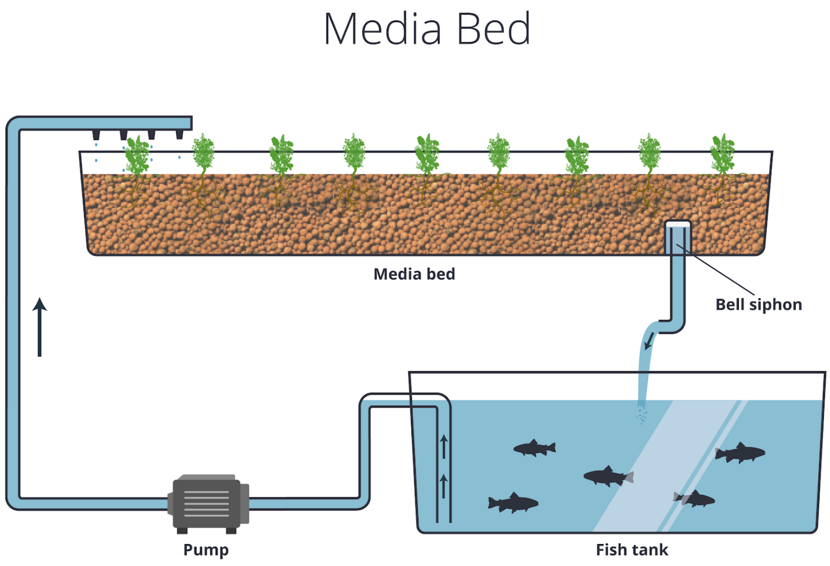


Figure 4 Media Bed.

Strengths:

In this system, the plants are supported by the media which also acts as both a mechanical and biofilter to capture and breakdown wastes in the plant bed. It is easy to operate, hence why it is best used for backyard gardeners and beginners. Large root mass plants such as fruit, flowering plants, vegeTables and root vegeTables can be grown. *(Aquaponics.com, n.d.)*

Weaknesses:

This setup usually produces less than the Nutrition Film Technique or the Deep Water Culture. It is also not space efficient and requires more labour than the other setups. On a large scale, the media is very heavy and can be very expensive. *(Aquaponics.com, n.d.)*

Deep Water Culture (DWC)

In a Deep Water Culture (DWC) that is shown in Figure 5, the plants are grown on rafts. These are usually polystyrene boards that float on top of the water. This tank is separated from the fish tank and a continuous flow is established between the two with filtration components. *(Aquaponics.com, n.d.)*

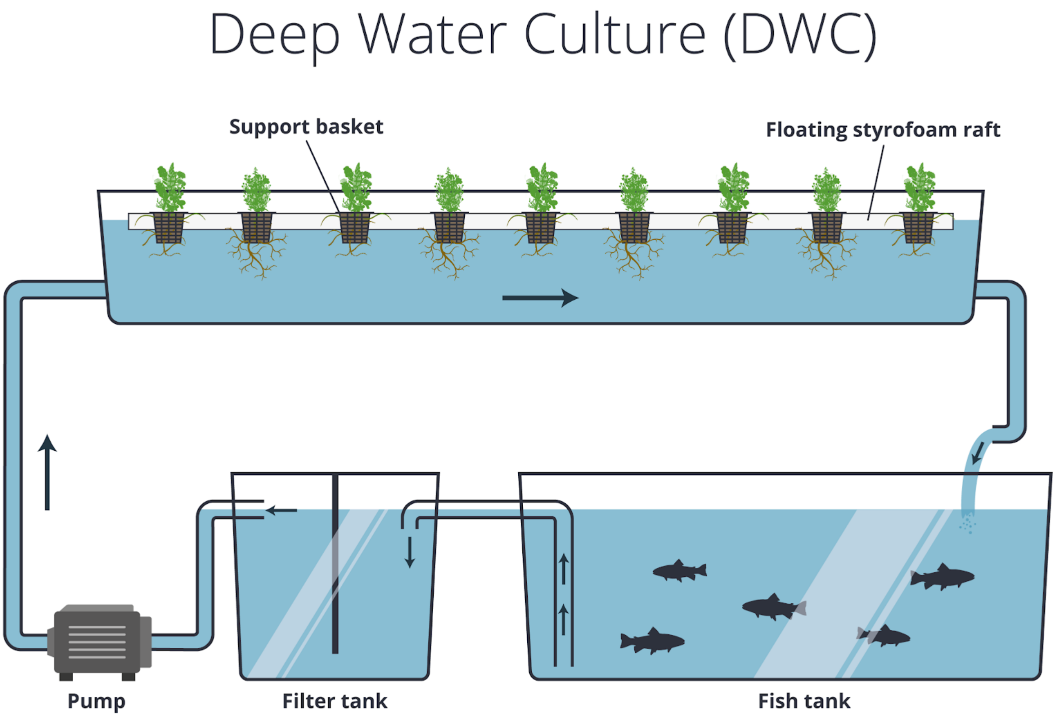


Figure 5 Deep Water Culture (DWC)

Strengths:
The large volume of water used in this method reduces stress on the fish and water quality problems as it provides a buffer, allowing the temperature to be more sTable. It optimizes floor space by creating a process line; therefore, it is a highly productive setup. Plant seedlings are transplanted on one end of the raft tank. This setup is more lenient as it allows larger margin of error compared to the two other methods. It is inexpensive to build, it can grow bigger plants than the Nutrient Film Technique and removing grown plants is much easier than the Media Bed technique. *(Aquaponics.com, n.d.)*

Weaknesses:
The larger volume of water in the system implies that energy must be used to heat or cool the water if needed. This system requires a higher feed input (more fish) than the other methods to have enough nutrients diluted in the large volume of water. As the roots are immersed in water, they might not receive the right amount of oxygen. Therefore, this setup needs supplemental oxygen to the plants also external filtration is needed. The lack of media means that some other form of filtration must be integrated into the system, for instance, a separate biofilter. *(Aquaponics.com, n.d.)*

Vertical aquaponics

Vertical aquaponics is a way of making the most of the space to grow plants. The challenge of building a vertical aquaponics is to ensure that each plant has enough room, light and nutrients to grow while trying to minimize the space between them. These types of systems can grow as much biomass in a 1.5 m tower than in 5 m² of horizontal aquaponics. *(Brooke, n.d.)*

Vertical aquaponics is space-efficient and can be built with cheap materials. For example basic plumbing elements, PVC pipes, 3D printed parts. *(Aqualogue.org, n.d.)*

Even though the flow of water is higher, vertical Aquaponics is a subcategory of nutrient film technique. Therefore they share the same strengths and weaknesses. *(The School of Aquaponics, 2017)*

Another problem to keep in mind while building the setup is the circulation of nutrients/oxygen. It is difficult to ensure that all the plants get the right amount of nutrients/oxygen as the topmost plants get more than the lower ones. To avoid this problem small tubes and outlets can be used to supply water directly to each plant. With their small diameter, these small tubes clog fast so filtration is really important.

The lighting of the plants can also be more challenging than in a horizontal setup because LEDs above the aquaponic will not provide light to all the plants equally. Therefore 'light towers' must be installed around the setup to provide the necessary light for the plants to grow. Another downside is that the size of the crops that can be grown in this aquaponics is limited. *(The School of Aquaponics, 2017)*

Zipgrow uses a combination of the nutrient film technique and the media bed technique. In their towers, displayed in Figure 6, the water drips down into an inert polymer foam, which is assembled between a square-shaped aluminium profile. The plants themselves are placed in between the two sides of the foam, sticking out on only one side of the tower. This makes it easier to light the entire tower. An advantage of this technique is that there are fewer temperature fluctuations because of the growing medium. Of course, most of the abovementioned disadvantages are still present in this tower system as well. *(ZipGrow, 2019)*

Figure 6 Zipgrow Tower. (ZipGrow, 2019)

2.2.2 Existing state-of-the-art systems

The existing state of the art systems are more hydroponics related. Therefore, the discussed state of the art systems are to get inspiration for the Hygrow aquaponic system.

EDEN ISS

Figure 7 EDEN ISS Greenhouse at Neumayer Station III, Antarctica. (EDEN ISS, 2019)

The goal of the EDEN ISS project is to further develop controlled environment technologies, to implement them into the ISS and future space missions. Their greenhouse, shown in Figure 7, is currently running on Antarctica. They are also still working to convert their existing Antarctica greenhouse design to a lunar and martian design.

The system is in its essence a high-tech hydroponic greenhouse. It consists of two sections: a greenhouse- and service section. In the greenhouse section, they grow leafy greens like lettuce, swiss chard and red mustard plants, also herbs like basil and coriander and furthermore tomatoes, cucumbers and peppers. The plants use no soil and are continuously provided by nutrient-rich water through the technique of aeroponics. A high performance LED lighting-system makes photosynthesis possible. The service section consists of all the controlling systems and a workbench with a sink to keep everything clean. It contains a nutrient-control system, atmosphere management system and the central control system. In the central control system, all the inputs from the sensors enter the computer modules. These inputs are then all controlled by a computer with a predefined algorithm. This algorithm outputs commands back to all the subsystems, which in its turn is basically able to control the greenhouse. *(EDEN ISS, 2019)*

This installation can be described as the most advanced hydroponic system in existence. Remarkable characteristics, like a central control system to automatically direct all of the different subsystems which allows the plants to grow in an almost optimal manner, combined with the harsh climate it functions in, makes it an example in the world of hydroponic plant growth.

Freight Farms

Figure 8 Greenery by Freight Farms. (Freight Farms, 2019)

Freight farms is a company that creates and exports hydroponic farming containers, aimed at urbanized local food production. The company is made out of three sections: Greenery, Grown and Farmhand. Greenery, which is displayed in Figure 8 is their own hydroponic container, fully optimized to be productive and efficient. Grown is a service they created to eliminate all the pain points users could encounter when starting their farm. Farmhand is an Internet of Things (IoT) management and automation platform which users can use to monitor their farm on the go. The container consists of two main areas, a nursery station and a cultivation area. In the nursery station, seeds can grow out to small plants, which can then grow in the cultivation area. They use an ebb and flow media bed system for this germination process. The correct water level and nutrient concentration are all controlled by sensors and the central Farmhand system. For their cultivating area, they use a vertical drip irrigation system, able to irrigate up to 8800 plants at once. The rows can be configured depending on the vegetable mix that is grown. The irrigation system is automated using smart drip emitters. The container itself is very well isolated and accommodated with all necessary climate control systems, like a dehumidifier, airflow regulators and a CO_2 regulator. *(Freight Farms, 2019)*

Other state-of-the-art companies
When it comes to the cutting edge in non-conventional farming, the above-mentioned systems truly are the state of the art in hydroponic indoor plant growth. The concept of aquaponics and aquaculture in general is still quite new, this does not mean that there are not any aquaponic or hydroponic companies who operate at a high tech level. *Aerofarms,* for example, considers itself as a leader in indoor vertical farming *(AeroFarms, 2019)*. *Growtainer* is another example of a company that is trying to push the boundaries in hydroponics by using container-sized modules, emphasizing on portability of the system. They use an ebb & flow media bed system *(Growtainer, 2019)*. *Aquaponics Iberia* is an example of a consulting company in aquaponics. These kinds of companies are emerging more and more, often created by aquaponic experts who want to educate more people on the subject, to make aquaponics more widespread *(Aquaponics Iberia, 2019*).

Twenty more examples could be given of these sorts of companies. They are all built on the existing research on aquaponics and hydroponics that is already out there. That is why it is good to take inspiration from these companies and technologies that are pushing the boundaries.

2.2.3 Existing 3D printed aquaponics

Although 3D printing aquaponics is a recent option and there is limited literature and research about it, there are some companies that have worked on similar projects.

The British architect, Mihai Chiriac from DS 10 Studio at The University of Westminster, designed an aquaponically self-sustaining house that can be 3D printed with plant-based bioplastic; all without creating waste and producing more food per square meter than any other agriculture method, see Figure 9. This material can be created at home by vegeTable scratch *(Laylin and Laylin, 2016)*.

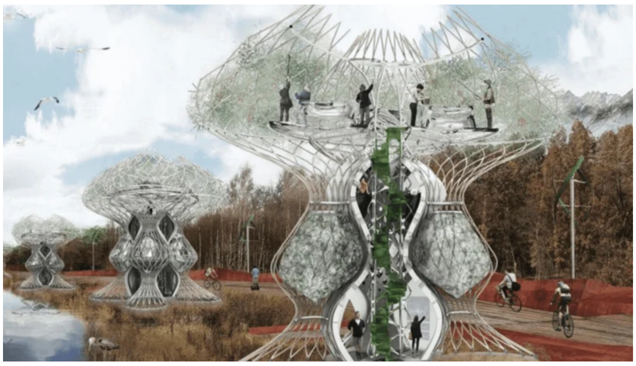


Figure 9 Design of a 3D printing aquaponically self-sustaining house. (Hunt, 2016)

3Dponics is a company founded in 2014 that offers free designs of hydroponic systems that can be downloaded from their webpage and customized. *(3Dponics, n.d.)* In 2015, 3Dponics designed the first 3D prinTable hydroponics system for medical marijuana *(Hoopes, 2015)*. Some more information about 3Dponics and examples of pieces can be found in hand off package document 02. aquaponics research report.

Cascaqua designed a small but static aquaponic system, see Figure 10. This was designed with small waterfalls to mask the sound of the pump. It can be printed in just 8 hours and requires to be printed with ABS *(Avooq.com, n.d.)*.

Figure 10 Cascaqua aquaponic system. (Avooq.com, n.d.)

2.3 Hydroponics

Hydroponics is the method of growing plants without soil *(SimplyHydro, 2008)*. There are different ways of growing plants hydroponically. In one popular method, the plants are placed upright in a plastic trough and a nutrient solution seeps past their roots. In theory, almost any plant can be grown hydroponically but some plants inevitably grow better than others *(Woodford, 2019)*. It is possible to avoid using fertilizer generally if plants are added to the system at a later date during the start-up process while the right nutrient levels are establishing.

2.3.1 Plants

Plants tend to die in new aquaponic systems since bacteria need time to develop in such a system. Fertilizer can be added to help plants grow in the first phases. Some fertilizers can damage other organisms, so the fertilizer must be chosen taking the system into account. *(Kishor, 2018)*

In the literature could be found a number of plants which tribes the best, but this is only a small selection and is not connected to valuable system-individual argumentations. Crop Diversification Center in Brooks, Alberta, has reported growing over 60 different food crops in their aquaponics trials, including leafy green vegeTables, herb crops, fruiting crops, beans and flowers. Because of this huge number of growable plants in aquaponic systems, the decision of plants for the system is more based on finding something which summarizes plants in different similarities. This is usually connected to the grower its objectives and the targeted design. *(Nelson, Pade, & Inc., 2010)*

The first classification should be based on system design. Some plants like tomatoes and corn are mostly grown in media bed systems to provide a structure for the roots and systems which are suiTable for bigger final sizes. Therefore they should not be considered to be used in comparing different systems. Bigger final sizes mean that those plants are more recommended for flat system designs. If space is limited and it should be made the best use of the room, like a container or an industrial hall, plants with a lower final size are to be preferred. This allows for achieving more plants per volume in a vertical system.

After this categorization, it is necessary also to take the targeted fish species into account. The room temperature is often connected to the water temperature and therefore this is the decision about the climate for both. Because of the demand for heating and cooling the climate is often connected with the surrounding climate and thereby also to the available fish species. This leads to the next sorting of the plants into temperatures where they thrive best for example in cold (15-22 °C), middle (20-25 °C) and warm (24-30 °C). At least now it is necessary to include the economic factor. For example, to make a profit the crops should have a high market value or also a short harvesting time. Herbs like basil, chives, cilantro and parsley are good options because they all have harvest times between 25 and 40 days and have a high profiTable value in the market. Also, different kinds of salad are often grown in commercial aquaponic systems. Salad has a low market value but a short harvesting time a high reliable harvest for economical calculations and low requirements to grow. Therefore the reliability versus diversity of produced crops should be considered. For example, crops do not have a fruiting stage, the nutrient requirements stay consistent and the harvest becomes more reliable. Other leafy green vegeTables that have similar properties as lettuce are swiss chard, pak choi, Chinese cabbage, collard and watercress.

This shows that different plants have different demands which should always be kept in consideration. In the start-up, plants have a low ammonia demand and the uptake of some nutrients like potassium or trace elements in the fruiting stage could change. Because the fish feed keeps usually the same and often does not contain the special nutrient concentrations for plants. This could lead to the case that the water in the system will accumulate or run out of some nutrition. A combination of different vegeTables like herbs and leafy green plants could be a solution for changes in the nutrition demand. Another classification that should not be forgotten is the different disease susceptibility and pest resistance. *(Nelson, Pade, & Inc., 2010) (Somerville, et al., 2014) (Kishor, 2018) (Kim, 2018) (Martin, 2017) (Grove, 2016)*

The last classification which breaks down the huge number of plants in a few plant species is the decision on plants which are good to start-up and for operators who are new in the field of aquaponic systems. In the beginning, it should be concentrated on the functionality of the system. Therefore plants should be avoided which have a high disease susceptibility like tomatoes and cucumbers. In order to have a smooth start-up of the system without bigger changes of nutrient concentrations, it is advisable to choose plants which have the same nutrient requirements throughout their cultivation and may also require less overall consumption. Plants with fruiting stages like tomatoes, melons and peppers undergo different stages of growth, from the formation of the leaf mass to the fruit. Between the stage, the nutrition requirements are varying and therefore they should be avoided for the first system to be designed. There is also a higher risk of diseases and pests in fruiting plants. Plants who have low nutrient demands are from herb species and from the family of swiss chard or spinach. *(Nelson, Pade, & Inc., 2010) (Martin, 2017)*

To summarize all above-described argumentations about important points of the plant decision the Table 9 in 'Handoff package/02. aquaponics research/02'. aquaponics research' shows the described classification and more examples of plants used in aquaponic systems.

2.3.2 Growing media

Another important part of the hydroponic part of aquaponics, is to choose the right type of growing media. There are several conventional substrates for hydroponic seedling production. The target of every material is to provide good physical contact with seeds. The substrate source could be based on organic and mineral components or also on synthetic media like plugs, cubes and blocks. The selection is often based on the local availability, how quickly they decompose and the amount of additional solids needed. Grow media should consist of mineral components and synthetic media. *(Kim, 2018)*. Some systems, such as NFT or DWC, require a container and grow up material for the plants to keep them in their spot and to ensure the support of the roots. This task is usually done by plastic pots or cups and nets with an extra-wide lip. Additionally, there should be both enough holes, to ensure a good root growth, and enough holes, to hold back the substrate. *(Sean, 2019)*

2.3.3 Nutrient demand

Different species have different nutrient demand. Especially if the species which should be farmed together are from different fields like plants and animals. If the system should be run in a cycle and the only nutrient input is the feed for fish, some necessary nutrients for plants will run out and some from plants unused nutrients will accumulate in the system. Therefore it is important to know the nutrient demand for plants and which nutrients should be supplemented to avoid losses in required concentration. In an aquaponic system, this is often the case for iron (Fe), calcium (Ca), magnesia (Mg) and potassium (K). Iron could be added with a source of chelated Fe like a solution of Fe(III)-EDTA. The concentration of Ca and Mg can be maintained with $Ca(OH)_2$ as solution or with $CaCO_3$ as powder or crushed shells and $MgCO_3$ or $Mg(OH)_2$. Through the hydroxide this could be used also to maintain the pH. (Thorarinsdottir, 2015)

2.3.4 Humidity demand

Humidity is a factor of the system which is connected to the ventilation system, this is only important for the hydroponic part. Humidity is connected in the plant to the self-priming system of taking water from the ground or in an aquaponic system from the water. This also depends on the receptiveness of CO_2 from the air. To achieve the optimum growing conditions it is necessary to provide the humidity level plants thrives the best. Because there are some differences between plant species it is recommended to provide a level which is most convenient for all plants. Usually, plants can grow in humidity levels between 45 and 75 % and tropical plant species which need a higher temperature also need a higher humidity level. *'Handoff package/02. Aquaponics research/ 02. Aquaponics research*

2.4 Aquaculture

The term aquaculture refers to the cultivation of aquatic animals in controlled aquatic environments for commercial, recreational or public purpose. Aquaculture is one of the fastest-growing forms of food production in the world. Since harvest from many wild fisheries has spiked globally, aquaculture is widely recognized as an effective way to meet the seafood demands of a growing population. (National Oceanic and Atmospheric Administration, 2011)

There is a rule of thumb which easily shows the advantage of connecting aquaculture with hydroponics to the system aquaponic (Martin, 2017):
"In aquaculture you produce 1 kg of fish meat for each kg of fish food given, but in aquaponics you produce 1 kg of fish meat plus 5-10 kg of vegeTables (remember that most of the mass of plants come from fixing CO_2) for each kg of fish food given (Rakocy et al. 2006)."

2.4.1 Types of fish

Fish are the elementary component of the Aquaponic system which means the starting point of the cycle. The fish will be fed by the people who work on the system and nature will do the rest, although they should be watched every day to control their well being. To choose which type of fish is the best for the project, it should be fixed is they are only there to support the plants or if they should be edible. This means that economics and marketing options of the aquaponic system should also be taken into account. Just as how much care the species need, how much is desirable to raise and sell and what climate conditions are prevalent. *(Kishor, 2018)*

Fish decision
The types of fish that are chosen depends on various factors. These can be the type of plants that are willing to grow, warm (24-30 °C) or cool (16-24 °C) water fish, and the breeding of the fish. Also, the legality of different species and their availability should be taken into account. Friendly aquaponics says "getting fish can be the hardest part; get some "gold" instead!" *(Friendly Aquaponics, n.d.)*. Beside most used fish for aquaponics, there should be also thought about the availability and possibilities of using local fish *(Kishor, 2018)*.

Because in the literature there are many different fish species recommended to use for aquaponics. It is important to find the most suiTable species for each individual system. This means that tilapia, the most recommended fish species generally for aquaponics, is not always the most suiTable for the system to be developed. At first, it is necessary to know which climate surrounds the system to make a classification of the species in cool and warm water. If the aquaponic system is to be operated in northern European cold climate, it is advantageous to grow cool-water fish to avoid a high expenditure for heating. Recommended cool water species for aquaponics for these regions are trout, sturgeon and carp.

Another influence on the decision is the optimisation for one region or for regions worldwide in different climates. Worldwide means to find species which are mostly distributed in the world and have nearly everywhere a high availability. For this system design tilapia would be the fish of choice. However, it could happen that it still is not available in each country like in Finland. Therefore it is to be expected that the fingerlings for stocking must be imported and often only in large numbers. Under these circumstances, it may be decided for locally available fish species.

Another advantage of local fish is the economical point of view. At first, it could be cheaper to buy local fingerlings than imported often used tilapia. Furthermore, the profit of the system is influenced by the market value of the fish to be sold. Tilapia has generally a high market value. But now it is also with the availability, in some regions like Finland tilapia is not very well known and widespread. This means that entering the local market is difficult and therefore often possible to produce local fish species with a much higher market value. In northern countries, carp and trout are very common and profiTable grown in ponds. To find local suiTable species for aquaponic systems for a special area it could help to compare in this region in ponds grown fish species with recommended species for aquaponics in the literature. Sturgeon is also a cool water fish species which has a high market value and is known in most European countries, but because of its high acquisition costs, beginners should consider which maximum expenses can be risked at the beginning for the start-up.

Influence on the fish species is also based on the nature of the aquaponic system itself. During the start-up to reach a sTable operating point or also during operation it is possible that higher changes in water quality parameters can occur. In this regard, it is advantageous to opt for species which can stand higher changes like tilapia for warm water and carp for cool water. Trout is on the other side in terms of water quality a very demanding fish and therefore not recommended for beginners. Another influence is the maximal growable density. If the goal is to accommodate the system in a space-saving way to maximise the outcome of a special volume of room, it is necessary to choose a fish species for growing in high density. Fish for high density are tilapia and carp and not recommended are trout and because of the bigger size sturgeon.

Also considered should be the adaptability to the new environment in the aquaponic system or to other fish species. For example, tilapia can be grown together with carps. The advantage of different species is minimizing risk by allocating the quantities of sales per fish species and increasing the food diversity to be offered. Connected to growing different species in one tank is the kind of feed for the fish. It is possible to grow omnivore species and herbivore species with the same feed, but not herbivore and carnivore. Another aspect of the fish feed which is associated with the decision for a species is the availability. In northern European countries like Finland, it could be possible that both the fish as well the feed must be imported. Because aquaponics is is one closed water cycle, the decided fish species influences with the temperature range the assortment of plant species which could be grown. Most different plants species can be grown in a temperature range between 20 and 25 °C. The least diversity of plants can be grown with cool water fish like trout where the optimal temperature is around 16 and should not exceed 18 °C. *(Kishor, 2018) (Aquasi, 2019) (Editorial Staff, 2019) (Connolly, K., Trebic, 2010)*

Especially for aquaponic systems in smaller scale, it could happen that it becomes almost impossible to find fish sources of local fingerlings in small numbers. To avoid this insight in too advanced a time, it could be useful to screen at the beginning of the prospective region for freshwater fish farms. If there could not be found any freshwater farm means to put at first most time in finding sources of fingerlings at accepTable conditions. In very small aquaponic systems only a small number of fish is needed. In this case, it is also possible to catch fingerlings of the right local fish species in surrounding natural waters. If it was decided for this way it should be calculated some time to change the feed from a natural source like worms into an artificial source. Especially difficult can it be for carnivore fish species, because of their natural stimulus for moving living food. This could be avoided when the source of fish is a pet store like a species of goldfish. Goldfish are usually everywhere for a cheap price available and easy to keep. They can stand changes in water quality and temperature and therefore often recommended for beginners. But because the sense of an aquaponic system is to raise fish and grow plants in the same time and to benefit from both as food, goldfish should be only used for the beginning until other sources of fish are found. *(Editorial Staff, 2019) (Kishor, 2018)*

Tilapia for Aquaponics

Because an aquaponic system is not always easy to maintain, changes in all parameters can occur. To minimize the risk of high fish losses, species that can survive under wide ranges, like tilapia, are often used. *(Connolly, K., Trebic, 2010)*. Furthermore, they are also suiTable for a large diversity of plants in aquaponic systems. It is the fastest-growing species, has a high stocking density and its meat is very appreciated in the US. Because of these benefits, most research results on tilapia in aquaponics systems are available. *(Connolly, Trebic, 2010) (Editorial Staff, 2019)*

2.4.2 Shrimps and their Benefits in Aquaponics

"Using freshwater shrimps to create a better aquaponics nutrition cycle." (Brooke, n.d.).

One interesting approach in the literature was to combine usual growing fish and prawns or shrimps in the same aquaponic system. In theory, all nutrients which enter the system by feeding the fish completely transferred into usable components for plant growth. However, after some time it is found out that solid waste accumulates in the system. Shrimps live more at the water its ground and therefore, they pick up all residual organic material which cleans the fish tank. This also means that they accelerate the decomposition process of organic material and therefore, less maintenance is needed. *(Somerville, et al., 2014).* Another advantage is that shrimps offer an easy way to expand the aquacultural food production variety of an aquaponic system.

2.4.3 Fish feed

Once the team has the fish, it is important to know how to feed the fish to be sure that they will be healthy and strong. In this chapter is explained which type of food the fish should eat, how often the team should feed them and if it is possible to grow fish food inside the aquaponics system.

Which type

When it comes to feeding, fish can be divided into different categories, for example in herbivores, omnivores and carnivores. They can also be categorised by method of eating, depending on the depth level in the tank where they eat. There are top feeding fish, middle feeding fish, bottom-feeding fish and grazers (fish which search for food on the surfaces of the aquarium). Furthermore, it is possible to distinguish commercial from non-commercial feed in terms of shape and form. (Home Aquaria, 2014) This is shown in Table 1.

Table 1 Commercial vs. non-commercial fish feeds

Commercial				Non-commercial	
Flakes	Granules	Discs	Frozen	Living	Home made
Crisps	Pellets	Gel foods	Freeze-dried		

Amount and frequency

The amount and frequency of feeding is dependent on the fish species and on the size of the fish. Generally speaking, small larval fish should be fed plenty and quite frequently because they have a high energy demand. As fish mature, feeding rates and frequency should be decreased, as well as protein content in the food. It is not necessary to switch feeds entirely, giving less of the proteïn-rich food is also possible. The precise amount of necessary feed that needs to be given can be calculated by the formula in chapter 2.7.1 Calculations fish and plant ratios, but a good way to do this without calculating is to see whether the fish eat the fed within 15 minutes of feeding. If they do, a bit more can be given, if they do not, a little bit less can be given. *(Craig, 2017)*

Fully closing the loop

An idea came up during one of the brainstorming sessions in the team. "What if the aquaponic cycle could be fully closed?". There would be no need to buy industrially made fish feed if one would use the waste products of the plants (roots, leaves…) as fish feed. This would save a lot of money. The key to achieving this depends on two factors: choosing the right plant species and making sure there is enough organic matter being produced to feed the fish.

The first criteria is most likely possible, but it highly depends on the type of fish species. Each species has its own feeding requirements. This includes the nutrition like proteins and vitamins for example. For most aquaponic fish it is possible to find a matching plant that can be grown to feed them. Not all the nutrients needed for the fish to grow optimally will be present in a purely plant-based diet. So if one wants to build an aquaponic system focused on fish production, this method will not be possible. *(FAO, 2019) (Tilapia Feed Formulation and Feeding Technique, 2019)*

The second criteria for this fully closed system to work, is making sure that there is enough matter to feed the fish. The problem here is that the ratio between the growth rate of the plants and the feed consumption of the fish will not be in balance. A plant simply grows to slow to support this system. *(Mann, T. 2015)*

Achieving these two elements within an aquaponic system in a container is not realistic. However, producing your own fish feed is possible if you do it externally. Growing these amphibious plants in combination with black soldier fly larvae has successfully been done by other people. Adding some more elements to this fish feeding mixture could result in a highly nutritious feed. It would be a very good option in terms of sustainability.

2.5 Water treatment

In theory, the input of the aquaponic system is completely transferred into fish and plant growth. This means that the water treatment is only needed to convert from fish unused nutrients into a plant-available form. This task is done by bacteria in the biofilter. Another source of solids are some inorganic compounds of fish food . At least the inorganic compounds enter the system and have to leave it as dead mass. To avoid an accumulation of unchanged particles in other parts of the system, a mechanical filter has to be implemented to remove solids.

2.5.1 Without separate water treatment

As described in chapter 2.2.1 Main types it is also possible to build an aquaponic system in which the hydroponic part can take over the task of water treatment. The most common way is the media bed culture that contains gravel. In this case, also solids which could not be broken down are collected in the media bed. Those zones could bring the system to a standstill or could be clogged.

2.5.2 Solids removal

In the literature different designs about removing solids from water could be found. The easiest way with the function of removing solids is to use a settling tank. The maintenance is reduced to a minimum. Because the settling of solids is driven by gravity the turbulence should be very slow. To reach a high efficiency it needs a lot of space.
In 'Handoff package/02. Aquaponics research/02. Aquaponics research' it is explained how different settling tanks work. *(Thorarinsdottir, 2015) (Rakoczy, et al, 2006) (Strzelecki, Tidwell, 2012)*

To increase the efficiency of the solid removal, additional centrifugal forces can be implemented through leading the inlet water stream on a centrifugal flow. The centrifugal drives the particles to the wall and the gravity forces to the bottom. This separates particles and the water faster. On the other side the clean water ascends and reaches the exit in the middle on the surface.

2.5.3 Biofiltration

It is possible to determine certain bacteria for special tasks. But usually there is always a huge number of different bacteria involved in converting nutrient sources or supporting the main working bacteria. This bacteria collection is named biofilm and can grow on nearly each surface which is not antibacterial. It is also necessary to buffer the system and stabilize the pH. pH measurement is one of the most important parameters to control. *(Sterzelecki, Tidwell, 2012)*

After releasing the first ammonia into the aquaponic system, ammonia and ammonium concentration peaks as shown in Figure 11. Because bacteria (Nitrosomonas) have to grow to the necessary number to use the newly won feed for them. This happens in the same way to the conversion from nitrite to nitrate (Nitrobacter). *(Sterzelecki, Tidwell, 2012)*

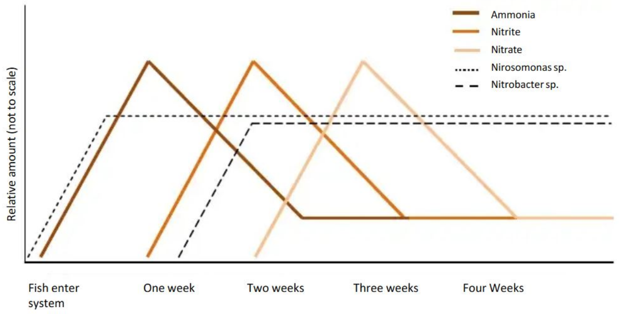


Figure 13: A not-to-scale graphical representation of the nitrogen cycle resulting from the addition of fish to an aquaponic fish tank (Nelson, 2008).

Figure 11 Resulting nitrogen cycle after start-up the aquaponic system with adding fish to the tank. (Sterzelecki, Tidwell, 2012)

In most aquaponic systems it is necessary to stop the nitrogen cycle at the point of nitration because this has to be used by the plants. If the concentration of nitrogen in the system reaches a level that is too high for the fish, it can also stop the function of the bacteria. In this case it is necessary to continue the natural way.

Nature uses a nitrogen cycle, which is driven by bacteria and includes nitrification and denitrification. One part of the nitrate is directly used for plants and the other part is converted through bacteria in the denitrification to nitrogen. In an aquaponic system the cycle stops after the nitrification. This allows to use all the produced nitrate for growing plants. *(Martin, 2017)*

To visualize the senns of using bacteria in the system Figure 12 shows the flow of converting nutrients from the fish food into usable nutrients for the plants. *(Somerville, et al., 2014)*

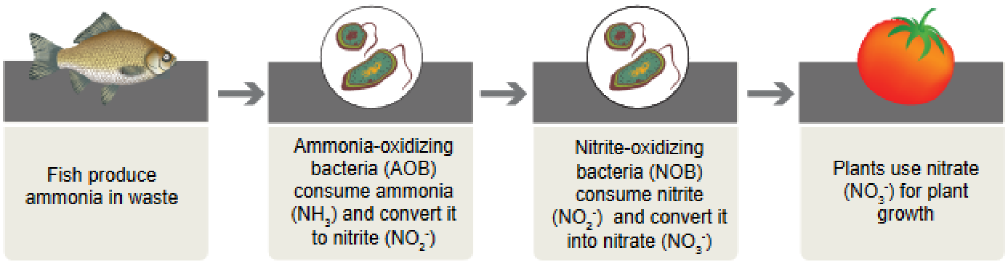


Figure 12 Implementation of the nitrification process in an aquaponic system. (Somerville, et al., 2014)

Like fish and plants also bacteria have conditions where they reduce working or die. The overall working conditions for bacteria are between 17 and 34°C, a pH value of 6 to 8.5, less than 3 mg/L of ammonium and nitrite, less than 400 mg/L of nitrate and between 4 and 8 mg/L of dissolved oxygen.

To convert the produced amount of ammonium, the right amount of bacteria is needed. One way to make sure that there is enough bacteria is to implement an aerated moving bed bio reactor (MBBR). In this type of biofilter it is possible to provide a huge value of surface area per volume with bio balls. Figure 13 a) show a running MBBR and Figure 13 b) shows an example for commercial available bio balls. *(Somerville, et al., 2014) (Sterzelecki, Tidwell, 2012)*

Figure 13 Aerated moving bed bioreactor (MBBR) (a) containing plastic filter medium (b) (bio-balls). (Somerville, et al., 2014)

If the MBBR is implemented in the aquaponic system there should be a mechanical solids separation device, as described in chapter 2.5.3 Biofiltration and must be connected like Figure 14 shows. This prevents that solids accumulate in the MBBR tank. *(Somerville, et al., 2014)*

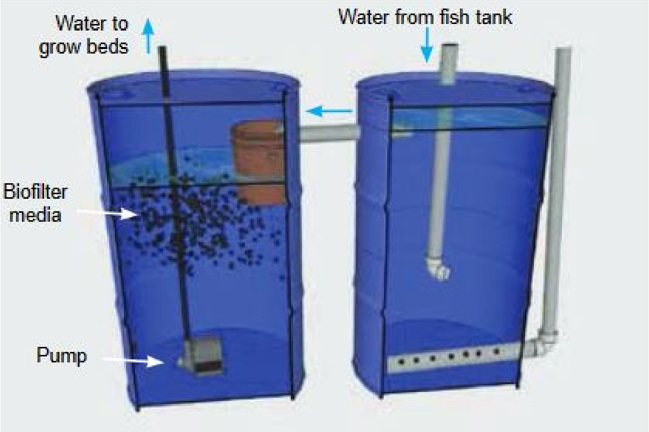


Figure 14 Combination of a cylindrical mechanical solids separator (right) with a biofilter (MBBR) (Somerville, et al., 2014)

2.5.4 Additional fish and plants for clarifying

Besides the clarifying devices that are described before, it is possible to support this task by using additional clarifying options. One way is already described in chapter 2.4.2 Shrimps and their Benefits in Aquaponics. In other literature is written about fingerlings fish which are used to avoid cloning of the connecting pipe between fish tank and first clarifier tank. Those small fishes reduce settled solids in the pipe and settling tank. Another way of reducing too high concentrations of nitrate in the system is to use duckweed. *(Rakocy, et al, 2006) (Somerville, et al., 2014) (Martin, 2017)*

2.6 Parameters

It is very important to maintain different parameters in the water to make sure the plants and fish stay healthy. “Parameters are definable, measurable, and constant or variable characteristic, dimension, property, or value, selected from a set of data or population because it is considered essential to understanding a situation or in solving a problem” (BusinessDictionary.com, n.d.). Important water quality parameters include: dissolved oxygen, pH, temperature, total nitrogen, and water alkalinity (Fao.org, 2015). These parameters and the parameters that are important for plants are further discussed in this paragraph. (Thorarinsdottir, 2015)

2.6.1 Species-dependent Parameters

In the literature general values of parameters for an aquaponic system were often mentioned. However, each system is designed for different species of plants and fish. Therefore, each parameter has an optimal value for each part of the system which could be species-dependent in further considerations. The discussed parameters are only an example and should be selected individually for each system design. The main focus in this chapter is on the influences of each parameter. This is important to understand the chemical functionalities of the system and rational interventions in case of deviations.

Figure 15 visualises the temperature dependence of plants, bacteria and fish, divided for warm and cool regions. It is not possible to reach the optimal conditions for each component. Especially for the temperature range of cool weather plants and fish up to 21 °C does not match the bacteria. This leads to a decrease of efficient converting nutrients.. The optimal conditions for fish and plants should be taken serious to maintain their health.

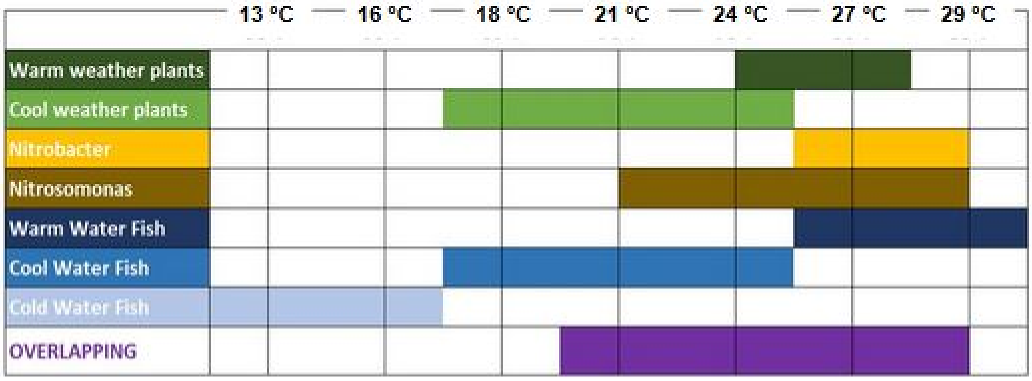


Figure 15 Temperature dependence of plants, bacteria and fish.

2.6.2 Temperature

In chapter 2.4.1 Types of fish, different types of fish are discussed. Every type of fish has a different origin and are therefore used to living in different environments. For instance, there are warm water fish and cold water fish. Depending on what type of fish is used, the temperature of the water should be adjusted, otherwise the fish can suffer or die (*Thescientificfisherman.com, n.d.*).

In *Small-scale aquaponic food production* is mentioned: Water temperature is an important parameter for bacteria, and for aquaponics in general. The ideal temperature range for bacterial growth and productivity is 17-34 °C. *(Somerville et al., 2014)* Temperatures between 18 °C and 30 °C are suiTable for plants to grow (*Fao.org, 2015*). For all these reasons listed above the water temperature must be controlled and maintained.

2.6.3 Dissolved Oxygen

“Dissolved oxygen (DO) is one of the most important parameters for growing fish and is also critical to the beneficial nitrifying bacteria that convert fish waste into nutrients plants can use” (*Sallenave, 2016*). Without oxygen, the nitrifying reaction will stop. (*Fao.org, 2015*). Therefore, the processes in the aquaponic will get disturbed, which can cause the death of fish and plants through reaching toxic nutrient levels. Plants could also experience root-rot, this can cause the roots to die and fungus to grow. (*Fao.org, 2015*)

The following Figure 16 shows the temperature dependence of soluble oxygen in water. At higher temperatures less oxygen is soluble.

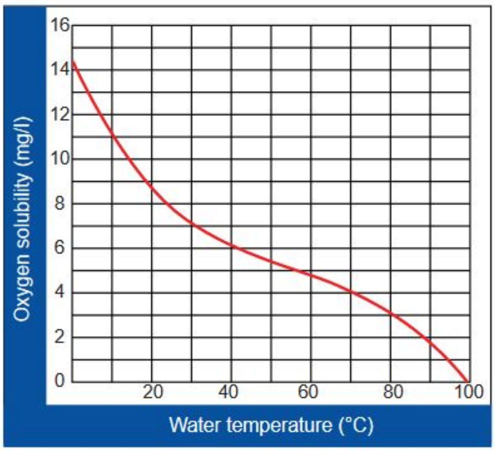


Figure 16 The oxygen solubility in water at different temperatures (fao, 2015)

2.6.4 pH-Value

One of the most important water parameters is the power of hydrogen (pH) (*Fao.org, 2015*). “pH is a measure of hydrogen ion concentration, a measure of the acidity or alkalinity of a solution. The pH scale usually ranges from 0 to 14. Aqueous solutions at 25°C with a pH less than 7 are acidic, while those with a pH greater than 7 are basic or alkaline.” (*Helmenstine, 2019*). pH influences many other parameters (*Sallenave, 2016*). “It is important to maintain pH at levels that are accepTable to both fish and plants.” (*Sallenave, 2016*). “If pH levels get too low, nitrification will slow down or stop and ammonium will accumulate in acidic solutions to levels that are toxic to the fish.” (*Sallenave, 2016*).

As visible in Figure 17 in a basic solution ammonia is chemically preferably formed. Especially at higher temperatures more ammonia is un-ionized. To avoid a loss of fish due to toxic concentrations the pH-level should be maintained to stay below 7.5.

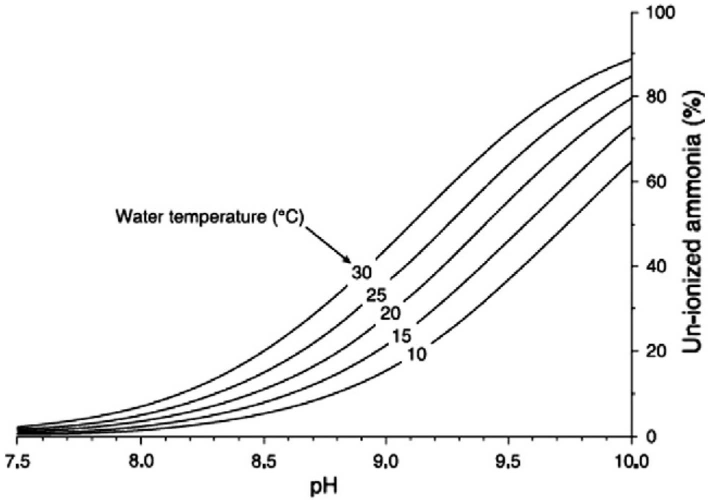


Figure 17 Dependency of ammonia and ammonium balance (Editorial, 2019)

Because of the pH-dependency of the balance between ammonia (NH_3) and ammonium (NH_4^+) the overall concentration of nitrogen in both compounds is often characterized as total ammonia nitrogen (TAN). The highest impact of the TAN value can be reached at high temperatures (32 °C) and high pH (8.4), where already 0.1 ppm could be toxic.

“The pH is the most important parameter for plants in an aquaponic system because it influences a plant its access to nutrients.” (*Fao.org, 2015*). If the pH goes outside the tolerance range, plants experience nutrient lockout. However, it is not possible to maintain an optimal pH for all nutrients. In contrast, fish can tolerate a wide range of pH, but can not handle changes of pH in a short period of time. Therefore, it is important to keep the pH level as sTable as possible.

To prevent the fish dying and the plants experiencing a nutrient lockout, it is necessary to maintain and measure the pH daily. For small-scale aquaponics a net-bag with crushed shells can be used as buffer system (*Fao.org, 2015*)

2.6.5 Nitrogen: Ammonia, Ammonium, Nitrite and Nitrate

Nitrogen enters the aquaponic system from the fish food as a protein. Some of the protein is used by the fish to grow, whereas the rest is released as waste in the form of ammonia (NH_3) and ammonium (NH_4^+). Bacteria converts the ammonia in the first step into nitrite (NO_2^-) and in the second into nitrate (NO_3^-). (*Fao.org, 2015*)

Ammonia is toxic to fish. Some of the most common symptoms of ammonia poisoning are: loss of equilibrium, impaired respiration, convulsions, red colouration and inflammation on the gills. Ammonia poisoning leads will eventually kill the fish. High levels of ammonia or lower levels over a long period, can result in fish stress, increased incidence of disease and fish loss. Therefore the ammonia level should be close to zero at all times.

Similar as ammonia, nitrite is also toxic to fish. High levels of nitrite prevent the transport of oxygen within the bloodstream of fish. Low levels over a long period have the same effects on the fish as ammonia. Nitrate is the most accessible form of nitrogen for plants because it is far less toxic than ammonia and nitrite. High levels of nitrate like 300-400 ppm (*Connolly, Trebic, 2010*) leads to excessive vegative growth and hazardous accumulation of nitrates in leaves, which is dangerous for human health. (*Fao.org, 2015*)

It is very important to convert ammonia and nitrite to nitrate. As a cause of that it is necessary to control the ammonia, ammonium, nitrite and nitrate levels to make sure that the tolerating levels are not being exceeded and the conversion through the bacteria is efficient and ongoing.

2.6.6 Additional parameters

Nitrogen-depending parameters and functionality of bacteria should be checked with an online measurement. One robuste option to check the overall nutrient concentration in the system is an electrical conductivity sensor. Bacteria could be checked with a redox-potential sensor. With daily online measurements trends can be earlier evaluated and reacted to it.

The above mentioned parameters like temperature, oxygen and pH also can be followed with daily online measurements.

2.6.7 Parameter suggestion - northern European climate

The following Table 2 is a suggestion of parameters for an aquaponic system in north Europa. It summarizes the chapter 2.6 Parameters and could be used as a general recommendation for designing a system which should operate in Finland. Species of cool water fish and cool weather plants should be selected so that they have optimal growth conditions. Concentrations of ammonia, ammonium, nitrite and nitrate mainly concern the fish and may differ depending on the species. The parameters in Table 2 are already given in low concentrations, as they are generally lower for cold water fish like described in chapter 2.4.1 Types of fish.

Table 2 Possible ranges of important parameters for an aquaponic system in northern European climate

Parameters	**Cool water Fish**	**Cool weather Plants**	**Bacteria**	**Cool water Aquaponics**	Unit
Temperature	10 - 22	16 - 25	17 - 34	**18 - 22**	°C
pH	6 - 8.5	5.5 - 7.5	6 - 8.5	**6.5 - 7**	-
Dissolved oxygen	4 - 8	> 3	4 - 8	**> 6**	ppm
Ammonia (NH_3)	< 0.1	-	-	**< 0.1**	
Ammonium (NH_4^+)	< 1	< 30	< 3	**< 0.5**	
Nitrite	< 0.1	< 1	< 3	**< 0.1**	
Nitrate	< 400	-	< 400	**5 - 150**	

2.7 Design Calculations

To calculate the overall system design and to size the different parts of the aquaponic system this chapter contains calculations, recommended ratios and values of each component. Like the parameters also the design calculations are species dependent, especially the stocking of plants and fish. For example, carp can be stocked in a higher density than trouts and salat needs a higher nutrient demand than parsley.

2.7.1 Calculations fish and plant ratios

In the literature could be found many different ways to calculate the stocking density for fish and associated with it the necessary plant mass to clean the water. Some calculations start from the available area for plants to calculate the mass of fish through the necessary amount of nitrogen for the plants and from this the mass of fish feed. The fish feed defines finally the mass of fish. Another way is to calculate the area for plants starting from a given mass of fish. Hereby the calculation is based on the targeted achievement of the aquaponic system. Also the size of the pond or tank could be the limiting factor and therefore calculations should start from recommended fish/water ratios. (Lennard, 2012)

Also important to know for calculations is that an Aquaponic system should be brought after the start-up into a sTable phase. This means that all parameters keep the same and the nutrient demand and supply stays sTable. All parts of the system have to each time the same load rate and could be designed for this case. To reach such a system the Nitrogen input (fish feed) and output (fish and plants) should keep steadily. In order to capture this value of the system, it is necessary to stock fish and plants in different sizes, depending on the individual growth rate. If one part of the system is harvested and restocked there should always be enough material in the system to maintain approximately the targeted values of parameters.

Feed conversion rate

The feed conversion rate (FCR) "is the mathematical relationship between the input of feed that has been fed and the weight gain of a population" *(Aquaneo-Techna, n.d.)* and is calculated by dividing the given feed through the animal weight gain. The animal weight gain could be obtained by subtracting the stocking mass from the final end mass of all fish. Figure 18 shows FCRs of different fish species and shrimps. It could be used to calculate the necessary feed in different growing stadiums and refers to the individual weight.

	Average F.C.R
Tropical shrimps	[1.6 - 2.0]
Omnivorous fish	[1.4 - 1.8]
Domesticated carnivorous marine	[1.3 - 1.6]
Salmonids	[1.0 - 1.2]

Figure 18 Comparison of FCR among different fish species and shrimps (Aquaneo-Techna, n.d.)

Fish ratios

Each fish species needs a different fish/water ratio. Another dependency of the stocking density is the fish length. Because the fish grow with time and if it is not targeted to move them the stocking density $D_{density}$ in *formula 1* could be also named harvest density. $C_{density}$ is a fish species dependent empirical value and L is the length of the fish which should be stocked or harvested. *(Sterzelecki, Tidwell, 2012)*

Nitrosomonas:

$$D_{density} = \frac{L}{C_{density}} \qquad [1]$$

The unit of fish density is usually kg/m^3. *Formula 2* shows an example calculation for a trout species with a $C_{density}$ of 0.34 $m^3 \cdot cm/kg$ (for L in cm) and a stocking length of 5 cm (finger length).

$$D_{density} = \frac{5\ cm}{0{,}34\ m^3 \cdot cm/kg} = 14,7\ kg/m^3 \qquad [2]$$

Growing fish in maximum density require expert management skills. To avoid high fish losses, it should be mentioned that new growers should start with half of calculated fish density. *(Sterzelecki, Tidwell, 2012)*

Plant ratios

In the case of dimensioning the system based on the mass of fish, there are again different possibilities to calculate the total mass of plants in the system.

VegeTables per fish

The first method uses an empirical studies in which 0.5 to 10 kg of plants per kg of fish can be grown. This is a very big span but usually it is possible to produce with a ratio higher than 5. With knowing the mass of plants and the type of vegeTables to grow it is possible to calculate the necessary area which should be provided for the water treatment or expressed otherwise to use the produced nutrients. *(Martin, 2017)*

Fish food per square meter

The second method uses the NH_3 cleaning area of the roots. The ratio of this calculation is then based on the input of food which will be transformed partly into ammonia. Without including the efficiency of the bacteria (temperature-dependent) and different fish metabolism which is connected to changes of protein content (Nitrogen) in the fish food, it is a very approximate ratio. In the literature it is recommended to use a ratio of 60 - 100 g fish food/m^2/day, using 80 g for a saver calculation. With the mass of fish which is to be achieved per year $m_{fish/year}$ and the feed conversion rate FCR related to fish species, the necessary surface of growing area *Plants* could be calculated. The surface forms the basis for calculating the mass of vegeTables for different plant varieties. Formula 6 shows the calculation of the growing area with a fish food rate. *(Martin, 2017)*

$$A_{plants} = m_{fish,\,year} \cdot \frac{1}{365\frac{d}{yr}} \cdot FCR \cdot \frac{1}{80\frac{g}{m^2 d}} \qquad [6]$$

By starting the calculations from the hydroponic side, named ratios could be also used to calculate the amount of fish and the species dependent necessary volume of water. To summarize above discussed and described possibilities to calculate the stocking of fish and plants, in the following Table 3 are listed important concepts and units of each component.

Table 3 Important concepts and units for calculating the mass of fish and plants for stocking an aquaponic system

Mass of fish	● **Ammonia as basis (fish feed)** ○ Feeding rate ○ FCR ○ Empirical values ● NH_3 cleaning area of roots ● kg plants / kg fish ● Fish feed / m^2 / day
Mass / area of plants	● Plants / m^2
Watervolume	● kg Fish / m^3 water ● individuums shrimps / m^2

2.7.2 Calculations water treatment

Biofilter tank

The goal of the biofilter is to convert the ammonium into plant available nitrate. It follows that the design is based on the mass of ammonium produced and thus first the ammonium has to be calculated which enter the system via the food.

Nitrogen is found in fish food as a source of protein. Fish food can contain 5 to 50 % of protein but usually studies work with 32 % of proteins. The average content of N in proteins is 0.16 g N per gram protein. From this mass of Nitrogen will enter the water 61 %, 55 % in the form of urea and 6 % in undigested food, which is not used by the fish. To close the transformation of nitrogen, in the end 1.2 gram of NH_3 is produced per gram N. If the normal growing ratio for aquaculture of 1% per day should be achieved, it is necessary to feed the fish with a mass of about 2 % of their weight. With the previous values it is possible to calculate the mass of produced ammonium in kg/day, which forms the basis for calculating the surface area of necessary bacteria for the conversion into nitrate.

Depending on the environmental conditions the activity of the bacteria varies usually between 0.2-2 g NH_3 /m^2 surface/day. Because this is a big span of efficiency, 0.57 could be used to be on the safe side. For the calculation of the final amount of biofilter material the last needed value is the surface area per biofilter material unit. The unit could be a dimension of weight, volume or the number of used material. The following Table 4 gives some examples of used materials for biofilters for a rough idea of their surface areas. *(Martin, 2017)*

Table 4: Surface areas for used biofiltration materials and necessary volume per g of fish feed (Martin, 2017)

Material	**Surface area per unit** (m^2/m^3)	**Volume required** (Liter material / g of fish feed)
Bio balls (design dependent)	300-600	0.5
volcanic gravel	300	1

To calculate the exact amount of ammonium, it is necessary to know the finally used fish food, which is related to the choice of the fish. Because the biofilter is the part in the system which converts the most fish-toxic un-ionized ammonia into less toxic nitrate the biofilter should be always oversized. So the exact calculation of biofilter size plays a subordinate role. *(Martin, 2017)*

Settling tank

The size of the settling tank depends on the settling efficiency. In the literature there are recommended different designs. In smaller scale aquaponic systems it is common to use the same size as used for the biofiltration tank. Both parts of the water treatment are usually oversized to be on the safe side and to avoid high maintenance for this part of the aquaponic system. If it is recognized that the efficiency of the settling tank is too low, it can be increased by implementing more surface If the The following Table 5 summarises above discussed calculations for the water treatment design.

Table 5 Important concepts and units for calculating the size of settling and biofilter tank (Thorarinsdottir, 2015)

Settling tank	● Settling efficiency (design dependent) ● stocking density of fish ● Small scale: same size as biofilter
Biofilter	● Surface area / m^3 (design dependent) ● Conversion efficiency of bacteria (temperature dependent) ○ Temperature ○ Water salinity ○ Water exchange rate in biofilter tank ○ Fish stocking density ○ Fish feed content

2.7.3 Calculations water supply

Generall water circulation

The calculation of the water pump size to circulate the overall water value is based on the stocking density. For a high stocking density of 30 kg fish/m^3 an overall water cycle of two times per hour is recommended. This means that for a tank of one m^3 a water flow of 2000 liter per hour is needed. If the fish stocking is lower the circulation could be reduced to its half. *(Martin, 2017)*

Flow rate for different systems

It is also necessary to calculate the flowrate that plants need for optimal growth conditions. In the literature different flow rates for DWC, NFT, MBC and for the vertical tower could be found. Often the flows of the hydroponic system is connected to the flow which is provided for the fish tank. The flow rate is usually dependent on the length of the NFT or towers and measurements of the MBC or DWC.

Water pump

A common water pump is the usual way to move water in an aquaponic system. In aquaponic systems it is possible to have also a higher concentration of solids and parts of algae in the water. Therefore a robust pump should be used. Because it is one of the most expensive parts, it is possible to replace the water pump with an airlift. Airlifts have no moving parts and are less susceptible to clogging. However the implementation needs some knowhow and practical tests. Therefore it is recommended to use a standard water pump for starting up a new system. *(Storey, 2016-b)*

Airlift

In the literature there could be found some examples for calculating the air needed for pumping a special volume of water to a special height. However this calculations are only examples because there are many different designs that have very different efficiencies. Important to know is that airlifts have the best efficiency if these are used for pumping water between small differences in water levels or just to circulate water on the same level through filter systems. Another economic factor is that it is only necessary to buy an air pump instead of an additional water pump. Also combinations of a small low energy consuming water pump and an airlift could be used. (fao, 2015)

2.7.4 Calculations air supply

Calculation for DWC

In a deep water culture the roots are submerged into the water they have a lack of oxygen supply (2.2.1 Main types) and therefore optimal growing conditions can only be achieved by supplying oxygen in form of air to the DWC tank.

Calculation for fish tank

The air supply in the fish tank for dissolved oxygen (DO) is the most important part. Depending on the fish species the minimum DO-level should be between 4 to 6 mg/L and is therefore the first limiting factor. Up to a stocking density of 45 kg/m^3 oxygen supply by aeration with air is sufficient. In literature this is marked with aeration. DO supply with pure oxygen is then used for higher stocking densities *(Strzelecki & Tidwell, 2012)*

Calculation for biofilter

Also the biofilter requires air supply. Bacteria converts the ammonium produced by the fish with oxygen into nitrite and in a second step into nitrate. In the literature there could be found general ratios for the air supply. Another possibility is to calculate roughly the amount of oxygen for converting a special amount of ammonium into nitrate and from this the volume of air.

Calculation for airlift

If an airlift should be used instead of a water pump it significantly increases the amount of air to be provided. Because without practical experience it is difficult to estimate the necessary flow of air, the air pump should be oversized to avoid a collapse of the system. Calculation programs like “Airlift Basic Calculation” from M. Eljammal could be used (https://de.scribd.com/document/206903835/Airlift-Basic-Calculation).

Additional information could be found in:

- “A new method of selecting the airlift pump optimum efficiency at low submergence ratios with the use of image analysis” from Ligus, Zając & Masiukiewicz (https://pdfs.semanticscholar.org/c5e5/224dacb06de31977e1469f173e3c5655b340.pdf).
- “An experimental analysis of two phase flow for air lift pump design” from Awari, Ardhapurkar & Wakde (https://www.witpress.com/Secure/elibrary/papers/AFM04/AFM04027FU.pdf).
- “Air-Lift History and Air-Lift Pumps” from Johnson (http://www.northidahokoikeepers.com/sitebuildercontent/sitebuilderfiles/air-liftpresentation.pdf).

Table 6 Summary of possible components to calculate for the air and water pump

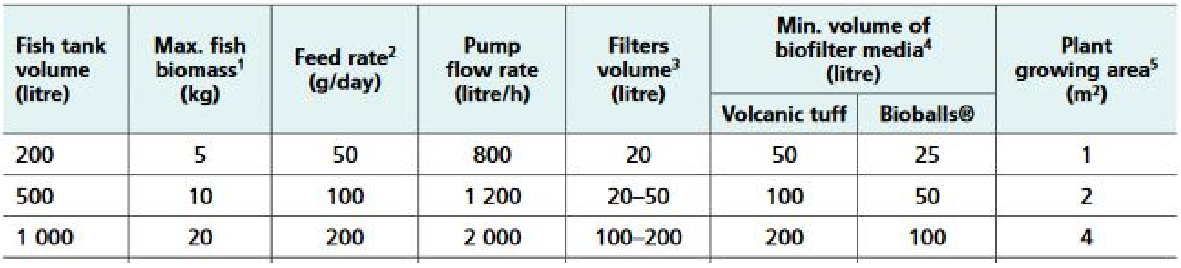
Air pump	● Oxygen supply ○ Fish tank ○ DWC ○ Biofilter ● Airlift (design dependent)
Water pump	● Water circulation ● pumping hight ○ Tank volume cycle 2x / hour ● Flow rates for different systems ○ DWC, NFT, MBC

The Table 6 above shows the components of an aquaponic system which should be generally considered for calculating the water and air pump. Because these are the key factors of an aquaponic, both is recommended to be always oversized. For the fish tank and biofilter it is important to provide enough oxygen to convert the ammonium, for the water pump to reach a high enough flow for cleaning the system and moving solids and nutrients. Especially if an airlift should be implemented, a separate infinitely variable air pump is practical.

2.7.5 Practical system design for small-scale

The following Table 7 shows a practical system design for small-scale aquaponic systems, recommended from fao. This could be used as general calculation values for fish and plant stocking. However it should be known, it is not species-dependent and therefore only as an approximation to evaluate.

Table 7 Practical system design for small-scale aquaponic units (fao. 2015)



Fish tank volume (litre)	Max. fish biomass[1] (kg)	Feed rate[2] (g/day)	Pump flow rate (litre/h)	Filters volume[3] (litre)	Min. volume of biofilter media[4] (litre)		Plant growing area[5] (m^2)
					Volcanic tuff	Bioballs®	
200	5	50	800	20	50	25	1
500	10	100	1 200	20–50	100	50	2
1 000	20	200	2 000	100–200	200	100	4

2.8 Controlling aquaponics

Checking and controlling the aquaponic system regularly is very important to detect potential problems and solve them before they damage the plants and/or fish. Visual checks of plants and fish is required, but there are other elements that can be checked without being physically next to the aquaponic thanks to sensors. The control system of the project can be divided into six modules: a data acquisition unit, an alarm unit, a system rectification unit, processing units, a graphical user interface and a data storage.

2.8.1 Data acquisition unit

The data acquisition unit is made of various sensors which continuously collect data from the aquaponics. The main sensors needed for the project are a water temperature sensor, a water flow rate sensors, a light sensor, a pH level sensor that collects the pH level in the system, an air temperature and humidity sensor, a dissolved oxygen level sensor, a soil moisture sensor, and an electrical conductivity sensor to check the nutrient and salinity levels

2.8.2 Alarm unit

Problems are detected by defining a range of accepTable values for a sensor and alert when the sensor detects a value outside of this range. There are different means to alert the user, such as a buzzer or an alert on the graphical user interface.

2.8.3 System rectification unit

When a sensor reads a value outside of its range, the system can either alert the user or rectify the system on its own. At that time is when the system rectification unit is needed. It can adjust the system by activating different actuators, such as a water heater, a secondary water pump, and one Servo-Motor that dispenses fish food at certain moments of the day to ensure fish growth.

2.8.4 Processing units

First, the different sensors used can only transform a physical quantity (pH, temperature, humidity…) into an electric current. This current then needs to be detected and transformed into something understandable for the user. To do so, the information will go through two processing units. The first one is a microcontroller. In this project, Arduino microcontrollers will be used. Arduino boards can be fitted with shields that allow the user to add functionalities. For instance, a Grove Mega Shield will help to reduce the number of connections on the breadboard.

Arduino boards operate with a 5V energy supply, it is then impossible to control electric equipment that use more than 5V (12V, 24V, 230V…) by wiring it directly to the Arduino board. To do so, relays can be used. This allows to control higher voltage actuators by switching on and off the respective electric circuits.

Microcontrollers are great to read the data from the sensors, but they are not made to store or present the data to the user. To do so, a real computer is needed as the Central Control Unit for the entire system. A popular solution is to use a Raspberry Pi, it is a small and inexpensive computer. The Raspberry Pi will act as the central node of the network, actuators, motors and sensors. It will be the interface between the sensors and the user. The recent versions of Raspberries (Raspberry Pi 3B+ for example) have Wifi and Bluetooth built-in so this could be the best option for the microcontrollers to send the data. For the user to see the data, a Graphical User Interface is needed. To do so, a screen, a mouse and a keyboard can be connected to the Pi or a website can be hosted on it. *(Ya Kyaw, T., Keong Ng, A. 2017)*

2.8.5 Graphical User Interface (GUI)

The Graphical User interface (GUI) is the connection between the user and the aquaponic system and all of its sensors. A GUI usually shows the state of different sensors, their history and the ability to control different actuators. All these elements are generally compiled into a dashboard.

To make the aquaponics easy to use, a GUI must be integrated into the system. The first objective was to create a GUI that would be accessible through the internet. So that a physical access to the aquaponic is not required to monitor it. The first option that came to mind was building a website. This method, especially the web server, requires a lot of knowledge and can be difficult to learn as a beginner. so, other options that would allow the group to do the same thing but without spending as much time learning the language.

Python is a programming language that is often considered as “beginner-friendly” as it is well documented with a lot of online resources and already made libraries . Python is a good fit for the project. There is a library to create a GUI connected to the Raspberry Pi. If an online version of the dashboard is needed, Python can also be used. This will of course take more time and effort, but a “web version” of the dashboard can be created using Django. Using Django as the back-end is not as common as using Node.js for example but it is used for websites such as Instagram or Mozilla.

The first objective will then be to program the local GUI using Python and if time and resources are available, a web version and/or a mobile application of it can be programmed. This will allow the user to display sensor values and remotely control the actuators.

2.8.6 Data storage

All the data from the sensors must be kept and stored into a system. This data could be useful to have a better understanding of how the aquaponic behaves and evolves over time. After research, RethinkDB is the best suited option. RethinkDB is a free and open-source database. It has been developed especially for real time applications, which is exactly what the setup will consist of: it will receive data from the sensors and send it back to the user through the GUI in real time. This database solution is compatible with either Python or Node.js if the back-end changes in the future for whatever reason. *(RethinkDB, n.d.)*

A simplified idea of our setup is shown in the following Figure 19.

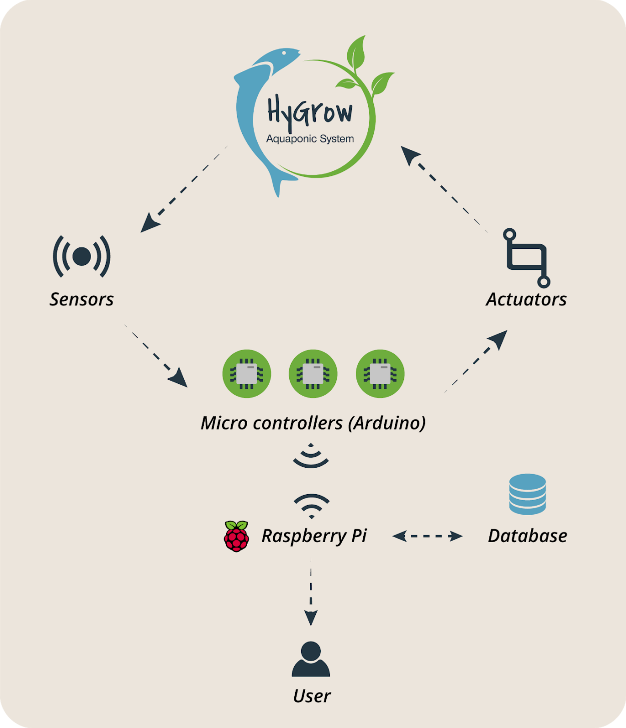


Figure 19 Setup idea.

2.8.7 IoT and cloud-based solutions

Nowadays, smart and connected objects are becoming more and more present in our society. To monitor the IoT (Internet Of Things) elements, different solutions exist. For instance, Wapice *(Wapice, n.d.)*, Arduino IoT Cloud *(Arduino, n.d.)*, Thingsboard.io *(Thingsboard.io, n.d.)*, Thinger.io *(Thinger.io, n.d.)* or Temboo *(Temboo, n.d.)*.

The main advantage of using these technologies is that most of the programming work is already done. There are already programmed parts of code to perform different tasks that can be combined and used to suit the project. The open-source solutions are generally preferable as they are usually well documented, regularly updated and do not rely on a corporate company to work.

2.9 Aquaponics and 3D printing

For the project, 3D printing offers many advantages compared to conventional manufacturing techniques. In this chapter, some prinTable parts and systems that can be used in the Hygrow project are described. For more information about 3D printing, see ‘Handoff package/02. Aquaponics research/02. Aquaponics research/6 3D printing’.

2.9.1 PrinTable parts and systems

3Dponics system
The following Figure 20 shows a hydroponic system available at 3Dponics website that uses 3D printed parts and waterproof material that is really easy to get. With the help of an air pump and a rubber tub, the water can go to the top of the system that is held with bamboo sticks. On this point, the water starts falling to the first vegeTable that is planted with the help of a cut bottle. This one has a hole above so the water can flow until the last plant below. There is a tank where the water stays until is pumped again to the top. *(Zoe, 2015), (3dponics.com, 2015), (Grunenwald, S. J., 2015).*

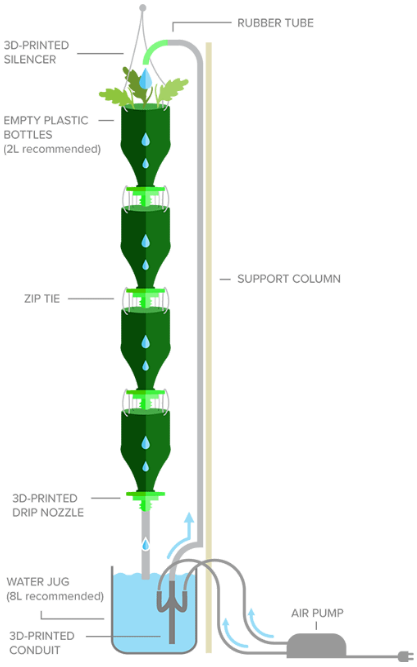


Figure 20 3Dponics system. (3dponics.com, 2015)

Materials:

- 3D printer
- 4 empty plastic bottles (can be printed)
- Hagen Marina 200 Quiet Aquarium Air Pump
- 10 feet of rubber tubing
- 20 zip ties
- 2 bamboo sticks
- Support structure with a top hook (e.g. a coat stand)
- Growth medium (e.g. gravel)
- 4 small plant of choice (e.g. tomatoes, peppers, herbs)
- 8 l reservoir
- Scissors
- Knife
- Hole punch

The empty plastic bottle can be downloaded and 3D printed from Thingiverse. In the next Figure 21 it shows in detail a 3D CAD design of the cut bottles.

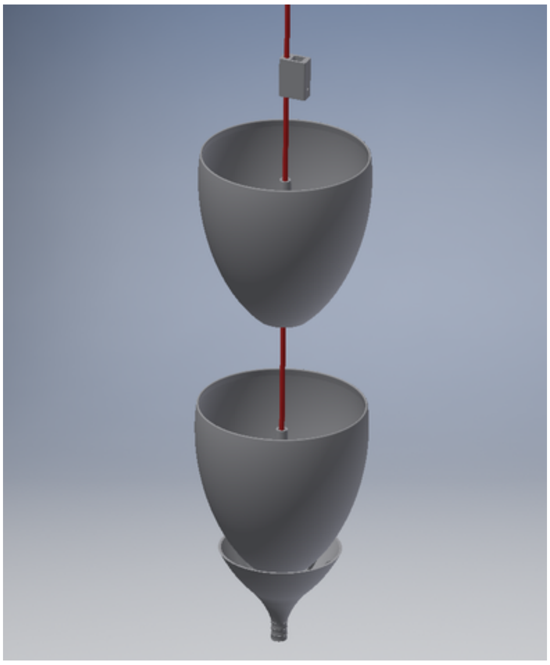


Figure 21 Detail of the empty plastic bottle. (Snabel_a, 2019)

In the next Table 8 below there are some comparisons about the system.

Table 8: Strengths and weaknesses of the 3Dponics system.

Strenghts	Weaknesses
• Easy to build • Cheap • Easy maintenance • Light weight • Little space • Done before - success guaranteed	• Light difficult to control around all the plants • No fish – try both systems • Less plants • Water flow 24h/day - energy 24h/day • Done before - not a challenge

To summarise, this system is easy to build and cheap, but not suiTable in big scale because it cannot be used to grow a large number of plants. The 3D CADs from the team are freely available on their website and they just occupy a small space. It is a suiTable system to start for hydroponics beginners.

Filters

Other possible pieces to print can be some filters for the fish tank and for the debris of the plants, as the ones of the following Figures: Figure 22, Figure 23 and Figure 24. Not many filters have been founded and their sizes are limited, so the team concluded that the best choice would be a team its design.

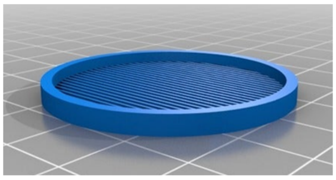


Figure 22 Filter 1. (DrLex, 2017).

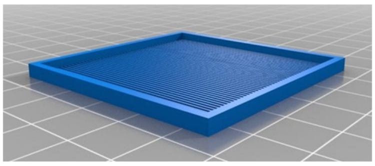


Figure 23 Filter 2. (DrLex, 2017).

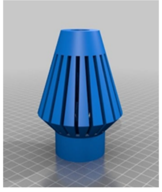


Figure 24 Filter 3. (The Walrus, 2017).

Spray nozzle

Having a spray nozzle is necessary to move the water more and and force the debris to go to the filter tank, and as a consequence, helping the bacteria to grow. For this piece, there are also options online as the one below Figure 25.

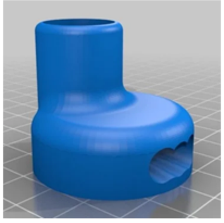


Figure 25 Nozzle 3D CAD. (Robots-dreams, 2013).

Pots

There are also some pots that can be downloaded and printed, as Figure 26, Figure 27 and Figure 28. However, the team can design them into their exact sizes.

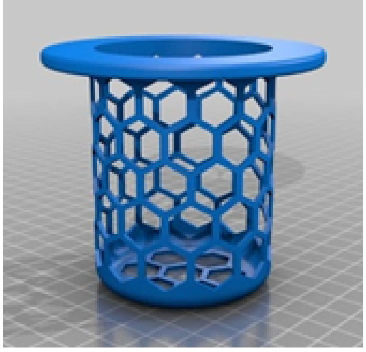


Figure 26 Pot 1. (Planmaker, 2019).

Figure 27 Pot 2. (Cochayuyo, 2019).

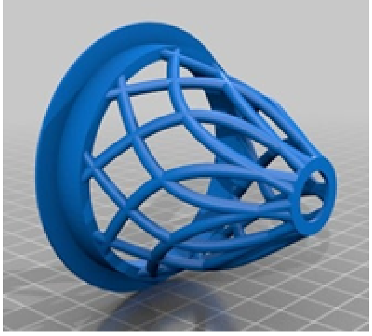


Figure 28 Pot 3. (Torres, 2019).

Bioballs

Bioballs are the basic material to put into the biofilter tank, with the help of them, bacteria will grow faster. In the internet there are some examples of bioballs that can be downloaded and 3D printed. Here are some examples: Figure 29, Figure 30 and Figure 31.

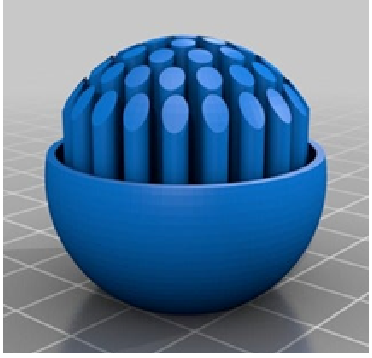


Figure 29 Bioball 1. (JHelzer, 2014).

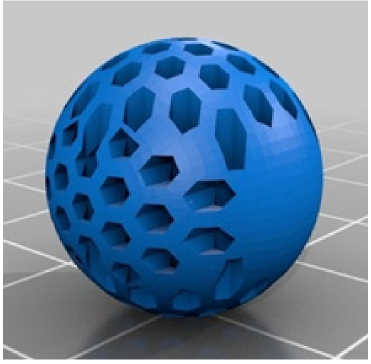


Figure 30 Bioball 2. (Lalo 101097, 2016).

Figure 31 Bioball 3. (Amedrano, 2014).

Compost shredder

A composTable shedder in an aquaponic system is used to chop the residues that come from the plants. If it can produce a bigger moment, it will be able to mince harder waste. The following Figure 32 and Figure 33 show the available design, that can be printed with a moment of 25Nm or 70Nm depending on the size. This second version it is known that can chop any vegeTable and fruit and also chicken bones. The price to print all the parts is less than €55.

The material needed are 23 screws of different normalized sizes, two square pipes, four ball bearing and 1kg of PLA filament. If the price is compared to other products on the market, this shredder is at least 50% cheaper. All the parts are open source and there are also instructions that explain how to build it. (Krassenstein, E., 2014), (F, W., 2015).

Figure 32 Compost shredder example 1. (Jones, J, n.d.).

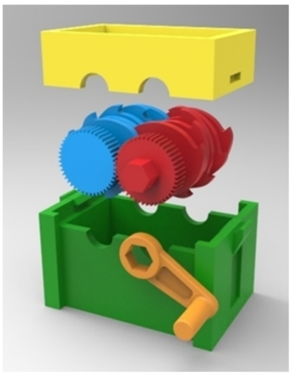


Figure 33 Compost shredder example 2. (Jones, J, n.d.).

2.9.2 Conclusion

3D printing is a good option for some customized pieces from the aquaponics. However, standard and big pieces should be purchased. The pieces that do not have to be transparent should be made of ABS. If it is a requirement of the design that a piece floats, HDPE can be used, but the final product will not have the same quality as an ABS one. When a see-through material is required, PETT is a good option, although it has special requirements in the way it should be 3D printed. Finally, PLA can be used for the parts that are not going to be in contact with the water. In the following Table 9 the materials are compared in order to have their characteristics in a more visual way.

Table 9: 3D printing materials comparison.

	Mechanic properties	Weatherability	Nondegradable	Cheap	Good results	Easy to use	Sustainable	Characteristic properties
ABS	✓	✓	✓	✓	✓	✓	~	-Is the cheapest -Available in many colours
PETT	✓	~	✓	✓	✓	✗	~	Colorless
HDPE	✓	✓	✓	~	~	~	~	Floats
Bioplastics	✓	~	✗	Depends on the type	✓	Depends on the type	~	-Come from natural sources

After surfing the Web, some designs of pieces have been chosen as the most suiTables for the aquaponics. Probably not all of them can be used in the project, and it is a task of the group deciding the best ones. In any case, there is also the option of modifying some sizes of them or being inspired by them to design other elements.

2.10 Lighting

The aquaponic system needs light for the well being of the fish and to support the growth of the plants. Relatively normal lighting can be used for the fish, but the plants need specific light frequencies and intensity for optimal growth. Fish need to be able to tell the difference between day and night, while plants need a specific amount of hours of light per day.

2.10.1 Light for plants

Requirements

Plants use light as an energy source during photosynthesis. Their requirements regarding indoor growing can be broken down into three sections: required wavelengths, intensity and photoperiodism (amount of light hours per day).

Wavelengths

Conventional plant growing uses sunlight as a lightsource. However, plants are exposed to much more than just visible sunlight. Figure 34 displays the emitted radiation frequencies of the sun.

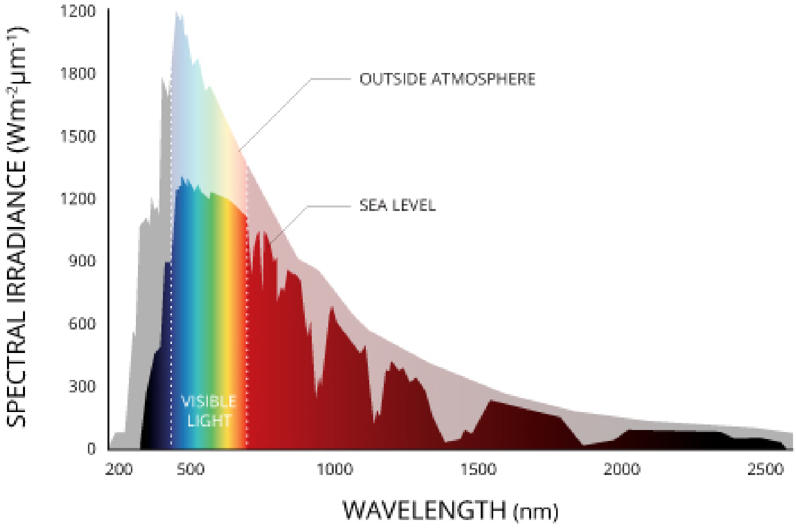


Figure 34 Emitted radiation frequencies of the sun. (Fondriest, 2019 - a)

It is clearly visible that the radiation which reaches the earth is largely composed of visible light an infrared (IR) light, combined with only a small amount of ultraviolet (UV) light. It is also useful to know that the color temperature of the sun is 5900 Kelvin (K) on average, with a peak irradiation at 500 nm. ("Principles of Remote Sensing", 2019)

The question that now arises is whether plants actually need all of these wavelengths. The short answer is no. To understand this, Photosynthetically active radiation (PAR) has to be included in the research. PAR is the part of the solar radiation spectrum that plants can use during photosynthesis. The PAR spectrum is equal to the visible light spectrum for humans, 400-700 nm. This excludes UV and IR radiation. UV light cannot be used because of its higher energy density, which can lead to the destruction of molecular bonds. This can affect DNA or other crucial parts of plants. IR light on the other hand has an energy level which is to low that it does not have enough energy to activate molecules for photosynthesis.

Within plants, chlorophyll ‘a’ and ‘b’ are the most important pigments when it comes to capturing and using the light. Figure 35 shows the wavelengths in which they operate.

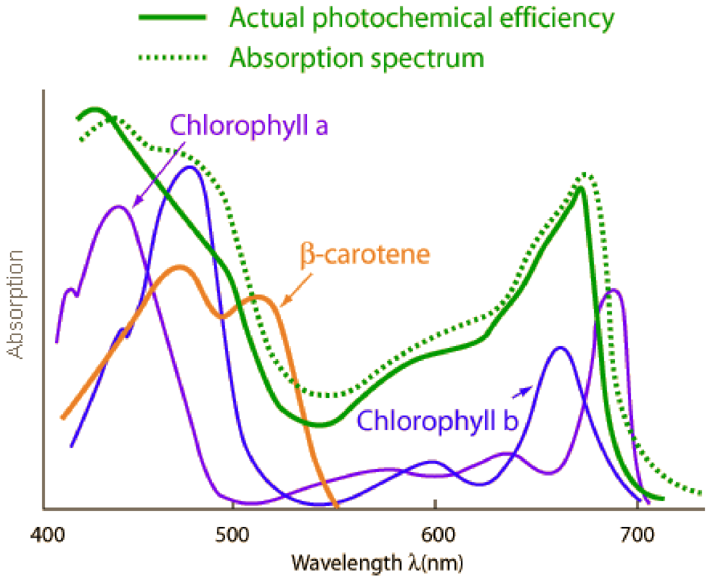


Figure 35 Light Absorption for Photosynthesis. (Hyperphysics, 2019)

It is visible that chlorophyll operates in the 400-500 nm (blue) and the 600-700 nm (red) band. Extra pigments such as carotenes, take up and use some of the green light. However most of the green light is still reflected, which causes humans to perceive plants as green. In Figure 36 is the rate of photosynthesis displayed in relation to the wavelength. It is apparent that blue and red light are favourable for plant growth.

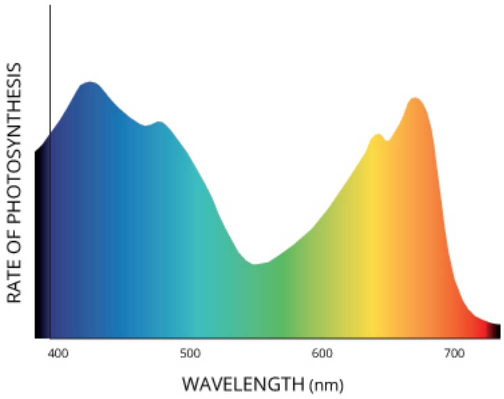


Figure 36 Optimal photosynthetically active radiation is the band from 400-700 nm. (Fondriest, 2019 - b)

These graphs only show the generally needed wavelengths. They do not show anything about the difference of required wavelengths in the respective stadia of plant growth. For example, blue light is useful to have in the early stages, when the seedlings are growing. It helps with the chlorophyll production. On the other hand, a boost of red light can help in the flowering stage of a plant. During the rest of the growth of the plant, purple light is preferred. This is basically a combination of the red and blue light. Depending on what plant is being grown, a good combination of red and blue light should be implemented, because the usage of only red light results in significantly more poor growth results. (Yorio, Goins, Kagie, Wheeler & Sager, 2001)

This said, having light that spans over the entire spectrum, with only certain focusses of light in certain stages of growth, would theoretically be ideal for the plant its health. This means also including a small portion of green light in the mix. ("Different Light at Different Stages of the Plants Life cycle", 2018)

Intensity

The second important factor for indoor plant growing is knowing the required intensity of the light. The light intensity is equal to the photosynthetic photon flux density (PPFD). This is defined as "the rate at which moles (6.02 × 1023 quanta) of PAR land on a unit area (μmol quanta m^2s)." (Carruthers, Longstaff, Dennison, Abal & Aioi, 2001) In other words, the amount of light hitting a square meter in one second. For plant growth, it is interesting to know the optimum point of intensity in function of photosynthesis gains. Figure 37 shows this relationship on a general level. In this case, the light saturation point lies at about 500 μmol/m^2s. This differs significantly between species of plants. In a study conducted by Erwin & Gesick they looked at optimal light intensity points for swiss chard, spinach and kale. Those values were around 300 μmol/m^2s. (Erwin & Gesick, 2017) In other indoor growing applications, values for leafy greens differ from 200 μmol/m^2s in early growth stages, to 250 in later stages μmol/m^2s. (Greenery Product Booklet August 2019, 2019)

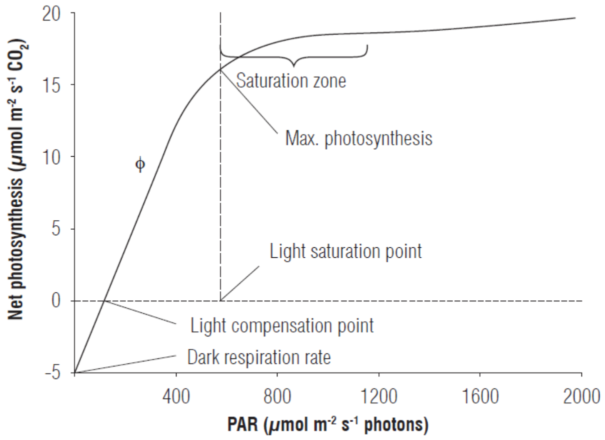


Figure 37 Ideal light saturation curve which represents the photosynthetic rate response to the PAR. (Rivera-Mendes & Romero, 2017)

Photoperiodic

Photoperiodism is a phenomenon in plants, where they react to the lengths of dark and light periods. This can be very prominent in flowering plants. Photoperiodism can be divided in short-day plants, day-neutral plants and long-day plants. (Bareja, 2019) Examples of short day plants are rice, soybean and onion. They do not like days of more than 12 hours of light. Day-neutral plants are not dependant on a day and night cycle for flowering. They only flower when they are old enough. Examples include corn, garden peas, cucumbers and tomatoes. Long-day plants like lettuce, swiss chard, spinach and potatoes require at least 14 hours of daylight. ("Short-day & Long-day Plants: Photoperiodism", 2019)

Types of grow lights

Grow lights come in all kinds of different shapes and sizes. Some technologies are old or new, some are cheap or expensive. It is useful to explore the most relevant options in existence.

Incandescent lights

These lights are the standard light bulbs people use to light their homes. It is available in common stores and are inexpensive. They are sufficient for some in-house plants, but other than that, they are not made for plant growing. The problem is mainly that they do not output the right wavelengths and they generate a lot of heat.

Fluorescent lights

These lights come mostly in bar or bulb shapes. The T5 fluorescent grow light is well known as a perfect light to start indoor growing. The bar shape helps to cover a big area and the light can be fairly close to the plant as they do not output that much heat. They are however not good to use in the vegetative and flowering stages of the life cycle. The lifespan is very good in fluorescent light, they can work for up to 80.00 hours.

High intensity discharge (HID) lights

HID lights consist of two types: High-Pressure Sodium (HPS) and Metal Halide (MH). They all work by igniting a gas.

- HPS lights are known to produce light that is more on the orange-red side of the spectrum, which makes them ideal for the later stages of the plants its life. However, they are notorious for their heat output and energy consumption. If energy cost is not a problem, this is a great option, as they come in large sizes.
- MH lights generate light that is more on the blue side of the spectrum, which is great for the early stages of growth. They also use more energy, but they are less expensive.

Light-emitting diode (LED)

LED used to be expensive and unknown in the growing community. In recent years it has become the most promising technology because of its many advantages. However, the biggest disadvantage of LEDs is probably the initial purchase cost, although prices are still dropping. LEDs have great performance while not consuming a lot of energy and thus also not outputting that much heat in comparison to the other technologies. Because of this heat reduction, they are great to have close to the plants. Only in large greenhouses where there is a need for top lighting, traditional HID technology is still better. Another advantage is the fact that they can reproduce very specific wavelengths needed for plant growth. Flexible LED-strips can help make sure that this light actually reaches the right spot, even in specific situations. Furthermore, LEDs have a long lifespan, more than 50.000 hours, about double of HID lighting. Overall, LEDs are initially a bit more expensive, but long-term energy savings make this economically viable. ("The Pros and Cons of the Different Types of Grow Lights Available", 2017) (Robert, 2019)
A study about the difference between LEDs and HPS in hydroponic growth of Boston lettuce showed that in growing Lettuce, LEDs saved 33% more energy than HPS light, while outputting almost the same dry weight of plant matter. (Martineau, Lefsrud, Naznin & Kopsell, 2012)

Additionally, another study about the impact of adding green light in combination with red and blue light found that supplementation of green light to the red and blue mix in LEDs helps to enhance the lettuce growth and the overall health of the plant. They added 24% green light in the 500-600 nm band. This makes sense when looking back to the wavelength to photosynthesis production graphs. When designing the aquaponic setup, adding a small amount of green light (between 0-25 %) would be beneficial. (Kim, Goins, Wheeler & Sager, 2004)

2.10.2 Light for fish

Fish do not have particularly special light requirements like plants do. They do however need some light to distinguish day from night. The light should not be very bright, as this will result in algae growth. Also, complete darkness should be avoided. Without any light, fish tend to experience stress and fear. Sudden changes in brightness, like turning on the light in a dark room, causes stress. Ideally, fish prefer light that mimics their natural habitats. Indirect sunlight in combination with soft lighting at night to give the impression of moonlight. Normal 12-hours light cycles are recommended. (Somerville, et al., 2014)

2.11 Energy supply

Based on the power that is needed to supply the aquaponic system with energy. research is done with wind energy and solar energy as renewable energy supply sources. Table 10 contains a summary of the amount of power that is required.

Table 10 Summary of power needed.

Equipment	**Operating power**
Airpump	$2 \cdot 8$ W
Arduino	24 W
Heating	200 W
LEDs	$10 \cdot 9$ W
Raspberry pi	10 W
Water pump	23 W
Total	**363 W**

In total, 363 W is needed to power the aquaponic system. To generate that power, it is necessary to understand the differences between wind energy and solar energy.

Wind energy is generated by wind turbines while solar energy is generated via solar panels. Because of the Finnish climate, it is better to use wind energy instead of solar energy, because the sun does not shine that much in Finland unless it is summer. However, the wind is a solid option for energy supply, because it blows all year around. The average wind speed in Finland is 8 m/s. According to the graph in Figure 38, a 1 kW wind turbine can generate approximately 450 W or 10.8 kWh.

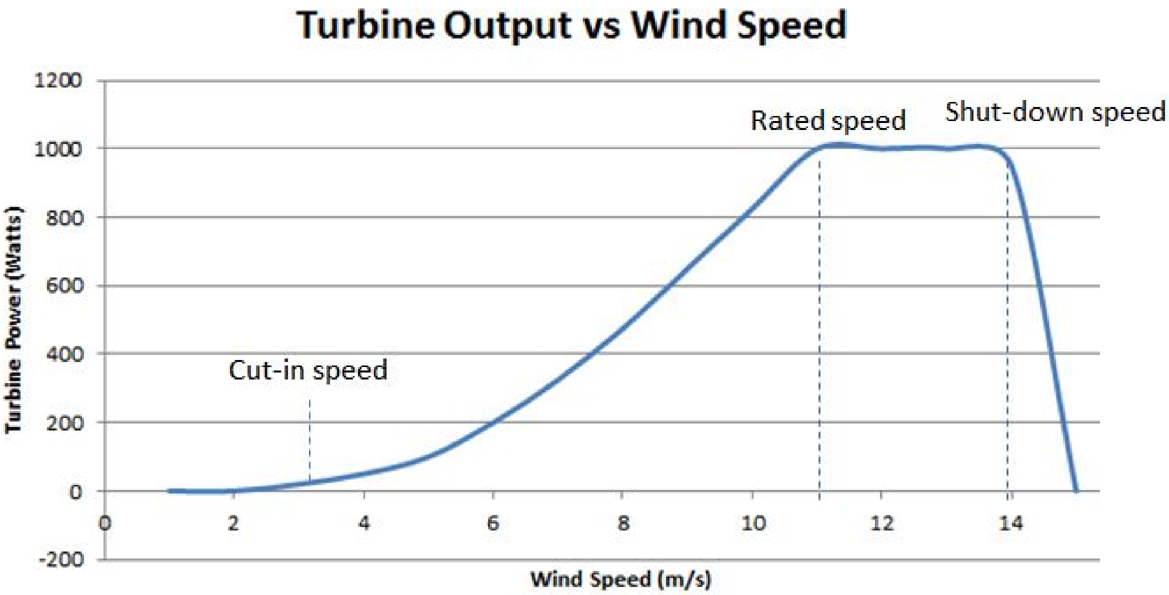


Figure 38 Turbine Output vs Wind Speed (Lombardo, T. 2015)

Detailed information can be found in 'Handoff package/07. Energy supply'.

2.12 Housing

Housing needs to be designed in a way that prevents possible change in the climate of the aquaponic setup. Variables like wind, humidity and precipitation must be taken into account for designing the outer layer of the housing since the housing may not be affected by dryness or humidity. In addition to that, the outer layer must be able to withstand forces from wind or hail. A new climate will be created inside the container for the fish and plants to live in. This climate needs to be protected from temperature change and maybe even humidity change. This will be done by proper insulation.

The housing will be exposed to different conditions in each environment. To simulate these environments, heat transfer needs to be taken into account. There are three types of heat transfer, conduction, convection and radiation, and these are explained in 'handoff package/06. Housing/ 06. Housing'

Multiple parameters should be taken into account for choosing which insulation fits best. Parameters which should be taken into account are: Density, Thermal conductivity factor, Specific heat capacity, Embodied energy coefficient, Durability & Condensation control. This results in Table 11.

Table 11 Insulation materials with different parameters (Handoff package/06. Housing/ 06. Housing)

Insulation material	**Density** (kg/m^3)	**Thermal conductivity factor** (W/Mk)	**Specific heat capacity** $(J(kg * K))$	**Embodied energy coefficient** (MJ/kg)	**Durability** (years)
Rockwool	30 - 150	0.035 - 0.05	840	16.8	+/- 60
Glass wool	16 - 40	0.035 - 0.05	1030	28	50+
EPS	15 - 30	0.037 - 0.042	1500	88.6	Final age has not been found yet
Cellulose	27 - 65	0.038 - 0.040	2020	0.45	20 - 30
Wool	23	0.038	1800	6	n/a
Hemp	25 - 38	0.039 - 0.040	1800 - 2300	10	n/a
Copper	+/- 8800	413	390	100	n/a

Condensation control is about controlling condensation in the air. Since the results of the research on condensation control are not as discreet as the results on for example the durability, the results are discussed in this paragraph.

Radiant barrier

A radiant barrier is a low-emittance surface where the emittance is 0.10 or less. This means that less than 10% of the radiation is absorbed by the material which its radiated on. *(Handoff package/06. Housing/ 06. Housing)*

2.13 Life cycle assessment

Sustainability is an important issue to achieve the goal of the project. Life Cycle Assessment is a tool that considers the entire life cycle of a product. All the stages are evaluated independently and the accumulated environmental impact can be analyzed. It is defined as “a cradle-to-grave approach for assessing industrial systems “. This means considering the materials since they are collected raw from the earth to create a product until their disposal again to the earth *(Curran, 2006)*.

In literature, there are many comparisons between hydroponic systems, but none of them compare the exact ones combined in the project. In order to know the most sustainable of the three of them, the next aquaponics group will need this LCA when making decisions.

With the LCA of the whole system, the sustainability advantages of the aquaponics are expected to be proved. In addition, making a comparative LCA, the most environmentally-friendly hydroponic system can be selected.

One of the studies that can be taken into account was an LCA made from a micro aquaponic system (1,5m^2) for educational purposes built by the University of Padova using recovered material. It confirmed that aquaponic systems need a lower water input than traditional farming methods, while electricity was the most important impact, with a cumulative annual energy demand of 1040 kWh *(Maucieri et al., 2018)*.

It is also relevant was an LCA made on a cold-weather aquaponic food production system. From the ten considered categories, it was concluded that the main ones that should be optimized are heat, electricity, equipment and fish food, in this order. It was found that lower heat consumption results in a general reduction of the other impacts. To reduce the other impacts, it is proposed the use of renewable energy sources and long-term operation of the aquaponic system *(Ghamkhar et al. 2019)*.

The group has done a study comparing the impacts in the building of the PVC pipe towers with the effects of its disposal in a harmful waste scenario, incineration.

3 Design

3.1 Introduction

Now that the research is done, it is time to make things tangible. In this chapter are the first steps described for making an aquaponic setup. First is discussed which aquaponics system is going to be designed. Not only the set up of the aquaponic system will be explained, but also how the plants are chosen, which fish are the best, the lights that are going to be used and which parameters related with the environment are going to be registered and controlled.

In the explanation below, it is justified how the container is going to be supplied with energy in the future, as how it is going to be more efficient and how the energy is going to be stored, while thinking about a sustainable practice for the environment.
As it is going to be exterior, one important field is how it is going to be insulated. A simulation will be created to understand how energy behaves and it will be justified in how it is going to be solved in order to be placed in Finland.

To understand all the decisions, the reader should realize that they are not only chosen by the research but also by a process of construction. In this chapter pictures and specifications will be shown that the team concluded after finding out that not everything is possible or achievable.

In Figure 39, a brainstorming session is shown that was made in the beginning of the research.

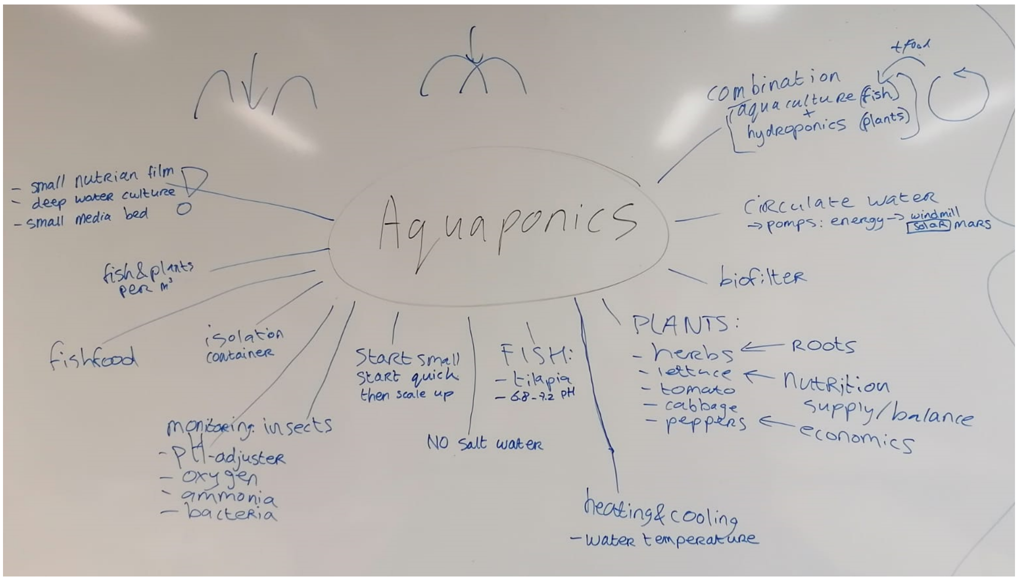


Figure 39 Brainstorming mind map.

3.2 Criteria for choosing the right setup

Choosing the most suiTable aquaponic setup will depend on the preferred goal. Before making this choice, a list of all the criteria to take into account has to be written. The basis could be the advantages and disadvantages of each system described in chapter 2.2 Types of aquaponics. The first important criteria is the amount of work and labour one is willing to deliver in order to keep the aquaponic setup running. The labour for an aquaponic system includes planting, monitoring, harvesting and cleaning of the setup. This work is dependent on the ability of the system to provide a buffer to aim for slow parameter changes in the system. For example, a system with a good buffering capacity will not be as easily influenced by external factors such as temperature. The amount of maintenance needed also depends on the probability of the system clogging. As plants and especially fish enter the system, it is important to avoid a collapse of the system due to incorrectly estimated available human resources and the inability to perform the basic maintenance needed. For example, DWC-systems are usually easier to maintain thanks to their accessibility, buffer and lower chances of clogging compared to vertical tower systems.

Another important criteria to keep in mind while choosing the setup is the “aquaponic education” of the end user. For example, the know-how of the aquaponic system its operator. Some systems need a lot of expertise and experience to avoid failures and breakdown of the whole aquaponic setup. Therefore, the level of the user, beginner or professional, must be considered. In addition, what the operator wants to get from the system is an important factor for deciding on the setup. The setup might change if one wants to produce only plants or both plants and fish.

The type of plants one wants to grow in the aquaponic system is also crucial. Depending on the final size of the plant and the root system, there are different possibilities. For example, tomatoes are easier to grow in media bed systems and lettuce and basil grow especially well on DWC-rafts. Additionally, fish do not have a big impact on the type of aquaponics, as the aquaculture part is basically the same for all of them.

The final, but the most limiting and crucial factor, is the available space and environment. Some systems are more convenient for vertical farming and some are more for a horizontal design. Nearly all aquaponic systems are possible to design as vertical systems, but it should be considered which amount of overall weight is accepTable. For example, for vertical farming the tower system is usually the most practical one to build, the lightest in weight and has the most plants in the same amount of space compared to other systems. In order to gain some diversity and to minimize the risk it is also possible to think of a combination of different designs for plants.

3.3 Possible combinations of types

As discussed in chapter 2.3 Hydroponics, each hydroponic system also has their negative influence on the crop production. It might be possible to achieve a greater outcome when systems are combined. In this case the weaknesses could be changed with the use of strengths of a different system. The result could be an easier system management and a more reliable system but it could also give higher food production. There are no statements in the literature about combinations of different systems so it is an interesting opportunity to gain new insights about aquaponic systems.

Vertical Tower - Deep Water Culture

The decisive point of the vertical tower is that it needs, compared to the other systems, the least amount of overall water. Because the water supply only happens by spraying or splashing water from the top of the tower, the system runs out of water in the case of a broken pump or blocked tubing. Especially the clogging of a tube, what is often reported, increases the maintenance and can lead in a short time to a complete loss of the all the crops of one tower. To improve this negative point, it is necessary to implement in the tower system for each planting position a small water reservoir. In the case of an irrigation loss there would always be enough water available for the plants to survive more than one day. The additional water reservoir should fulfill the task to stockpile a certain value of water, but should also lead the waterflow in the direction of the following plants underneath. The different floors can also be imaginable in the shape of a kind of distillation column. As an additional result, it is possible to use the root system as filtration unit for solids. Also, the newly gained water value can help to stabilize the system and changes in pH, temperature and nutrition peaks have a softer appearance. However, it should be noted that this multiplies the manufacturing costs. Strengths and Weaknesses are summarized in Table 12.

Table 12 Summary strengths and weaknesses combination vertical tower and DWC

Strengths	**Weaknesses**
Water Reservoirs create buffers in case of system failure (power outage or clogging)	Might be impractical to maintain or harvest
Provides water for plants underneath	More difficult to build
Roots as filtration for water	
Extra water helps to avoid pH, temperature and nutrition fluctuations	

Nutrient Film Technology - Deep Water Culture

The nutrient film technology has the advantage that it uses, like the vertical tower system, the free flowing air as an oxygen source and requires relatively little water. However, the problem arises here that in the event of a failure of the water supply crops of the whole system or in the case of clogging on plant unit starts to dehydrate.

In order to cope with the problem, one water reservoir per plant position is required. This can be achieved in the form of a small ramp. Like in the described combination before, also here it is then possible to use the roots as a clarifying unit for solids. It should be noted that the total water volume in the system increases, but compared to the deep water culture less water is needed. This adjustment of the system would not significantly increase the manufacturing cost. Strengths and Weaknesses are summarized in Table 13.

Table 13 Summary strengths and weaknesses combination NFT and DWC

Strengths	**Weaknesses**
Water Reservoirs create buffers in case of system failure (power outage or clogging)	More difficult to build
Extra water helps to avoid pH, temperature and nutrition fluctuations	
Less water than conventional DWC	

Deep Water Culture - Nutrient Film Technology

The basic idea of the previous combinations was to make the systems more reliable in the case of a broken water supply. Exactly this is the big advantage of the deep water culture. With this combination, the entire root structure is stationary in the water an additional oxygen supply in the form of ventilation of the water is needed. However, water can not take the same concentration of oxygen compared to the O_2-level of air. Also, active fumigation of the water under the rafts can not achieve the oxygen supply to the roots which is possible by direct air ventilation.

To achieve a higher oxygen supply to the roots for this system, what lead to a faster growth of the plants (therefore a larger harvest), it is necessary to increase the contact of the roots to air. In the case of the deep water culture, it is possible to increase from time to time during the growth of the plants the distance between water and polystyrene board. The slow enlargement of the distance is necessary to make sure that the roots have always contact to the water. The gained air volume in the root region can additionally be provided with ventilation to ensure the exchange of air. Compared to the other combinations, this is the most cost-effective and safest technology to grow crops in an aquaponic system. Strengths and Weaknesses are summarized in Table 14.

Table 14 Summary strengths and weaknesses combination DWC and NFT

Strengths	Weaknesses
Reliability and previously mentioned advantages of DWC	Technical challenge of adding extra ventilation (not necessarily needed)
Faster growth of plants	
Distance to the water can be adjusted according to growth stage of plant	
Extremely easy to incorporate in setup design	

Discussion

As seen in the chapters above, there are strengths and weaknesses in each combination. The first option maybe it can be difficult to build but it is very solid, it can be automated and the plants and fish can survive if there is a failure in the system. In the second option can be used less water, maybe it can be a pro, but if the system is circular, using a lot of water it is not really an issue except from the fact that it can be heavy. The third combination can be really useful if the wish is to have plants growing fast and build a simple setup. Each one has their differences, the team sees more suiTable the first and the third option. The first one because it can be automated and easier to control. The third one because it is simple to build and the plants can grow really fast.

Conclusion

Finally, the team decided that there would be three different proposals to be able to see which parameters differ from others and which idea can be definitive in the container. These ones are explained in the next chapter.

3.4 Design and system functionality

In this chapter it will be explained which design was chosen by the team and how it works. The design iterations will be chronologically described, ending with the final design. Later on, the system will be explained piece by piece to understand how it functions.

The university provided a room in the basement of Technobothnia. The basement had limits regarding space, but it was adequate to facilitate this small test setup. An advantage of this room was that it had no windows and temperature & humidity rates were sTable, so climate control was not necessary and there was no sunlight influencing the results of growth of plants.

Design development and decision

In this chapter will be explained how the team arrived at the conclusion of which setup they were going to develop. Some ideas that evolved and designs adapted to the necessities of the basement are shown.

First design

At the beginning of the semester, the team thought the goal was to have a module ready to go straight into the container. Therefore, they preferred to work with the Deep Water Culture (DWC) as the only technique, because it had more advantages than other hydroponic systems. The main reasons to go with this technique were ease of startup, control of parameters and system failure management. Figure 40 shows the first sketch of the team their idea.

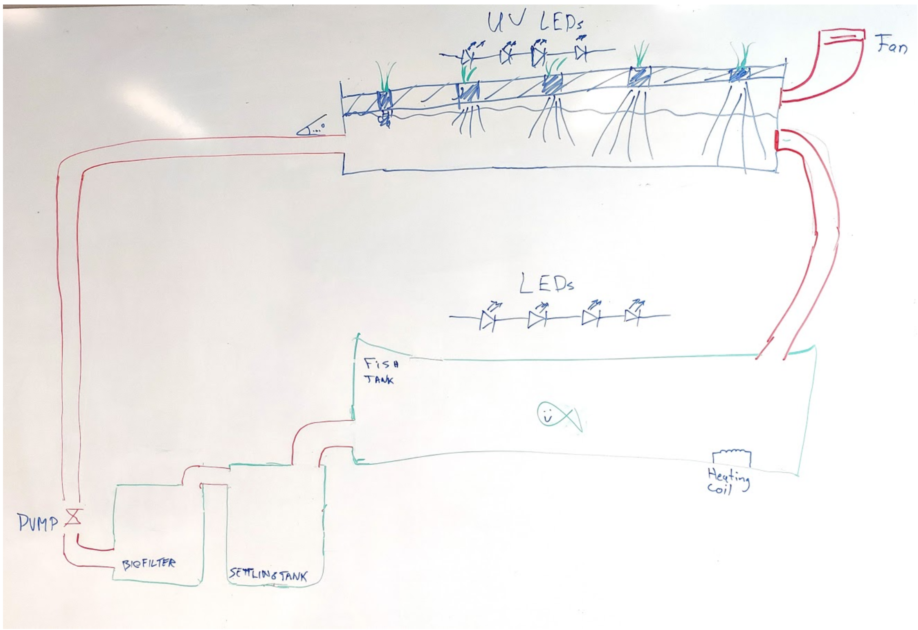


Figure 40 First design sketch.

An adaptation to normal deep water culture was already incorporated in this design, as a response to a disadvantage of DWC: lack of air supply to the roots. Through the use of a production line system where with each stage of the plants their lives, the raft would be moved to another level, a ventilation system could be installed to guarantee plenty of oxygen to the plants their roots. This system is visualised in a rendering in Figure 41. Note: the sizes of certain elements like the pump and the tank are out of proportion in this rendering, because progression is at this point not far enough into the research to have numeric values for the sizes of the components.

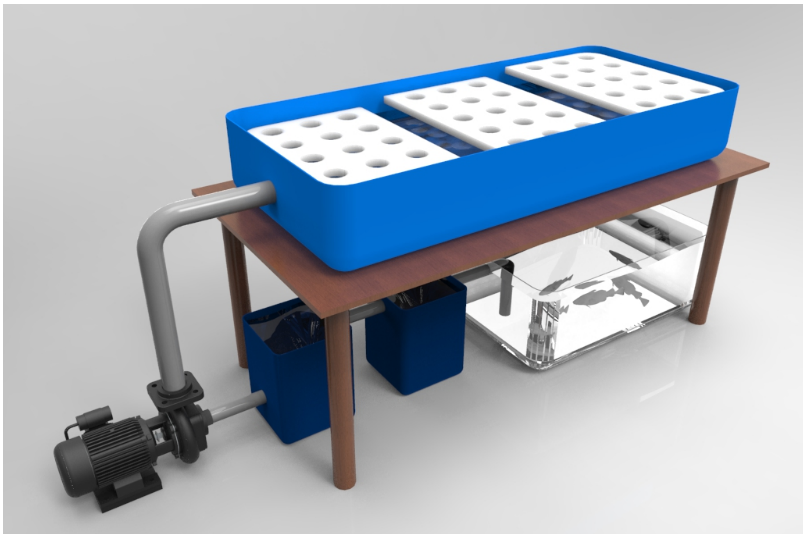


Figure 41 First design rendering.

Another aspect of standard DWC that was innovated on in this design, is the water flow. Normally, the water would just come into the tank through a pipe, but in this design a water distribution pipe could be installed, as is displayed in Figure 42. This makes sure that every row of plants gets an equal amount of nutrient-rich water.

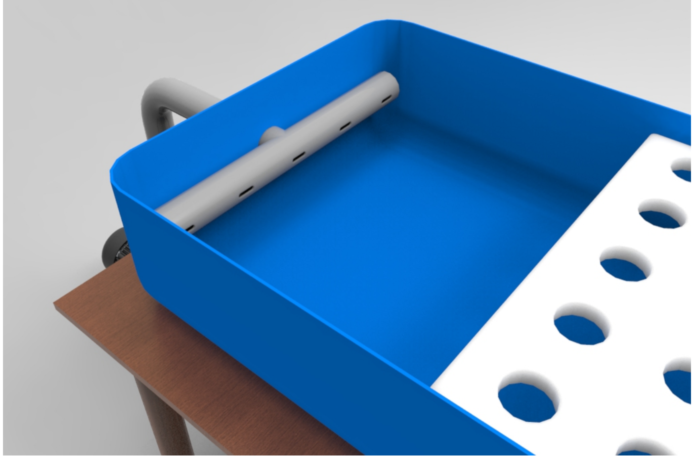


Figure 42 Water distribution system.

<u>Second design</u>

After a meeting with the coaches where the first design was shown, they wanted to see more vertical systems. So the team went back to the drawing board and came up with what they thought was the ideal setup, which included both DWC and tower systems. This idea is displayed in Figure 43. These towers function like a Nutrient Film Technique (NFT) system which was more appealing to the eye and more plants could be grown in the container compared to the DWC system.

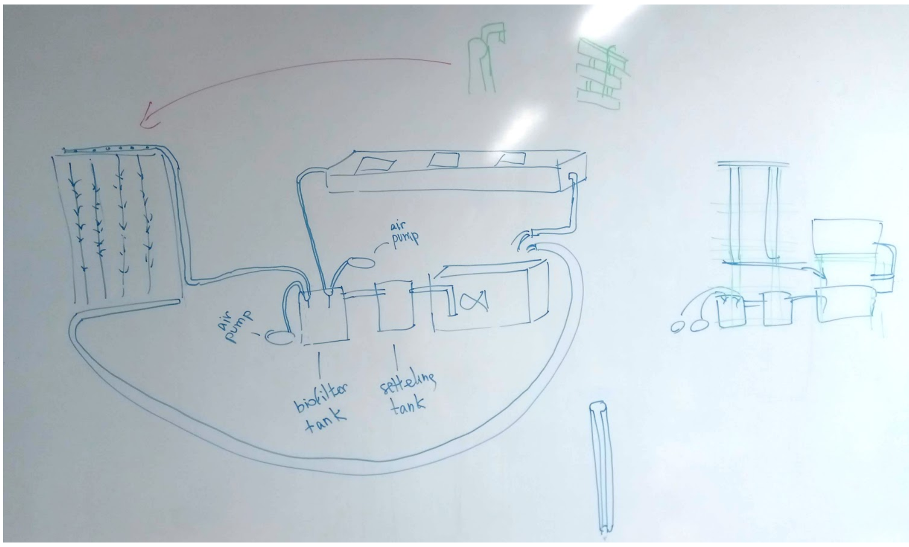


Figure 43 Second design sketch.

In this design, the use of pallets was introduced to facilitate the towers. Water supply could be provided through tubing which runs on the side of the pallet and exits through nozzles on the top. The biofilter would be used to provide water to both the DWC and the towers, through the use of an air pump.

Figure 44 Second design rendering.

<u>Final design</u>

After another meeting when the team showed the second design, the coaches were not satisfied because they had another vision for this semester in mind. They wanted the team to not just make what was best on paper, but to experiment more. That is why the team added 3Dponics in the third design. After this meeting the goal of the project was clear: create an experimental test setup to see what is the most convenient easiest to work with and works best, so a recommendation can be made for the next team. If possible, make it so that some parts of this setup can be transferred straight into the container. It was agreed to go on with this goal and chose this setup to build, adapted to the dimensions of the basement room. In Figure 45 the idea of the final design is shown.

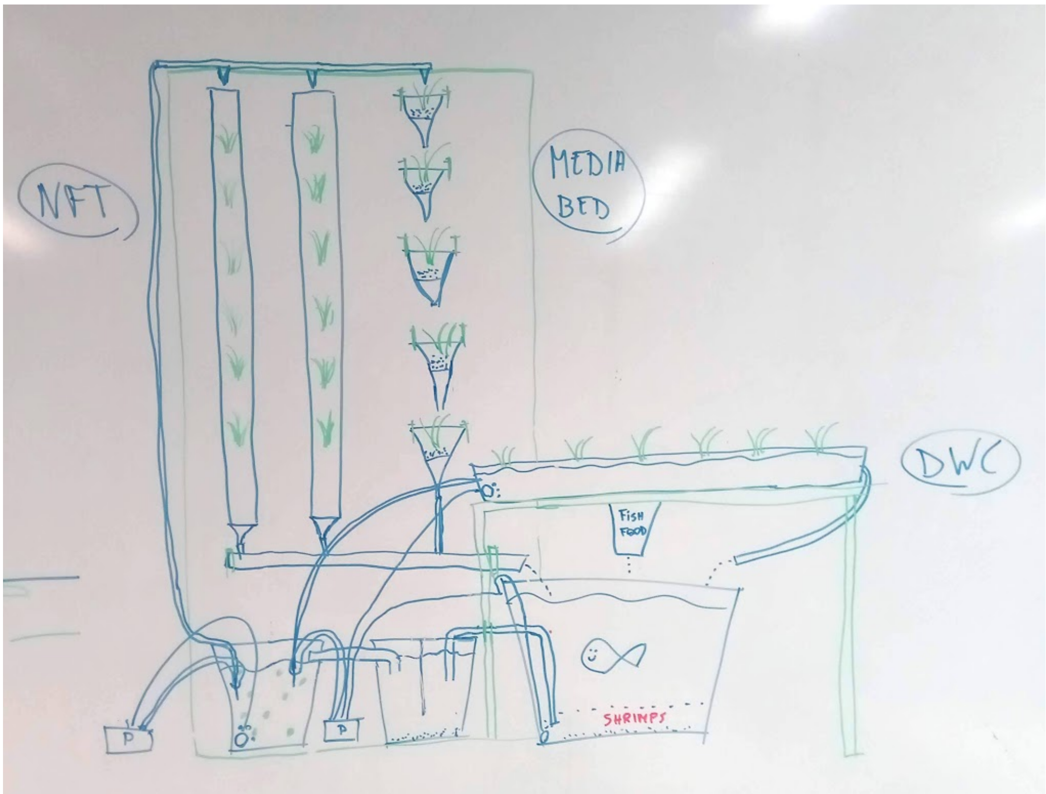


Figure 45 Final design sketch.

The 3Dponics completes the test system, because it represents a form of media bed hydroponics. Together with DWC and NFT, this system includes the three main types of hydroponic plant growing techniques. As shown in the rendering in Figure 46, the 3Dponics is mounted next to the other towers on the pallet, so it can also be supplied by the tubing from the top of the pallet.

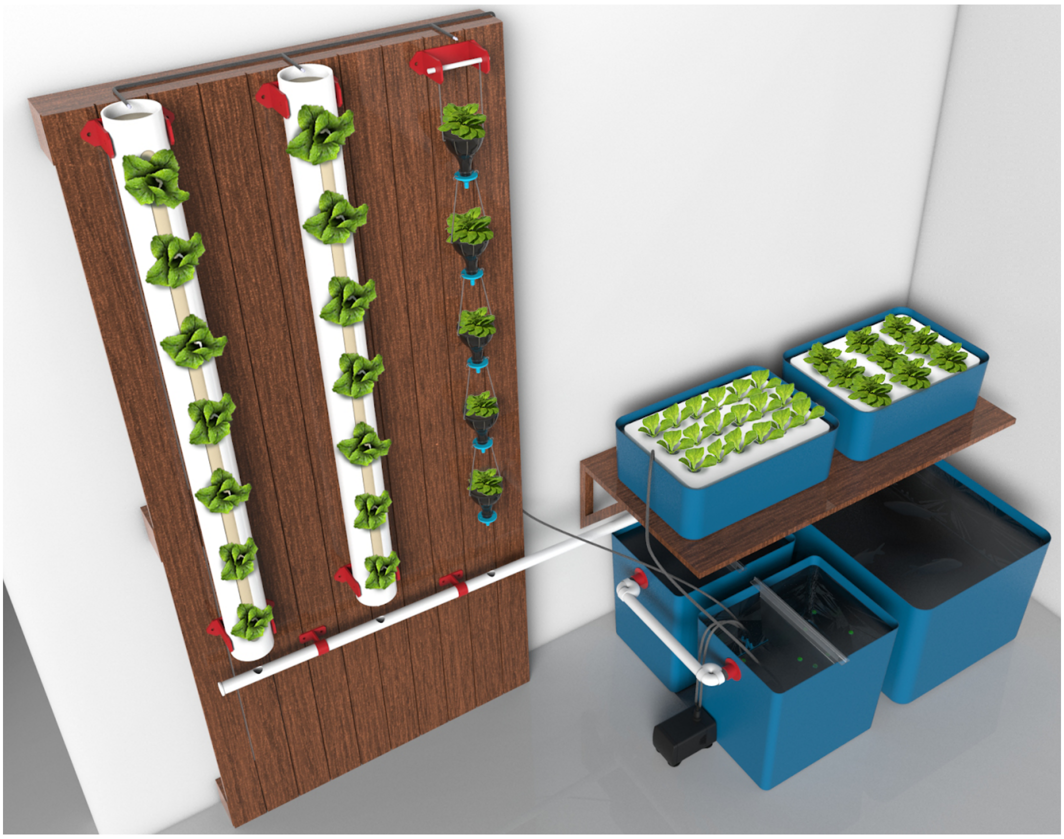


Figure 46 Final design rendering.

Design explanation

The chosen design can be explained by dividing it into four main sections: a fish tank with a filtering section, a DWC section, a tower section and a 3Dponics section. These four parts of the system are shown in Figure 47, together with the water flow direction.

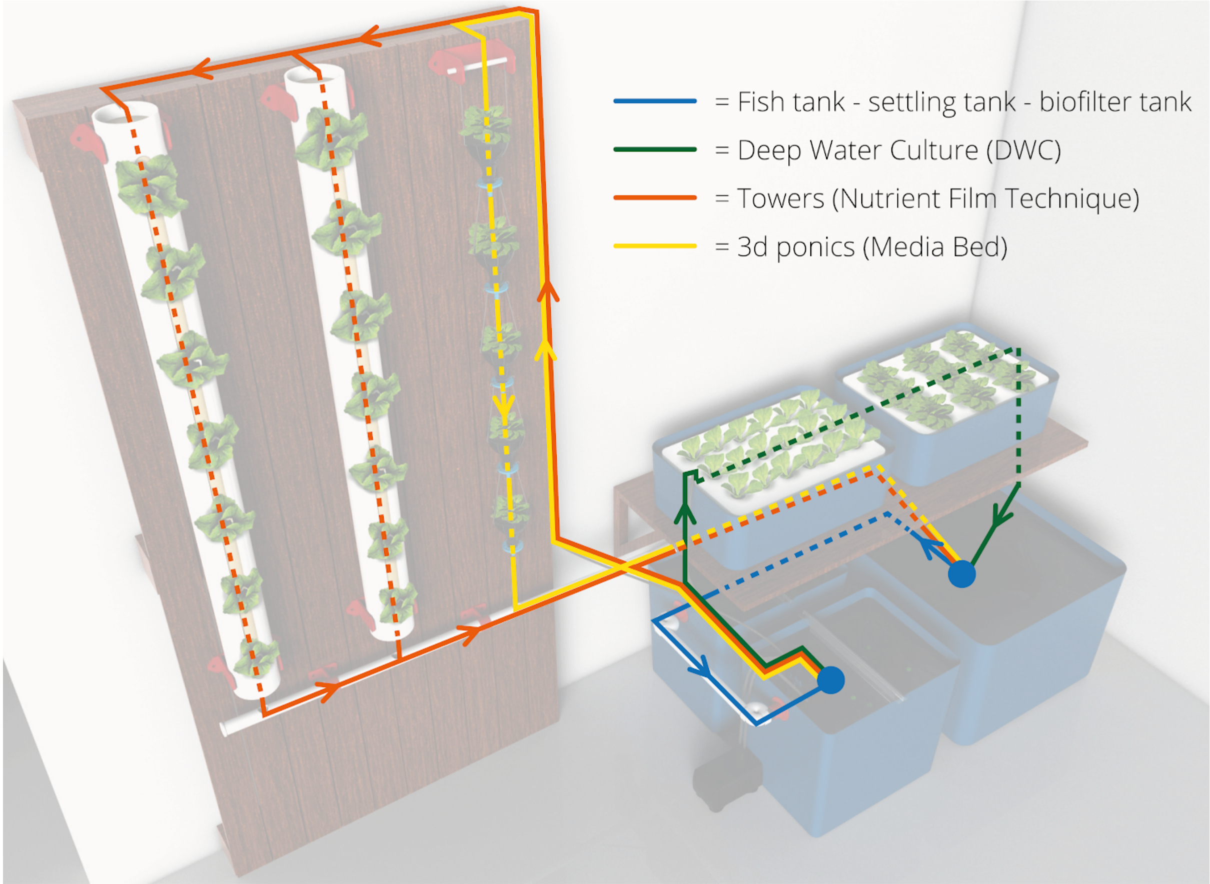


Figure 47 Water flow visualisation.

<u>Fish tank and filtering section</u>

The loop starts and ends in the fish tank (Figure 48). Here, the fish get fed by the automated fish feeder and thus excrete waste. This waste falls to the bottom of the tank and is sucked up by a white pipe to the settling tank. This happens completely automatically. An airstone has also got to be installed in this tank to provide oxygen to the water so the fish are able to breath.

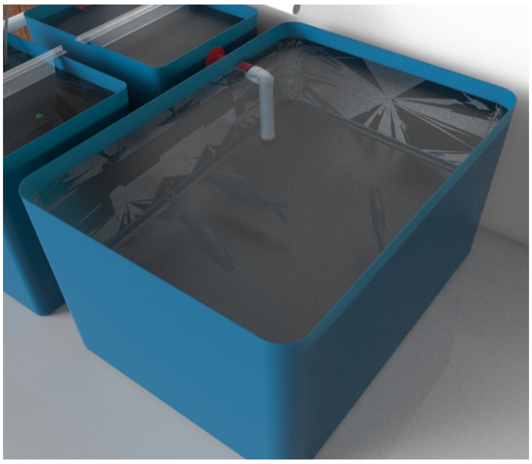


Figure 48 Fish tank rendering.

After the fish tank, the water enters the settling tank. This tank is connected to the fish tank and biofilter tank (Figure 49) by 3D printed connection parts and white pipes. The purpose of the settling tank is to clean the water through accumulation of solids on the bottom of this tank.

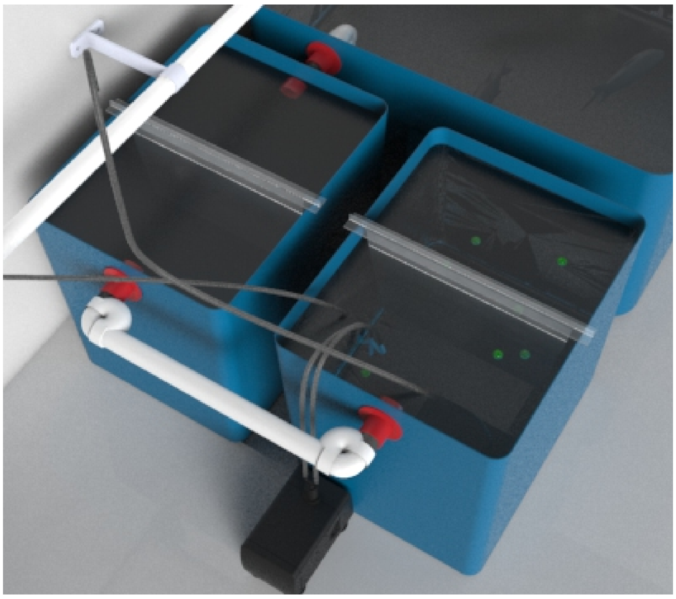


Figure 49 Settling and biofilter tank rendering.

After the solids are filtered out of the water, the water goes to the biofilter tank through another set of white piping and connection parts. The point of having a seperate biofilter tank is to create a place which is optimised for bacteria to grow. This is done through the use of bioballs. These balls need to have as much surface as possible, so that bacteria can grow on them.

Notice in Figure 49 that both the settling and biofilter tank have a methacrylate sheet. The purpose of the sheet in the settling tank is to reduce the speed of the water, so that the water has to pass under the sheet, thus taking the solids with it. The sheet in the biofilter tank is there to that water has to travel a longer way through the bio balls to the pumps. This ensures more contact between the water and the bacteria, so that more of the ammonia is converted to nutrients. There is also an airstone in the biofilter tank, to ensure the bacteria have enough oxygen to thrive.

After the biofilter tank, the water can go to two different destinations, the deep water culture section or to the towers. The water for the deep water culture is pumped by a normal aquarium pump, whereas the water for the tower systems is being pumped by an air pump. This pump adds air to a 3D printed airlift piece, which pushes pockets of water up the tube through the tubes. This way of pumping is not able to provide as much water, but this is not an issue because both the towers and the 3Dponics only require a constant supply of droplets.

Deep water culture (DWC)

The first of the three hydroponic systems is the deep water culture. This system has two different tanks because there are no tanks with the shape of the first design available. In this way, the plants can also be separated by size. As seen in Figure 50, the water passes through the first tank where the smallest plants are. After that, the water flows to the second tank where the bigger plants are. Then, after the second tank, the water drops down to the fish tank through the white pipes. Also, each of the two tanks have an airstone to give to the water enough oxygen for the plants and a distribution pipe, as visualised in the first design.

Figure 50 Deep Water Culture rendering.

The plants themselves are grown on food safe polystyrene boards. In these boards are holes, big enough to fit 3D printed pots. These pots have small holes that help the roots of the plants to pass through them and get the nutrients of the water.

As said in 3.4 Design and system functionality, the tower system on the pallets consists of two different parts: nutrient film technique towers and 3Dponics (media bed). As seen in Figure 51, both have the water pumped from the biofilter tank through tubes. Once the water is up, it gets distributed to the three towers with the help of T-pieces and valves to regulate the water output.

Figure 51 Towers system rendering.

<u>Towers</u>

In this design there are two nutrient film technique (NFT) towers. These are based on the zipgrow tower design shown in Figure 52. The reason of having two of them, is because of the ease of making them. This way it is possible to do some comparisons between the two. The concept is simple: water flows down through food safe polyurethane foam which is squeezed within a PVC pipe. Crucial is the density of the foam, shown in Figure 53 It has to have a low density to make sure that the water can driple down properly. This low density also helps in providing oxygen to the roots. At certain intervals, plants are placed with their leaves sticking out of cutouts in the pipe. They are supported by the pressure of the foam. The water provides the roots with the necessary nutrients and when it is at the end of the pipe, it flows down through a 3D printed funnel piece to the drain pipe which carries the water back to the fish tank. In this design, the towers are mounted to the pallet by 3D printed parts.

Figure 52 Zipgrow Towers. (ZipGrow, 2019)

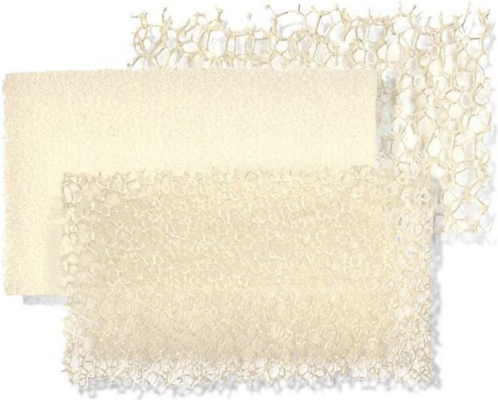


Figure 53 Polyurethane filter foam ("plant foam") (Modulor, 2019)

<u>3Dponics</u>

The last of the three hydroponic systems is 3Dponics. This concept comes from the internet and acts as a form of media bed. The system is explained in Figure 54.

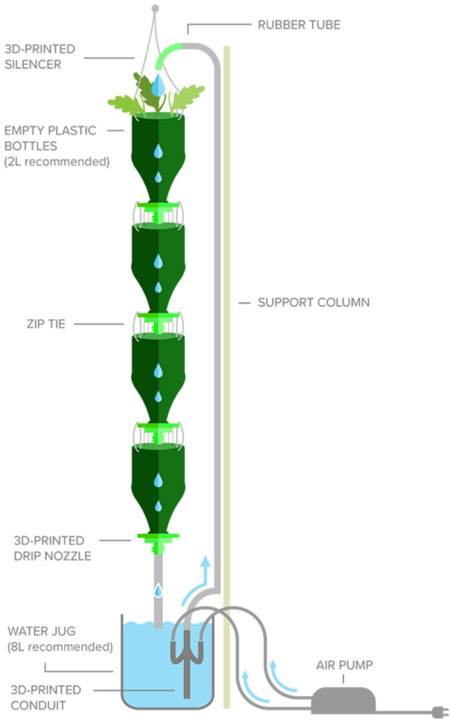


Figure 54 3Dponics system. (3dponics.com, 2015)

Water comes from the top and drops down onto the medium in which the plant grows. The medium is held by the top half of a PET- bottle which acts like a funnel to concentrate the water back to the nozzle, so it can drip down to the next bottle. These nozzles are 3D printed models which are provided on the 3Dponics website. The height of this system is limited by the height to which one can pump the water. After the water exists the last nozzle, it goes down the drain pipe, back to the fish tank.

3.5 Hydroponics

The following sections show the selection of plants to be tested and compared in the preliminary system. In addition to the decision for the right plants, it is also about the grown-up material, which has a non-negligible influence on the system.

Plant decision

Crucial to the selection was to plant crops that are easy to start, have a short growing season for the previous evaluation of the systems, and thrive in the colder climates (*Thorarinsdottir, 2015*). Also a short time for a fully sprouting of the seeds to accelerate the start-up of the system (*Grove, 2016*). Usually this is often connected to a short growing season. It was also important that for the sake of comparison the plants should come from different areas. This resulted in the following selection from the field of leafy vegeTables and herbs. (*Nelson, Pade, & Inc., 2010) (Rakocy, 2016*)

Leafy green vegeTables:

- Lettuce
- Swiss chard / spinach

Herbs:

- Mint
- Basil
- Parsley

The following Table 15 shows the necessary information of chosen plants to grow in an aquaponic system, being the most important parameters to take into account pH-level, electrical conductivity, temperature. In most systems the nutrient input through the fish food is for better health optimized on the fish. To avoid a run-out or an accumulation of some nutrients it is also important to control the macro and micro nutrients which are needed by the plant. Therefore the Table 15 contains also values for different important nutrients (*Sallenave, 2016*) .

Table 15 Parameters and values for the cultivation of lettuce, swiss chard, spinach, mint, basil and parsley in the aquaponic system (Goddek, 2017) (Godfrey, 2018) (Grove, 2016) (Somerville, Cohen, 2014) (Dyer, n.d.) (Storey, 2016-a) (Luv2garden, n.d.) (Kulkarni, et. all, 2018) (Tibbitts & Bottenberg, 1976) (Martin, 2017) (Fao.org, 2015) (Thorarinsdottir, 2015)

	Lettuce	**Swiss chard**	**Spinach**	**Mint**	**Basil**	**Parsley**
Light (hrs)	10-12	12-18				
Temperature (°C) (max. range) [day/night] night temp. appr. 10 °C less	15-22 (7-22)	16-24 (5-30)	16-25	13-21 [18-21/ 10-13]	20-25 (18-35 16-29) [>21 / >10]	15-25
pH	5.6-7	6-7,5	5.6-7.3	6-7	5.5-6.8	6-7
EC (mS/cm^2)	0.8-1.2		1.5-2.5	2.2-2.4	1.6-2.2	
Time to harvest (days)	24-32 (max. 60)	25-35			25-42	20-30
Humidity (%)	50-85			70-75	60-65 (<70)	
Plant spacing	18–30 cm (20–25 heads/m^2)	30–30 cm (15–20 plants/m^2)	(100 plants/m^2)	similar to basil	15–25 cm (8–36 plants/m^2)	10–15 plants/m^2
Plant hight (cm)	20-30	30-60	similar to lettuce	similar to basil	30-70	30-60
Yield (kg/m^2/year)	20-30	50-60	33-37	20-30	20-30	20-30
Recommended aquaponic methode	MBC NFT DWC					
Concentrations (mg/L)						
NO_3-N	137		20		42	
Ca	180				12	
Mg	44				7	
K	48-106				45	
Fe	2.5				2.5	
PO_4-P	10		17		8	

Chosen grow-up material
Rockwool listed in chapter 3.2 of ‘Handoff package/02. Aquaponics research/02. Aquaponics research’, is the most used grown-up material for hydroponics and has a lot of advantages for using it also in an aquaponic system. It provides sufficient moisture, supports root growth and allows for good ventilation of the roots with oxygen. Those positive points are connected to the plant itself. Most important for the hydroponic and therefore also for the aquaponic system, is the property that it is an inert material. This means it does not release solids to the system because of decomposition. Because it is the most used material it is also easily available in gardening shops.

Humidity and temperature
Because the ventilation was determined by the building ventilation, the temperature and humidity was thus taken over and not changed. This means that water and air have the same temperature and lies around room temperature (18-24 °C). Comparing the temperature ranges of chosen plants room temperature is suiTable for all if it is assumed that the temperature does not exceed 22 °C which is the maximum for lettuce. If it is determined that the temperature changes a lot with the seasons outside or the humidity is too low, it is possible to adjust this with an air conditioning system and room humidifier.

Nutrients and parameters
To supply suiTable growing conditions the most important nutrients like nitrate (NO_3-N), iron (Fe), potassium (K), calcium (Ca) and magnesia (Mg) have to be measured on a regular basis. Nitrate can be measured quickly by a color test-kit and it could be also toxic to fish. Therefore it should be the most controlled nutrient. Fe and nutrients with low concentrations like K, Ca, Mg usually are analysed with a more complex measurement with a flame atonic

3.6 Aquaculture

The container is planned to be placed in Finland. It is a country with cold climate and therefore the most available fish species are cold water fish. Another advantage for those kind of fish is that the water temperature is low and needs less energy or insulation to keep the heat up in the system. Table 16 gives some important parameters about possible local fish which are growable in an aquaponic system in colder climate. The goal of the system was decided that reared fish is also utilized. This means that goldfish are no longer taken into account. In order to have an idea of parameters for warm-water fish, the most commonly used fish tilapia and is added to the Table below. *(Urho & Lehtonen, 2008)*

Table 16 Parameters of Finish fish species growable in aquaponic systems (Urho & Lehtonen, 2008) (Editorial Staff, 2019) (Thorarinsdottir, 2015) (Aquasi, 2019) (Somerville, et al., 2014) (European Commission, 2012)

	Fish species growable in Finland				**warm water fish**
Parameters	**Trout**	**Perch**	**Sturgeon**	**Carp**	**Tilapia**
Temperature (°C) **(vitale)**	14 - 16 (10 - 18)	21 - 27 (18 - 24)	18 - 26 (10 - 30)	24 - 28 (0 - 32)	27-30 (14 - 36)
DO (ppm)	>6	> 6	> 8	> 4	> 4
pH	6.5 - 7.5	6.8 - 7.8	7.0 - 8.0	6.0 - 8.0	5.0 - 8.0
Salinity (ppm)	0 - 30	0 - brackish	0	0	< 10 - 15
Total NO2-N (ppm)	< 1.0	< 1.5	< 0.5	0.2	< 1.0
Total NO3-N (ppm)	< 200	< 56	< 25	100	100 - 200
Plate size (month)	14 - 18	10 - 12	14	9 -11	6 - 9
Diet	Carnivore	Carnivore	Carnivore	Omnivore	Omnivore
Water quality	high	medium	medium	low	low
Small scale Aquaponics	difficult	yes	no	yes	yes
Density (kg/m^3)	50 - 80	15 - 16	80 - 100	< 20	85 - 120

Table 16 above shows a number of fish species which are by literature local in northern countries. However, it always depends at the end on the local conditions and environment which fish is finally available. Catching fish from local waters is the last option and can be considered. However, it should be noted that the fish must be acclimated to breeding in tanks and prefers a more natural food at the beginning.

Most of the named cold water fish species are carnivorous diet and compared to tilapia high water quality requirements. To rise those species successful in an aquaponics system, especially trout, they need a strict management for parameter controlling. Because of a lower necessary water quality and an omnivorous diet, which is easier to provide, carp is the best species to use.

It is however not that easy to get the species that one wants, because there are no freshwater fish farms in the area around Vaasa. That is why the team had to rely on what was available by fishing and in the pet store. The two fish species that will be discussed next are species which are not immediately extremely ideal for aquaponics, but because of pragmatic reasons, they were chosen for the test system.

European perch
The first fish species which needs discussing, is the european perch (Perca fluviatilis). It is a wild fish which is widely available for fishing in Finland. As it is a fish that is being used in the setup, feeding requirements are essential to know. In the wild, perch are predatory carnivores which eat macroinvertebrates and zooplankton. (Jamet, 1994) If they are to be kept in captivity, like in an aquaponic system, they need to transition to artificial feed. This is because it is difficult to automate the feeding procedure of living food. Zhelyazkov G. I. did an experiment in which three groups of perch were created who all received a different diet in the conversion from natural to pelleted feed. He looked at growth and survival rate. He concluded that the chopped earthworms can successfully be used in the conversion to dry pelleted feed. In this paper they followed an 11-day conversion plan. To be more safe, a 14-day conversion plan was created, shown in Table 17, based on the 11-day plan. *(Zhelyazkov, 2018)*

Table 17, proposed conversion plan for perch from living to pelleted feed.

Days	Living worms %	Artificial fish feed %
1-3	100	0
4-6	75	25
7-10	50	50
11-13	25	75
from 14	0	100

According to a journal by Toner and Rougeot, using an automated fish feeder which turns on a few times during the night can positively influence the conversion process. The use of a small light can help to attract the fish and to make sure they see the food. *(Toner & Rougeot, 2008)*

African Cichlid
As said before, the possibility and availability of local fish is something to keep in mind. If the team does not find local fish, such as perch, the members will have to buy it and one of the best options is the African cichlid, in concrete, the yellow one.

Tropical fish is not the best but a good option for the aquaponics. It is true that this kind of fish can be aggressive, but this type in particular is the less of its species and can be mixed with other species, if they are strong enough to defend themselves, like perch. One of the recommendations to keep them calm is to have them in big tanks and also to put some rocks or structures, to be able to hide whenever they want. Their water temperature is between 23 ºC and 28 ºC. (*Woods, R., 2018) (Aqueon.com, n.d.) (Conservation, E., 2016)*

Even if this type of fish can live in captivity, its feeding behaviour is wild, therefore, it should always appear hungry, if not, it may be because it is sick or overfed. It is common for them to be aggressive, the first reason why they act like this is because of food, but that does not mean that they should eat a lot, in fact, they can go about 7 to 10 days without food. Comparing to the perch, this type of fish does not need a transition of food, they have a specific food for Malawi spices. The best method to feed them and know exactly how much they should eat is to make them eat during two minutes without leaving anything, two-three times per day. *(Elieson, M., 2019) (*Aquariumadviser.com, n.d.)

If there is also the desire to use prawns or shrimps because of their positive influences. Chapter 4.3 ‘Handoff package/02. Aquaponics research/02. Aquaponics research’ contains parameters and important information for growing them.

Parameters to raise freshwater shrimps and prawns
There are species known for rising in freshwater, brackish water and sea water. Because the salt concentration in aquaponics should kept at least for the plants very low, Table 14 contains only information about freshwater shrimps. *(Aquaponics Grow Bed, 2016)*

Before planning an aquaponic system with prawns or shrimp, there are some important points to consider. At first, it is useful to know that it is not a decision about using shrimps or prawns for the system. “The difference between the two is quite negligible.” *(Brooke, n.d.)*. The raising conditions to be provided are the same for aquaponics. It should also be known that it is possible to run a system only with prawns. But because prawns are very territorial it is needed a lot of space in terms of horizontal surface area to reach the same nutrient supply for plants which can be provided by fish. Therefore, they should be planned always in addition to fish. Carnivore and omnivore fish can eat smaller crustaceans and in this case it is necessary to keep the prawns and shrimps separated. To increase the horizontal surface area for more individuals, it is possible to use stacked layers of netting. It should also be taken into account that shrimps can be harvested with optimal growing conditions up to 3 times due to the short growth phase of 4 to 5 months. This means that during one growth phase of the fish, shrimps must be restocked and thus the handling in the fish tank should be taken into account.
(Somerville, et al., 2014)

Table 18 Information about freshwater shrimps to grow in aquaponic systems. (Somerville, et al., 2014) (Aquaponics Grow Bed, 2016) (Brooke, n.d.) (Friend, Mann, & Aquaponics, 2014) (FAO, 2002)

Parameters for shrimps / prawns		
Water quality (nursery and grow-out facilities)	**Temperature (°C)**	24 - 29 (16 - 38)
	Oxygen (ppm)	> 4
	pH	6.5 - 8.5
	NH_3-N (ppm)	< 0.3
	NO_3-N (ppm)	< 10
	Salinity	3 - 4
	Iron (ppm Fe)	< 1.00
Stocking as postlarvae	Prawn / shrimp	0.19 m^2 per prawn (2 ft^2)
	Generally	stocking: 3 - 4 prawns per 1.2 m^2 harvesting: 1 - 2 prawns per 1.2 m^2 (territorial - cannibalistic)
	Watervolume (stocking of 1 m^3)	30 prawns with 10 m^2 area in 1 m^3 50 prawns with 15 m^2 area in 1 m^3
	Design	raised in settling tank: + use of available separate tank - only for small amounts - solides in fish tank
		raised in fish tank: - needs addition material to separate from fish + possible to raise higher amount of individuals (more horizontal surface area)
Time to harvest size	4 - 5 month	

To use prawns or shrimp only as additional biological cleaning option of the system the easiest way is to use as separate tank the settling tank to raise them. If the goal is to have a bigger diversity of aquacultural food, it is recommended to use the space at the bottom of the fish tank. Figure 55 is a visualisation of the two possibilities how to raise prawns in an aquaponic system. Especially for aquaponics in larger sizes it is an interesting way to reduce the maintenance for the system and to make the system more economical with using more added nutrients for food production instead of disposing a proportion by removing sludge. Because prawns need a lot of horizontal area, it is not recommended to use them in very small aquaponic systems. How it is also with the fish species, it always depends on the availability. If there are local hatcheries it is possible to get only a handful individuals as juvenile prawns for a small aquaponic system and also a big number for a huger system. Otherwise they can be ordered online. However it is not possible to obtain only a few individuals. There are some special online shops for aquaponics but very expensive (minimum about $50 per 25 pieces) and therefore it is only advisable for larger systems. Usually there are also some sources of prawns in small numbers available in pet stores. Because of the high acquisition cost, those are only recommended for small systems and to use as additional cleaning device. *(Friend, Mann, & Aquaponics, 2014) (Brooke, n.d.) (Live Aquaponics, n.d.)*

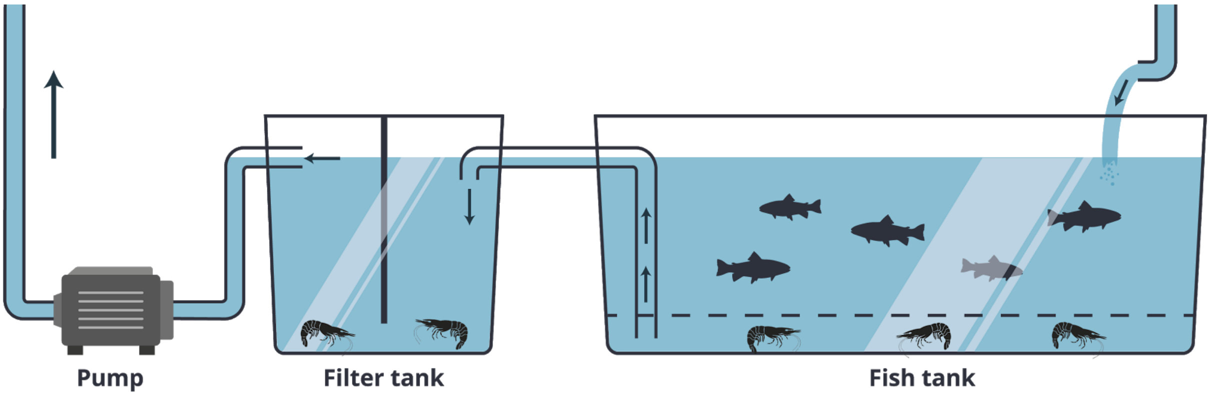


Figure 55 Prawn visualisation

3.7 Light

In designing the lighting setup within the aquaponic system, a distinction between the lighting for the hydroponics and aquaculture has to be made. The decisions in this chapter will be made based on the research, the applicability in our system and the project its budget.

Plants

In the choice of lighting for the plants, a number of steps will be discussed on how the decision is made. To start, the most optimal grow light technology has to be chosen. After that, a more detailed decision will be made and finally an explanation of the entire lighting design will be given.

<u>Choice of grow light</u>

To start, a comparison between the four most prominent grow light technologies is displayed in Table 19.

Table 19 Strengths and weaknesses of different grow lights.

	Strenghts	**Weaknesses**
Incandescent	● Low price	● Bad efficiency ● Heat production ● Output of wrong wavelengths
Fluorescent	● Low price ● Long lifespan ● Low heat production	● Bad for vegetative stages ● Bad for flowering stages ● Higher energy consumption
HID	● More usable wavelengths ● Dimmable	● Heat production ● Energy usage ● Lose effectiveness over time
LED	● Provide specifically targeted wavelengths ● Low heat production ● Low energy usage ● Can be flexible ● Long lifespan ● Long-term cost-savings	● Higher initial purchase cost ● Not perfect as higher top-lighting

When looking at this comparison, it becomes apparent that LEDs have the most advantages over the other three technologies. The ability to choose between wavelengths, makes it possible to control the exact type of light needed for the plants.

LEDs are also very sustainable, as they have a low energy usage and a long lifespan. This sustainability aspect is not only beneficial to the environment, but also to the cost of operating an aquaponic system in the long run. This high accuracy, in combination with the sustainability and cost-savings aspect, makes LED lighting the ideal choice to use in the aquaponic system.

Type of LED

Now that the type of grow lighting is known, a decision on the type of LED has to be made. LEDs come in a variety of different shapes and sizes. The most common are LEDs in traditional bulb formfactor, LED strips, LED interlighting and LED panels. The first option is very standard. It can be installed in a traditional socket like E27 and can be seen as a form of point-light, because of the circular layout of the LEDs. LED strips on the other hand, create a linear form of lighting. The advantage of this type of lighting is the flexibility. This characteristic is very useful in terms of adaptability to a specific system, as they can be creatively mounted anywhere the user wants. They can even be cut into pieces and soldered back together to create even more layouts. LED interlighting is a system wherein a number of LED strips are put together into one package. Three LED strips can for example be put together into one bar shaped light, which provides a wider beam area compared to single strips. Lastly, LED panels are the biggest form of LED lighting in terms of size. This type combines a given number of LEDs into a panel with height x and length y. They usually contain some sort of cooling solution, active or passive, because of the sheer number of LEDs on this given area.

For the aquaponic system, LED strips are the best choice because of their versatility. They can be mounted in whatever fashion desired and are not limiting in any occurring changes to the system. Price is also a considerable factor. LED interlighting and panels are the most expensive types, mostly because they require more engineering and cooling. These can easily surpass €300 per bar or €500 per panel, while LED strips can be bought for under €20.

Type of LED strip

Lastly, the type of LED strip needs to be decided on. LED strips can be divided into four subcategories. First there are the single color strips. These contain only one color and cannot be adjusted. Second, are the dynamic white LED strips. These can be adjusted in terms of color temperature: cooler or warmer. The third category are the non-addressable RGB strips. These have the ability to change the color of the entire strip at once. Lastly are the addressable LED strips. In these strips, the individual leds contain a microchip to control the exact color of the LED. In this type, any kind of color combination can be made. Additionally, there exists a category for LED grow light strips. These are strips which are pre-conFigured with a specific red and blue pattern, optimised for plant growth. They are essentially a form of addressable LED strips. For the aquaponics setup, only addressable or premade grow strips can be considered. In this case, the addressable LED strip would be more beneficial because of the control it offers. In premade grow lights it is never exactly known what wavelengths are being used and the ratio between red and blue cannot be changed. This is why the addressable LED strip is the best option for the aquaponic system.

Light system design

Addressable LED strips are not plug-and-play. They need to be programmed on a computer and controlled by a circuit board. These are the selected items in the lighting system:

- Breadboard: Me Auriga
- Connection cables: 6P6C RJ25 cables
- Adapters: RJ25 adapter
- LED strips: LED RGB Strip-Addressable - 1M

The working of the light setup is displayed in Figure 56 below. The Me auriga microcrontroller is programmed with a normal computer or a raspberry Pi. From the ME Auriga, the commands are sent through the 6P6C cables to the RJ25 adapters. These adapters allow to connect two LED strips each. In this setup there is a maximum of ten 1 meter LED strips. The flexibility of the LED strips allows to use more or less of them in certain places, depending on the desired light intensity.

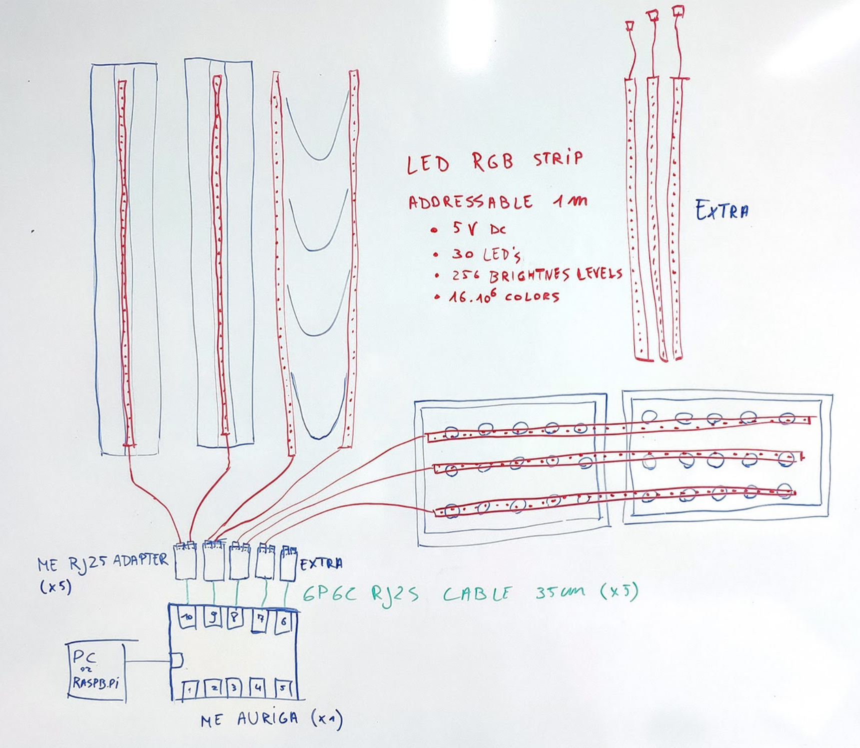


Figure 56 Light setup.

Fish

The design of the lighting for the fish is based on the research described in 3.7 Light, where it is described that fish just need lighting that mimics their natural habitat. They need a day and night cycle with periods of sunrise and sunset, so in total there are 4 stages for the light that have to be programmed. All the information about the software of the lights can be found in “Handoff Package/04.Controlling”.

3.8 UML diagram coding

UML stands for Unified Modeling Language and it is necessary to have a clear overview about what the programmed software is about. The diagram contains blocks with variables and functions within. Figure 57 shows the UML diagram used for this project to control the lights for the fish and plants. It also has a function to operate a servo motor that is used to automatically feed the fish.

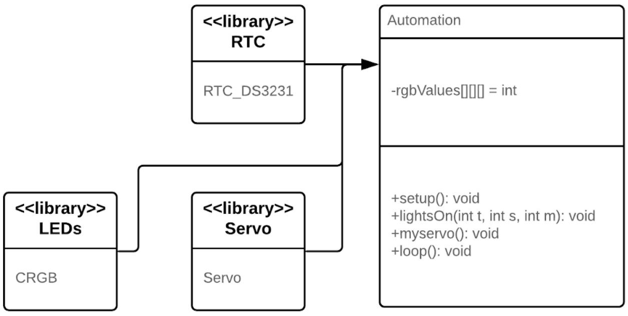


Figure 57 UML diagram Aquaponics

3.9 Sensors

All the data collected by the sensors is displayed on a screen, an OLED display, that can be used with an encoder. The sheet of the screen can be changed by turning the knob of the encoder, so it displays the different values of the different sensors. The system outputs temperature, humidity, moisture and lighting values on a screen and displays an alert when the value exceeds the safe range. All the sensors, the encoder, the button and the screen are connected to the Arduino one through a base shield V2.

As keeping this data in storage for later analysis is important, the Arduino was connected to a Raspberry Pi to store the data in it as a CSV file. A Python scripts takes the values sent by the Arduino via serial USB connection and stores them in a CSV file in the data folder of the documents folder of the Raspberry Pi. The Python script can be found in ‘Handoff package/04. controlling/Data.py’. In case of a power cut, the Python script must be able to restart itself when the Raspberry reboots. The shell script that launches the Python script at startup can be found in ‘Handoff package/04. controlling/Startup.sh’. More information can be found in ‘Handoff Package/4.1 Controlling’

3.10 Energy supply

A wind turbine depends on the type that is purchased. For now, a 1 kW horizontal-axis wind turbine will be taken into account when buying one. When searching for a 1 kW wind turbine on Amazon, the price is approximately €1,000.00 to purchase complete horizontal-axis wind turbines. *(Amazon. 2019)* Maintenance costs are different per supplier, so there is no standard price for maintenance, although many suppliers use an amount per kilowatt used. A form has been released in 2016 containing the maintenance prices for a wind turbine. In this form the maintenance price per used kilowatt is €0.99. *(Ofgem e-serve. 2016)* Cost recovery can be calculated with formula 3.

$$Cost\ recovery = \frac{Total\ cost}{Total\ earning} = \frac{(Purchase + Maintenance) \cdot 365}{0.17 \cdot 24 \cdot 365 \cdot 1kW} \qquad [3]$$

With purchase being the cost to buy a wind turbine, maintenance is what the repair cost is, 365 as in the days of the year, 0,17 is the price per kWh, 24 to calculate kW to kWh and 1kW for the wind turbine itself.

Table 20 contains a summary of the cost and earning of a 1 kW wind turbine when used in the aquaponic system according to formula 3.

Table 20 Summary of wind turbines cost analysis

Purchase	**Maintenance**	**Total cost**	**Total earning**	**Months for cost recovery**
€1,000.00	€990.00	€1990.00	€4080.00	6

When looking at the cost, it can be seen that the cost recovery for a 1 kW wind turbine is 6 months. Solar panels cost less when purchasing, but take a longer time for cost recovery. Cost analysis for the solar panel can be found in ‘Handoff package/ 07. Energy supply’. Based on this analysis, it is better to use a wind turbine, because the cost recovery turns into a profit when the wind turbine is used longer than 6 months. Also, the Finnish climate does not have a lot of sun, so it is wiser to use wind as an energy supply. Another convenience is that a previous EPS project was about building a wind turbine to power an electric lawnmower. *(Blekkenhorst, A., Bouley, F., Klaster, B. and Kohl, 2018)* The wind turbine is already designed and built and can be implemented immediately. However, the design of the parts of that wind turbine lacks information and needs to be improved. For now, the best option is to use a 1 kW wind turbine as an energy supply for the aquaponic system.

3.11 Housing

The insulation was designed based on the research from chapter 2.12 Housing. From 'Handoff package/06. Housing/ 06'. Housing can be learned that Expanded PolyStyrene (EPS) is the most suiTable for this project. Also a radiant barrier should be used for its benefits. This results in the following setup. Gases are poor in thermal conduction compared to solids and liquids, so air pockets will be designed to use this property (*Greenspec.co.uk., 2019). Ultimate* performance of insulation materials is influenced by the proper installation of the material. There should be no gaps between the slabs and other construction components (*Greenspec.co.uk., 2019).* When installing a radiant barrier, a few things should be taken into account. It is important to leave at least 2.5cm space between the radiant surface and the barrier. Just to be sure 40mm of space is added at both sides of the barrier. Also, the barrier should be placed parallel to the radiant surface for maximum efficiency *(Energy.gov., n.d.).* The radiant barrier needs space to maximize its efficiency, so by installing it, two air pockets are created. After 80mm the EPS can be placed, see Figure 58.

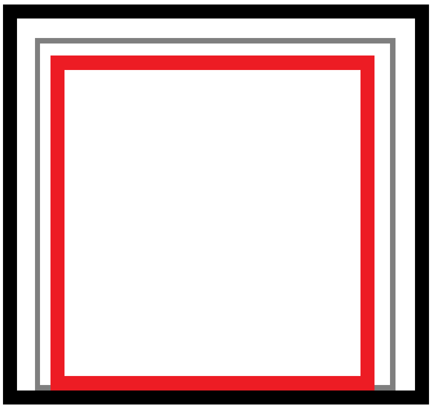


Figure 58 The designed insulation for the container.

In Figure 58 is the container illustrated with the designed insulation. In the Figure is the black square the container, the thin gray line is the radiation barrier and the red square is EPS insulation. Notice that the gray line is only against the walls since there is no radiation through the ground and that the insulation is placed directly on the floor to keep the design easy.

Testing an isolated container in different seasons in Finland will take a lot of time since tests must be run throughout the year. Since there was too little time in this project, a physical model was made to test different kinds of insulation. Since a COMSOL license was available, and this was the most suiTable option, the simulation was done in COMSOL. How the simulation was designed and conducted can be read in 'Handoff package/06. Housing/ 06. Housing'.

4 Building

4.1 Introduction

In this chapter, a chronological overview of the building process of the experimental test setup is given. Not only successes, but also failures are discussed, as a building process is never perfect. A more detailed and comprehensive description of this process can be written in ‘Handoff package/03. Setup process and maintenance/03.5 Setup process and maintenance’.

4.2 Fish

One of the first things that were bought, were the tanks. Once the team had the fish, settling, biofilter and DWC tanks, the quest for fish could start. The criteria for fish were quite open, but upon request of the supervisors, edible fish were prefered.

In the process of buying products, the team came into contact with some local fisherman from Vaasa. Three members of the team met up with them and had the pleasure of receiving three small perch. The perch were taken back to the university and placed in the EPS-room in one of the tanks. They acclimatized over the course of a week and were fed with chopped worms twice a day. An airstone was always present in the tank, to insure a steady supply of oxygen.

After having obtained the first three fish, more were needed. Because they had to be edible, they could only be bought from fish farms. The fish farms in Finland did not respond, therefore the team had to go fishing themselves. After three weeks, there was a small breakthrough when students from another EPS team caught a bigger perch. Unfortunately, the fish did not survive the night.

Soon after the event of the dead perch, the team decided that it was not sensible anymore to continue fishing. That is why six Malawi Cichlids were purchased from Vaasan Eläinkeskus, better known as the pet store. They were bought out of pragmatic reasons, because they are not ideal due to the warm water temperature. Luckily, they could handle room temperature.

At this point, nine fish are in the system, shown in Figure 59: three perch and six Malawi Cichlids. This totalled in about 250 g, which was in theory not enough, as the calculated capacity of the setup could handle about 3 kg. However, the system would at least work with these fish.

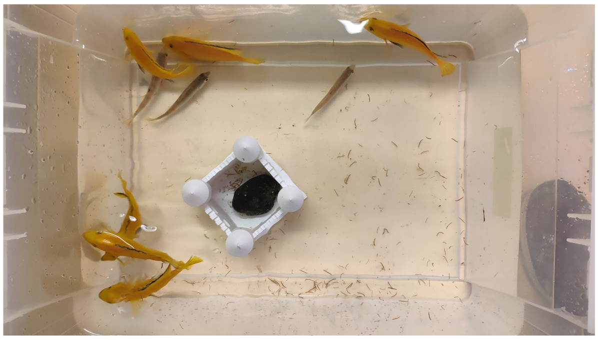


Figure 59 Total amount of fish: three perches and six malawi cichlids.

4.3 Plants

Besides fish, plants are a crucial part of the system. That is why the team seeded lettuce, rucola, spinach, swiss chard, parsley and basil in a tray quite early in the semester. Besides seeding, some already grown plants were bought: three basil and three mint plants. The idea behind these plants was to put them into the system to get it running more quickly.

The seeding was unfortunately not very effective, because as the seeds began to sprout, they all developed small leaves and long stems. This made them very unsTable and thus not exactly suiTable to continue working with. They were reseeded and placed under one of the LED strips, this again ended in poor results.

After the second re-seeding, the plants were placed in the basement room under LEDs. It soon turned out that this was also not enough light, therefore powerfuller lightbars had to be purchased. After reseeding under the new lights, the results were better. The result can be seen in Figure 60. More testing about plants can be read in 'Handoff package/03 Setup process and maintenance/03.5 Setup process and maintenance'.

Figure 60 Final reseeding result.

4.4 Fish tank and filtering assembly

4.4.1 Assembly process

The fish tank, settling tank and biofilter tank form an assembly because they are connected in a fixed way by pipes. The layout of the pipes with their lengths is visualised in Figure 61. The red parts on this drawing resemble the 3d printed connection pieces, as well as a small mechanical filter piece on the bottom of the suction pipe in the fish tank. All the detailed steps can be found in 'Handoff package/03. Setup process and maintenance/03.5 Setup process and maintenance'.

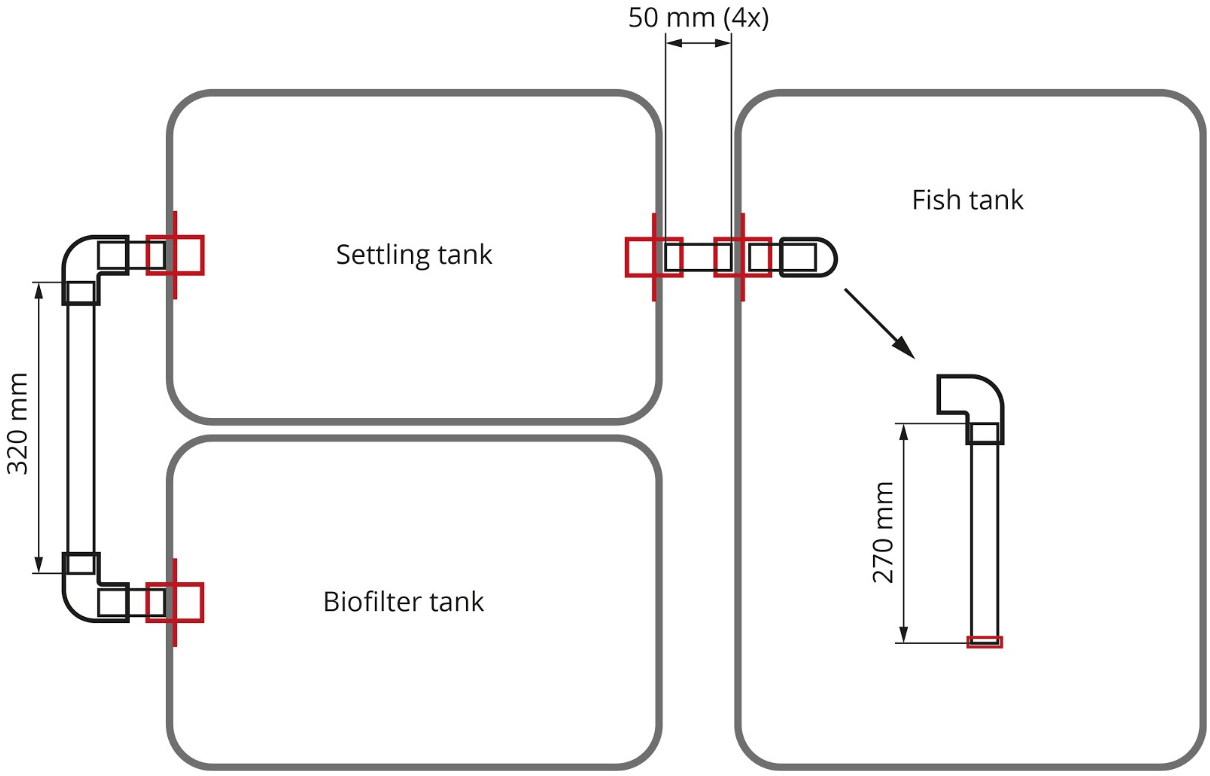


Figure 61 Pipes layout and dimensions.

In Figure 62, a picture of the assembled thanks is shown.

Figure 62 Assembled tanks.

4.4.2 Fish tank support frame

Once the system was filled up, it became clear that the plastic fish tank was not strong enough to stay stiff whilst being filled up with water. This issue needed to be addressed because of the problems is could cause. The team saw it as a priority to stabilise the fish tank by making a wooden frame around it.

Figure 63 shows the building process of the tank frame. A cutout in the sideboard was made for the connection pipe to the settling tank. To make sure visitors of the system could still see the fish, a piece of plexiglass was installed on the front of the tank.

Figure 63 Fish tank support frame building process.

After building the frame, it was installed around the fish tank (Figure 64). The frame provided plenty of support to the fish tank and no bending was visible anymore.

Figure 64 Frame installed around fish tank.

4.4.3 Plexiglass sheets

As explained in ‘Handoff package/03 Setup process and maintenance/03.5 Setup process and maintenance’, sheets are provided in both the settling and biofilter tank, to slow down the water flow. The sheet is designed in a very simple way since it consists of two pieces. The sheet fits in a slot and the holder is placed on the walls of the tank. Figure 65 shows the sheets in their final position within the tanks. In the right picture solids can already be seen, lying on the bottom of the settling tank. This design has proven to work perfectly as it kept on collecting more and more solids in the weeks after installment.

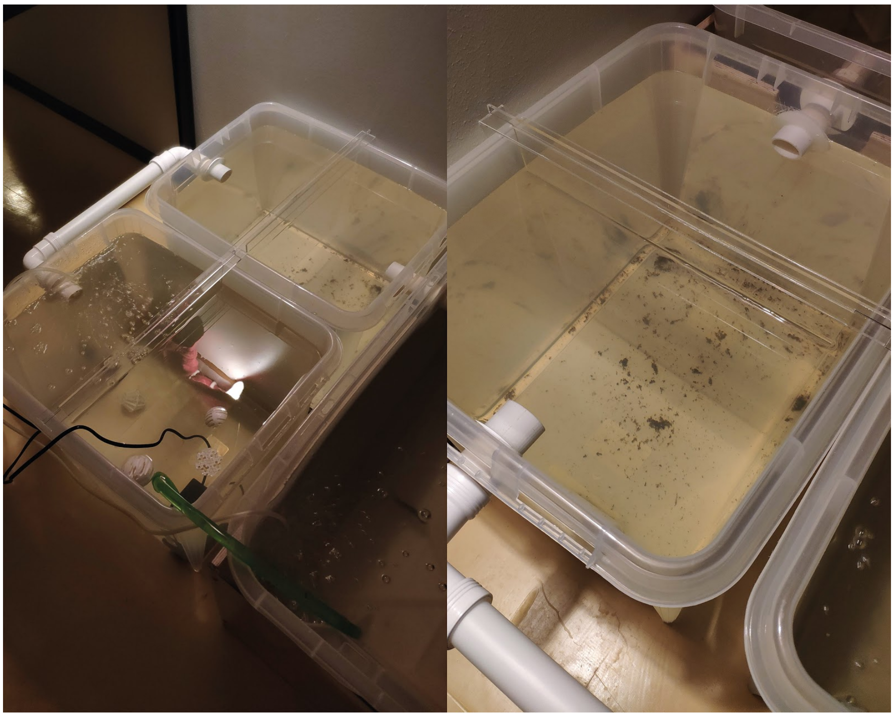


Figure 65Plexi sheets in tanks.

4.5 Deep water culture

The deep water culture system, consisting of two tanks was connected in the same way as the other tanks were. Two 3D printed connection pieces were mounted in holes in the tanks and sealed with silicon. A 5 cm piece of white pipe was cut and pushed in between the two connection parts as shown on the visualisation in Figure 66. At the end of the second box, a third connection part has been mounted, so a set of drainage pipes could be mounted on it, as can be seen in Figure 67. This drain carries the water back to the fish tank. The water supply for the first tank is being managed by the water pump in the biofilter, through a flexible tube.

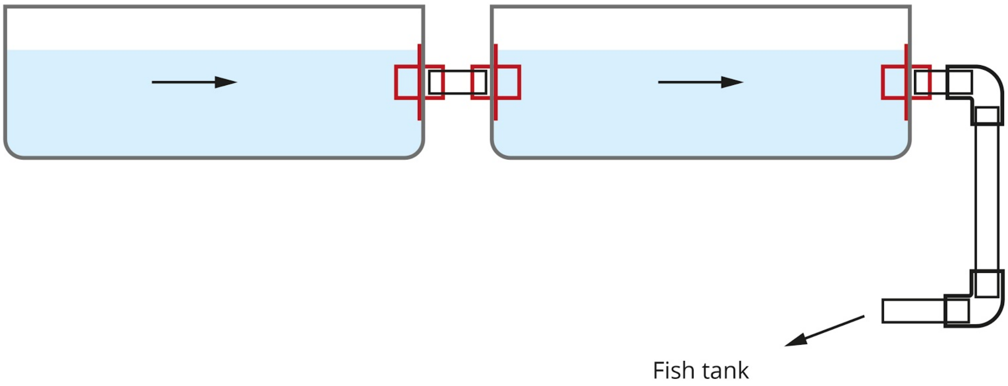


Figure 66 DWC pipes visualisation.

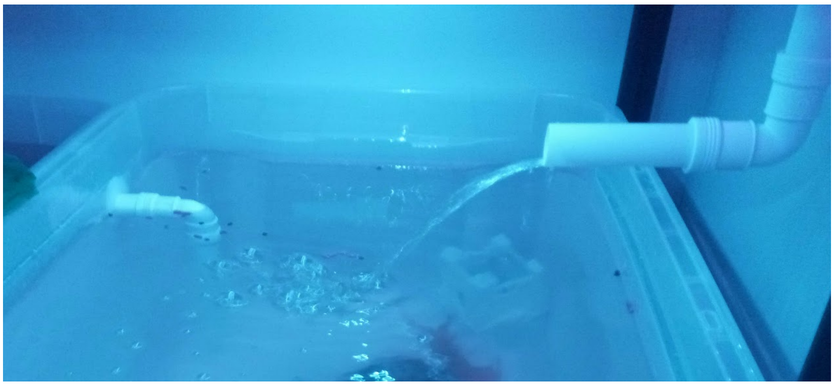


Figure 67 DWC drainage.

Later, the rafts had to be made. These were cut out of food safe polystyrene boxes, kindly provided by the 'Kala Fisk R.Cederberg' fish shop. Figure 68 shows the five boxed that the team received from this shop for free. In Figure 69, the process of making holes in the rafts is shown. One raft has six larger holes, for the larger plants that were bought from the shop, the other has twelve smaller holes to fit the self grown seedlings.

Figure 68 Polystyrene boxes from fish shop.

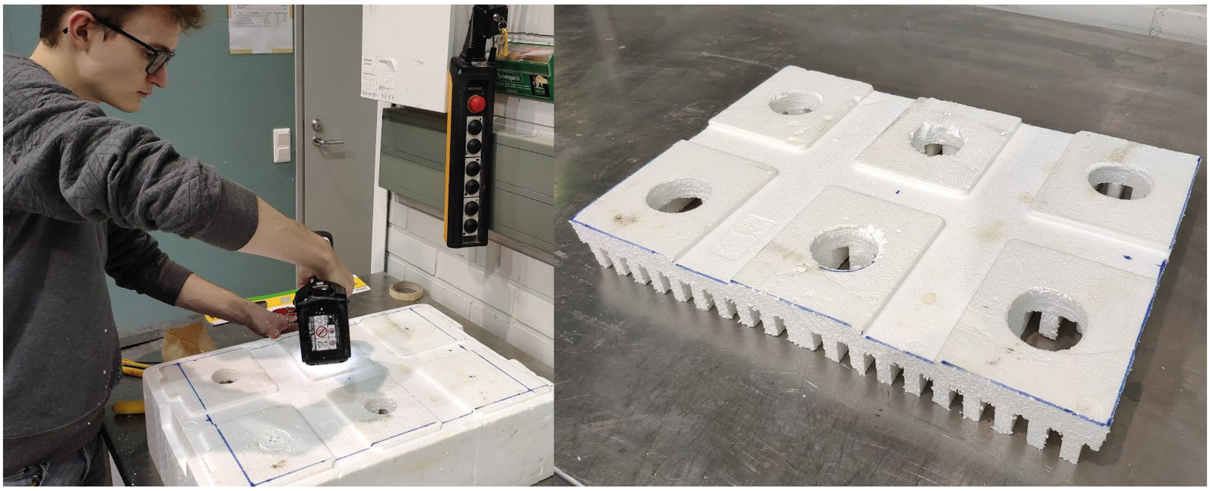


Figure 69 Making holes in the rafts.

The pots that fit in these holes were 3D printed. A design from the Thingiverse was printed and scaled to size as shown in Figure 70. Later, a self made pot was designed based on the one from the internet, with the benefit of not needing a separate base piece.

Figure 70 3D printed pot design from internet.

After installing the pots, the first plants could be put in the DWC. The already grown mint and basil plants were taken out of their pots and the roots were freed from soil as shown in Figure 71. Keeping the roots under running water turned out to be the best way to get the soil off.

Figure 71 Separating the soil from the roots.

Once the soil was removed, the plants were put in the pots. They had however no support, so as a solution metal wire was used to keep the stems of the plants straight. It was curled around the stems and the ends of the wire was inserted into the foam. This solution, of which the process is shown in Figure 72, proved to work very well.

Figure 72 Fixing the plants with metal wire.

4.6 Lights

Eight strips of addressable RGB LEDs and four pre-programmed LED strips have been bought and put in the setup. Three addressable RGB LED strips and two pre-programmed LED strips were placed for the DWC. Three addressable RGB LED strips were placed for the seedlings and another strip for fish. Finally for the towers, two pre-programmed LED strips were placed. The addressable RGB LED strip left, has been placed inside the electronic box, to illuminate the electronic components inside the box. The DWC and seedling lights were placed on a plexiglass surface, just above the plants, at a distance of 40 cm from them. The lights for fish were placed with tape below the Table, just above the fish tank and finally the towers their lights were hung in front of them at a distance of 50 cm.

Each of the addressable RGB LED strips has three wires, one for power supply, that need 5V, ground and a data cable, that must be connected to one output of the Arduino. For that reason, a power converter was used, with an input of 230V (connected directly to the power socket) and an output of 5V, to power the LED strips.

To avoid the reflection of the signal, a resistor of 470 Ω is soldered in the data cable between each LED strip and the arduino. As all the power cables of the strips must go to the same device, to the power convertor, The three power wires from the DWC and the three power cables from the seedlings were soldered together. The same was done with the ground cables. However, Due to the fact that the pre-programmed LED strips have a high enough light intensity, the addressable RGB LED strips can be removed from the setup. This way, the Arduino has a smaller chance of interference from other data cables. Figure 73 and Figure 74 show how the lights were implemented in the system.

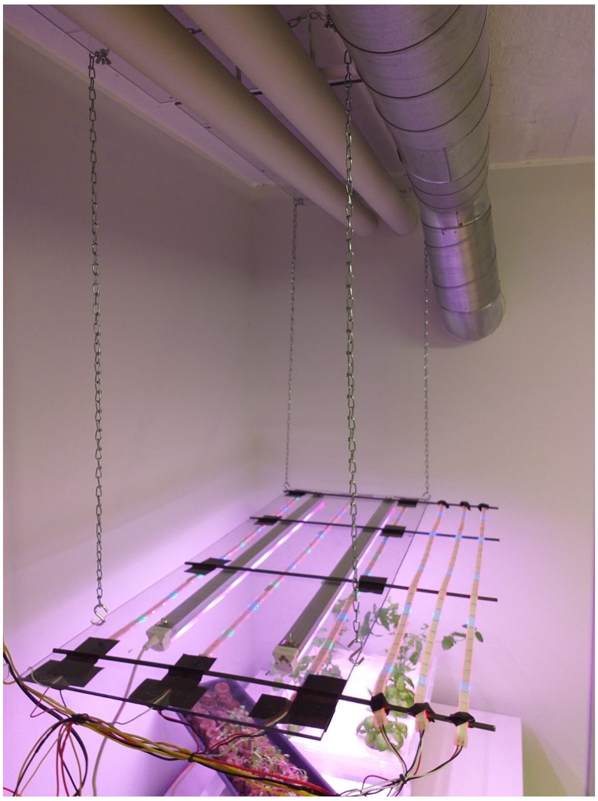
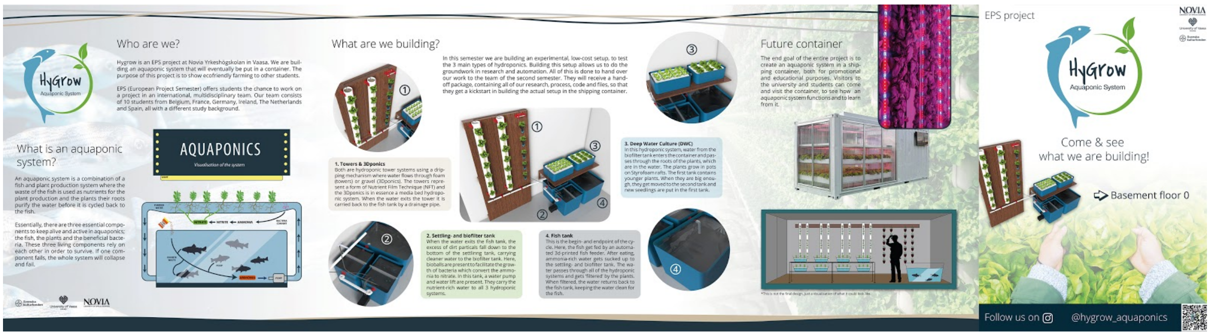


Figure 73 DWC and Seeds Lights.

Figure 74 Towers Lights.

4.7 High school visit

On the eighth of November, an open house day was organised at Technobotnia for high school children, to get them motivated to pursue a study in technology or engineering at Novia. The team was asked to participate in this day by showing the system so far. The lights were installed above the plants and the Malawi cichlids were also in the system. To make the basement room look a bit more welcoming, it was decided to create a big poster to hang on the wall with information about the project. Besides this big poster, about 10 other posters were printed and hung in the hallways. Both posters are shown in Figure 75, but a larger version of them can be found in the handoff package in 'Handoff package/05 Marketing/05.3 Promotion plan'.



HyGrow
Aquaponic System

Who are we?

Hygrow is an EPS project at Novia Yrkeshögskolan in Vaasa. We are building an aquaponic system that will eventually be put in a container. The purpose of this project is to show ecofriendly farming to other students.

EPS (European Project Semester) offers students the chance to work on a project in an international, multidisciplinary team. Our team consists of 10 students from Belgium, France, Germany, Ireland, The Netherlands and Spain, all with a different study background.

What is an aquaponic system?

An aquaponic system is a combination of a fish and plant production system where the waste of the fish is used as nutrients for the plant production and the plants their roots purify the water before it is cycled back to the fish.

Essentially, there are three essential components to keep alive and active in aquaponics; the fish, the plants and the beneficial bacteria. These three living components rely on each other in order to survive. If one component fails, the whole system will collapse and fail.

AQUAPONICS
Visualisation of the system

What are we building?

In this semester we are building an experimental, low-cost setup, to test the 3 main types of hydroponics. Building this setup allows us to do the groundwork in research and automation. All of this is done to hand over our work to the team of the second semester. They will receive a handoff package, containing all of our research, process, code and files, so that they get a kickstart in building the actual setup in the shipping container.

1. Towers & 3Dponics
Both are hydroponic tower systems using a dripping mechanism where water flows through foam (towers) or gravel (3Dponics). The towers represent a form of Nutrient Film Technique (NFT) and the 3Dponics is in essence a media bed hydroponic system. When the water exits the tower it is carried back to the fish tank by a drainage pipe.

2. Settling- and biofilter tank
When the water exits the fish tank, the excess of dirt particals fall down to the bottom of the settling tank, carrying cleaner water to the biofilter tank. Here, bioballs are present to facilitate the growth of bacteria which convert the ammonia to nitrate. In this tank, a water pump and water lift are present. They carry the nutrient-rich water to all 3 hydroponic systems.

3. Deep Water Culture (DWC)
In this hydroponic system, water from the biofilter tank enters the container and passes through the roots of the plants, which are in the water. The plants grow in pots on Styrofoam rafts. The first tank contains younger plants. When they are big enough, they get moved to the second tank and new seedlings are put in the first tank.

4. Fish tank
This is the begin- and endpoint of the cycle. Here, the fish get fed by an automated 3d-printed fish feeder. After eating, ammonia-rich water gets sucked up to the settling- and biofilter tank. The water passes through all of the hydroponic systems and gets 'filtered' by the plants. When filtered, the water returns back to the fish tank, keeping the water clean for the fish.

Future container

The end goal of the entire project is to create an aquaponic system in a shipping container, both for promotional and educational purposes. Visitors to the university and students can come and visit the container, to see how an aquaponic system functions and to learn from it.

*This is not the final design, just a visualisation of what it could look like.

EPS project

HyGrow
Aquaponic System

Come & see
what we are building!

➪ Basement floor 0

Follow us on @hygrow_aquaponics

Figure 75 Basement poster and promotional poster.

There was also an information panel about EPS placed in the room, to introduce the EPS program to the students. The goal was to get them excited about studying abroad. Also a live stream of the system was set up on a TV screen in the hallway on the ground floor. Due to this livestream, people got interested and could stop by the basement room to take a closer look. In Figure 76, the final look of the basement room is shown. During the day, seven groups came to visit the room. The team presented about aquaponics, the system setup and gave information about EPS. Afterwards, the supervisors thanked the team for the effort that was done to organise the presentation.

Figure 76: Basement room for high school visitors.

4.8 Electronics Box

A box to hold in all the electronic devices was built for devices such as the sensors, Arduinos, power converter and power sockets. The box is directly attached to the pallets. It is a wooden box, with a frontside made of plexiglass, therefore all the electronics are visual. The OLED screen was placed at the top part where all the data of the sensors is visualised. Also, the encoder and button to control the screen can be found on the top part. The temperature and humidity sensor are placed next to the box to avoid interference and wiring data catching. The sunlight sensor, to catch the correct measurements, was placed between the plant towers, so the value it catches is the same sunlight value that reaches the plants. The moisture sensor was placed in the gravel of the 3Dponics. The rest of the electronic devices were placed inside the box, leaving a lot of space for other sensors and arduinos.

All the sensors have holes to be able to attach them to a surface, so they were fixed to the box with screws. Then, for the Arduinos and the power supply, pieces were designed and 3D printed to hold the device and fix it in the box. To improve the appearance, an LED strip has been placed inside the box. In Figure 77, an image can be seen of the whole box with all the devices inside.

Figure 77 Electronic Box

4.9 Pallets and towers

After completing the electronics box, it was time to start working on the next part of the setup: the towers. The first step was to build the pallet rig out of two pallets, on which the towers could be mounted. The first step was to sand them down and securely connect the pallets on top of each other. Then, the electronics box could be mounted to the side of the pallets. It is secured with screws and holes were made in the side for cable management purposes.

Thereafter, the PVC pipes were cut shorter and holes for the plants were made. Then the towers were mounted to the pallets with metal L-pieces. The L-pieces were mounted to the pallets with screws. Then, the pipes were clamped together by using thread and butterfly nuts. Therefore, the towers can be taken off the pallets easily. Also, metal L-parts were mounted on the bottom of the assembly to prevent it from falling forward. Then it was time to put the foam in the pipes that holds the plants. Next, the funnels to collect the water in the drain pipe were 3D printed and mounted. Lastly, the drain pipe was mounted to the pallet with pipe mounting pieces. Figure 78 shows how the finished towers look like. The complete steps with detailed photos can be found in 'Handoff package/03. Setup process and maintenance/03.5 Setup process and maintenance'

Figure 78 Final tower system.

4.10 Water supply

The water of the system leaves from the biofilter tank and goes in two directions. One of the directions is the DWC tank, the other is the tower system. Both water supply systems are driven by pumps, either a water pump or a water-air combination.

4.10.1 Deep water culture

As previously mentioned in 'Handoff package/03. Setup process and maintenance/03.5 Setup process and maintenance', the water supply for the DWC is managed by a standard aquarium pump: the Eheim Compact 1000. A 3D printed adapter piece is mounted on its outled and on this piece, flexible aquarium tubing is mounted that goes straight to the DWC tank. Here, the tubing enters from the top, through a cutout in the raft.

Furthermore, the water distribution system was installed in the tanks, to get the water from the biofilter tank to the separate plant rows, as described in 'Handoff package/03. Setup process and maintenance/03.5 Setup process and maintenance'.

4.10.2 Towers

The original plan for the towers water supply was to use a 3D printed air lift part from the 3Dponics website to pump the water up. The model shown in Figure 79 alone could not make the water go higher than about 80 cm, which was not high enough.

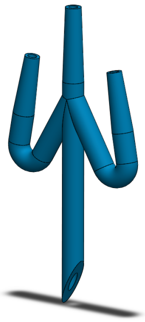


Figure 79 3Dponics airlift model.

The team wanted to continue experimenting with different 3D printed designs for airlifts to improve the height to which could be pumped, but due to time constraints another solution had to be found. That was when the team received another water pump from another EPS team. The pump, shown in Figure 80, was used in combination with the 3Dponics airlift to reach the desired height. The testing for this can be read in 'Handoff package/03. Setup process and maintenance/03.5 Setup process and maintenance'.

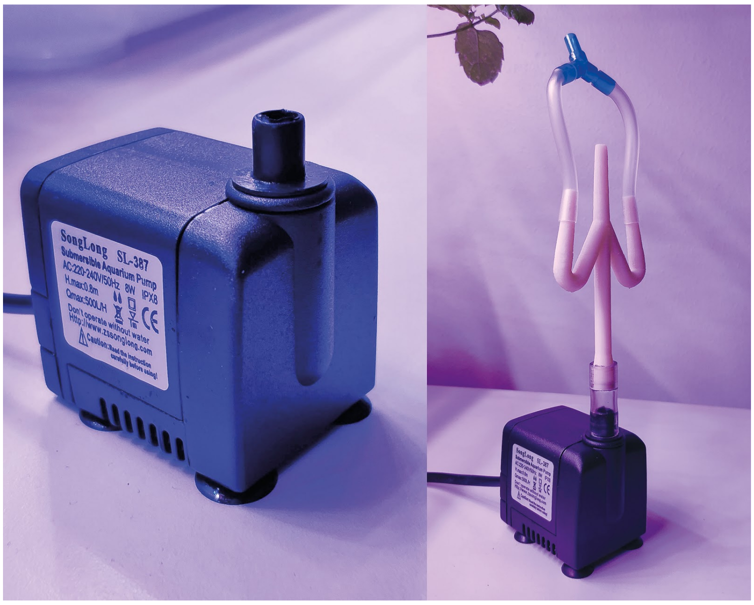


Figure 80 Song Long sl-387 water pump & 3d printed airlift

When the desired pumping height and amount was finally reached, the tubing could be installed. A tube is coming from the biofilter tank and going to the top of the pallets. The valves to control the amount of water coming out were crucial in this design. Without them, the 3Dponics would receive most of the water and the last tower would not receive enough.

After testing the water supply again with the pump installed in the biofilter tank, the water did not reach the top of the pallets anymore, so a seperate tank was installed straight under the tubing going up on the top of the pallets. This tank, shown in Figure 81, was connected to the biofilter tank with green flexible tubing.

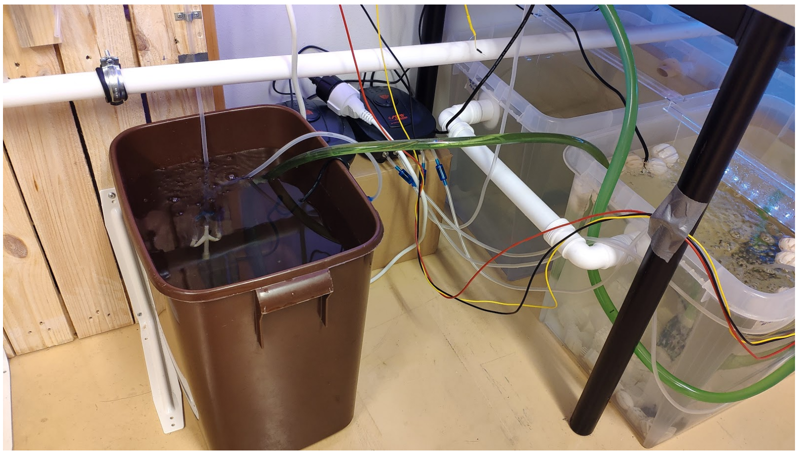


Figure 81 Extra water supply tank towers.

4.11 Fish feeder

Because manual labour should not be done every day, a fish feeder is implemented to feed the fish automatically. It is built by 3D printing with PLA and laser cut parts. It has a container on top of a tube that has a spiral inside. Assembled to the spiral is a servo motor that spins at given times. The fish feeder is controlled by an Arduino and has a real time clock connected to it. When a certain time of the day is reached, the spiral starts spinning, fish food falls into the spiral and is pushed out. Figure 82 shows the assembled fish feeder. Detailed information and parts can be found in 'Handoff package/03. Setup process and maintenance/03.5 Setup process and maintenance'.

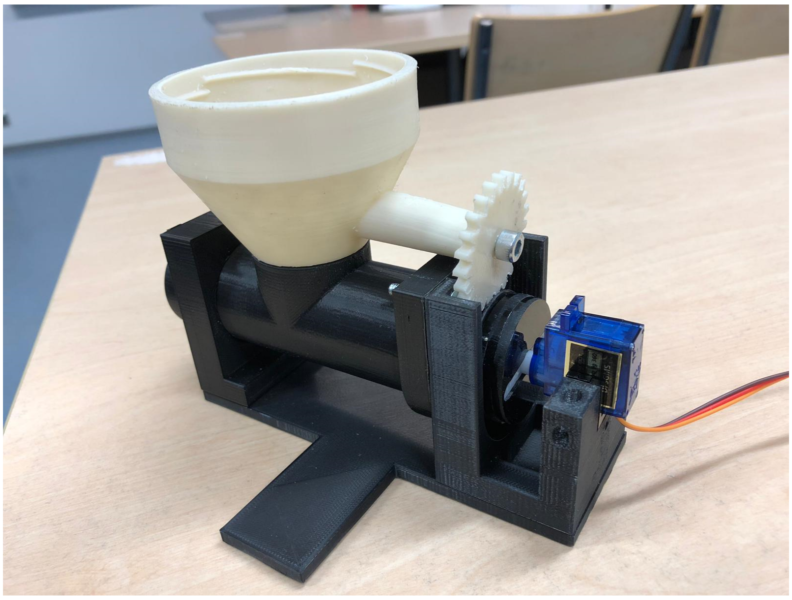


Figure 82 Fish feeder

Many problems occurred while testing the fish feeder, so it was decided to buy a fish feeder from the pet store. The original designed fish feeder does not work properly and needs more attention for it to work as desired. The bought fish feeder is there as a back-up.

4.12 3Dponics

The last hydroponic part that had to be installed was the 3Dponics. The way it works is explained in 'Handoff package/03. Setup process and maintenance/03.5 Setup process and maintenance'. The team had no confidence in the way the bottles are hung from one another. Therefore, a new holding system was designed for the bottles. Five plexiglass sheets were cut in pieces of 12 · 12 cm. A 65 mm hole was subsequently made in the middle of this square sheet. Small wooden slats were then cut and screwed to this sheet. The end result can be seen in Figure 83.

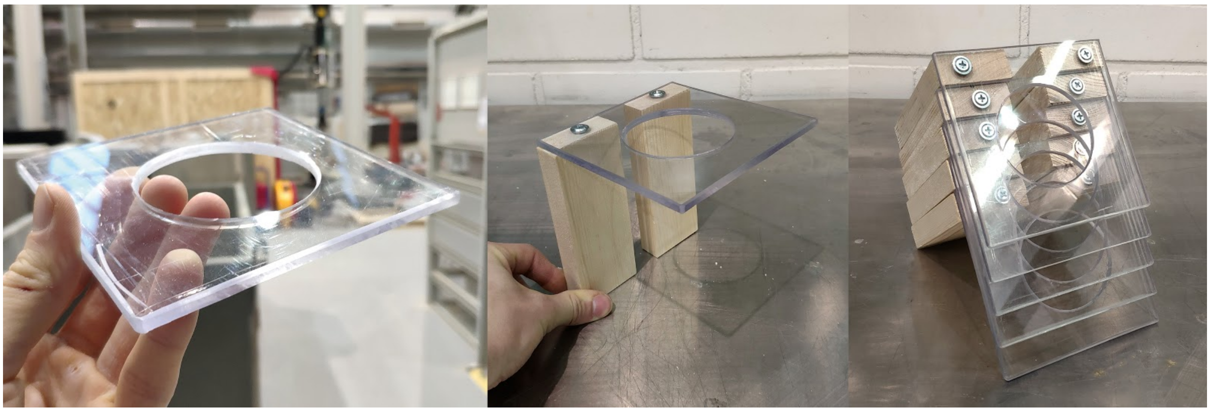


Figure 83 3Dponics holder parts.

The holder pieces were mounted on the pallets with 28 cm between them. Thereafter, the plexiglass circles that were cut out for the holder were recycled to use as a sheet to hold up the medium in the bottle. Small holes were made in these sheets to make sure that water could still pass through, as is visible in Figure 84.

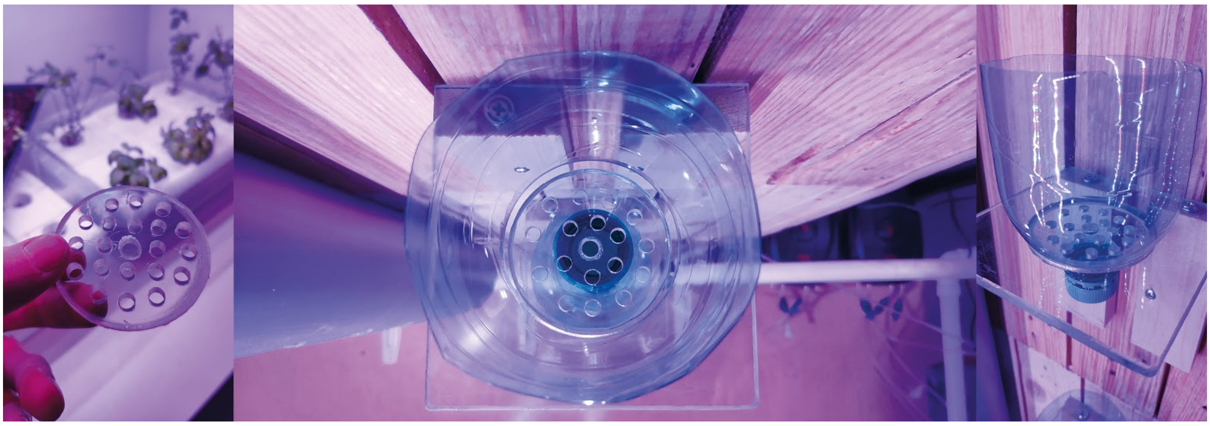


Figure 84 3Dponics plexiglass medium holder.

Afterwards, rocks of about 1 cm^3 were collected and placed in the bottle funnels. Non-return valves that were included in the Sera air set M were cut in half and silicon clued into a hole in the original bottle caps of the green bottles. This solution is shown in Figure 85.

Figure 85 3Dponics nozzles.

Finally tubes that were leftover from the air sets were cut and placed on the end of the nozzles, to prevent water from just falling down and splashing on the leaves of the plants. The final result of the 3Dponics system is displayed in Figure 86.

Figure 86 Finalised 3Dponics.

4.13 Building process finalisation

To conclude the building process, a number of final additions and adaptations had to be performed in the system. Firstly, all of the bioballs were added in the biofilter tank. This made it possible to finally add the bacteria solution to the water, as shown in Figure 87. This solution was quite dark, so the water immediately had a darker color.

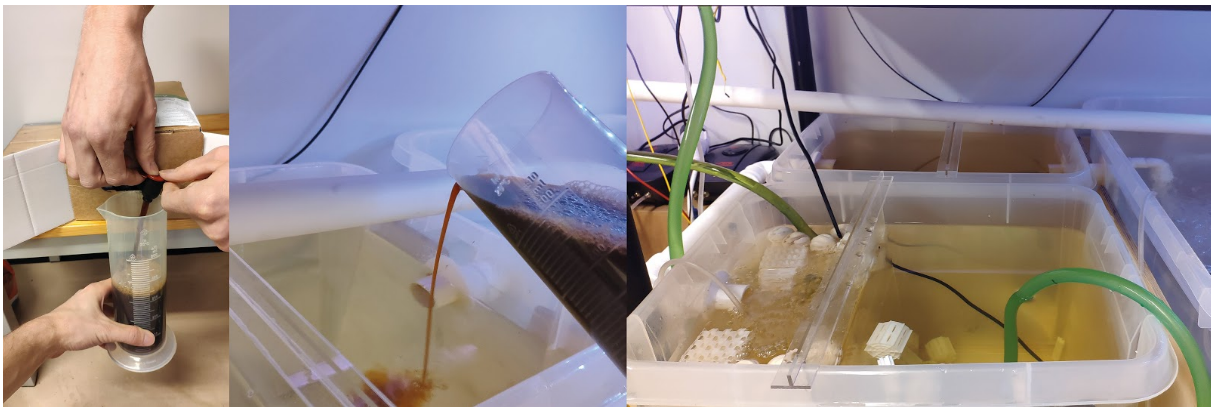


Figure 87 Adding bacteria to the water.

At this point, the water was flowing through all of the systems of the setup, the fish were in place and the biofilter was provided with bacteria. This meant that all of the elements were in place for the plants to be put into the system. This process is displayed in Figure 88.

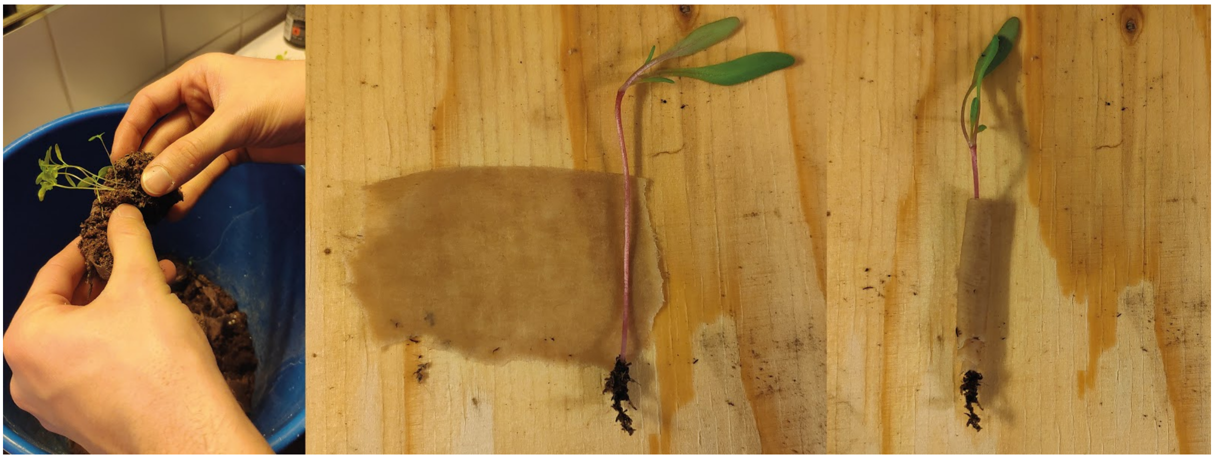


Figure 88 Plant transplantation process.

The seedlings were taken out of their growing plugs and wrapped in a wet coffee filter. This filter made sure that the roots would always be in contact with water, preventing them from drying out, as well as providing support. This coffee filter was applied in the towers and 3Dponics. In the DWC, the metal wire mounting system was used. After the plants were in, the sensors and electronics had to be mounted, completing building process. The final result is displayed in Figure 89.

Figure 89 Final setup.

5 Testing and results

5.1 Introduction

In this chapter, a number of aspects of the system that were tested will be discussed. The team hoped to have carried out more elaborate testing, but due to time constraints and setbacks with building, this was not possible. The tests shown here were not done in any scientific way, but more in a pragmatic and iterative way, except for the testing results of the housing. Furthermore, there is a focus on issues and actual results in this chapter, because none of the testing went perfect.

5.2 Water supply towers

Reason of testing
The towers and 3Dponics need a continuous supply of droplets so that the roots of the plants get all the water they need.

Desired result
The goal was to have a continuous water supply for the tower systems with a minimum flow rate of about 3 liters/hour. A pumping level of 2 m had to be reached. Once the water was up there, it had to be evenly distributed over the three systems using valves. This had to be done preferably with just an air pump and an airlift because of the lower power consumption.

Issues

1. As described in 'Handoff package/03. Setup process and maintenance/03.5 Setup process and maintenance', the first airlift designs did not reach the desired height, meaning either the design was bad or the air pump was insufficient.
2. Because there was no more time left to experiment with other airlift designs, the team turned to the pump from the 'Grove Smart Plant Kit for Arduino'. This pump turned out to be too powerful for the application. The pumping speed could not be altered, leaving turning it on and off in intervals as the only possible solution. This was considered a bit risky and possibly time consuming, so the team did not continue with this pump.

Actual results
Finally, combining the airlift with a small water pump, the desired height of 2 meters was reached. In this pumping setup, the water pump acts as a initialiser to kickstart the airlift pumping process. The flow rate was also measured, reaching a rate of 7.4 liters per hour on maximal water and air pump power. This is exactly perfect, because a flow rate of 3 liters per hour was needed, leaving a little headroom.

In Figure 90, the actual implemented configuration is shown with the newly 3D printed airlift part.

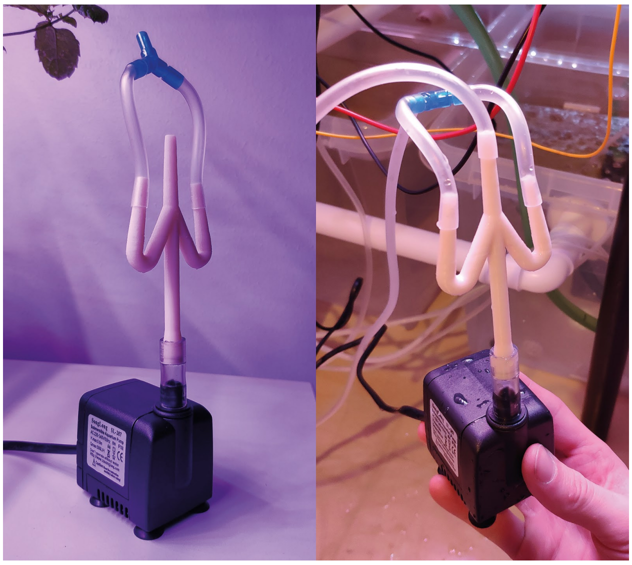


Figure 90 Airlift and waterpump combination.

After testing the combination again, not from a bucket, but from the actual biofilter tank, the team discovered that the water did not reach the top of the pallets anymore. That is why a separate pumping tank had to be installed, as shown in Figure 91, connected to the biofilter tank by a green flexible tube.

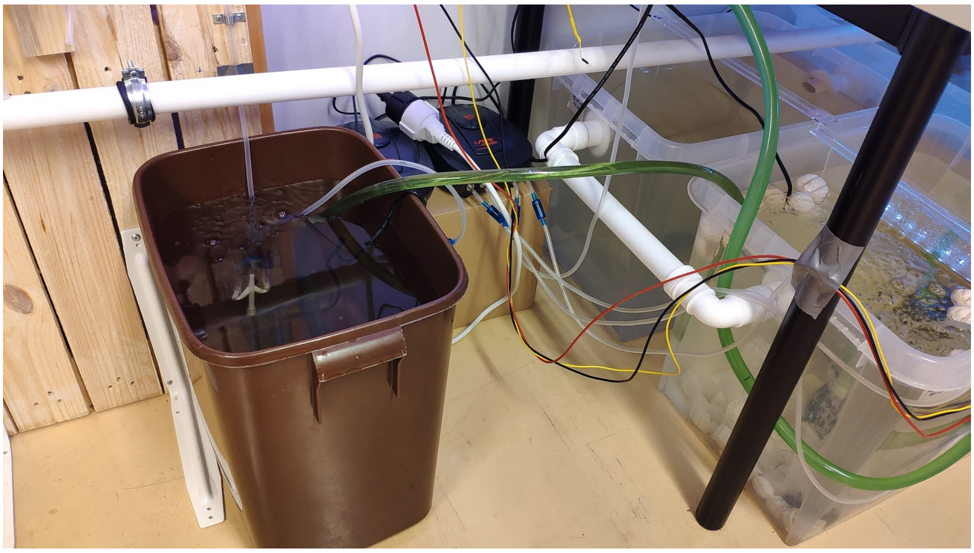


Figure 91 Separate pumping tank.

To finish off, the water flow had to be calibrated to ensure an equal water supply in each of the three systems. The calibration process ended with a final water flow rate of approximately 3 liter per hour. This is exactly what was needed for the tower systems.

5.3 Bioballs

Reason of testing
Bioball designs needed to be tested and evaluated due to the fact that existing models available from the internet were not material efficient enough and thus slow to print.

Desired result
Achieving a fast 3D prinTable bioball design which was low in material use and high in surface area, to accommodate as many bacteria as possible.

Issues
The actual testing and more detailed explanation can be read in 'Handoff package/03. Setup process and maintenance/03.5 Setup process and maintenance'. There, all of the specific issues are described. The most prominent issue however, was the fact that there was a long period of not being able to test and develop the designs because of a national postal service strike. This made it impossible for ABS material to arrive, of which the university had run out of.

Actual results
When the ABS had finally arrived, the team only had three days to print bioballs. Still, 110 bioballs could be printed, see Figure 92. Of those 110, 10 were designs from thingiverse, 40 were gyroid cubes and 60 were self-designed cylinders. Adding this with the number that was already present in the biofilter tank gives a total of approximately 120 bioballs in the system. This is an amount is definitely effective to grow and sustain bacteria in the biofilter tank.

Figure 92 Printed bioballs: from thingiverse, gyroid cubes and self-designed cylinders.

5.4 Growing plants

Reason of testing

Plants were grown both as already grown plants in pots and from seeds. This was started in the beginning of the semester, to ensure there were enough plants ready to place in the system once it was built. Later, some of the already grown plants were placed in the DWC to grow further.

Desired result

It was expected that the already grown plants, mint and basil would stay healthy and not die. Also, the team hoped that the seeds would grow out to young, healthy seedlings. Finally, concerning the plants in the DWC, it was expected that they would develop new leaves and roots in the water.

Issues

1. A lack of light both in the EPS-room and in the basement room caused the already grown plants and seedlings to grow very poorly. There was an excess of stem and a shortage of leaf surface visible in the small seedlings. That is why the team had to reseed multiple times. The process of reseeding can be read in 'Handoff package/03. Setup process and maintenance/03.5 Setup process and maintenance'.
2. Most of the plants were infected with some sort of parasite during the semester, visible as white spots on the leaves. This infection had to be on one of the plants already because they were not in contact with any other plants. A close-up of the parasite can be seen in Figure 93.

Figure 93 Close-up of parasite.

Actual results

A picture of the final seedling tray is displayed in Figure 94. Some of the seedlings were strong enough to make it to the actual aquaponics system. Unfortunately most of them were too weak because of their long stems.

Figure 94 Seedlings end state.

The plants in the DWC ended up with a quite positive result. Development of small leaves was visible, as well as the development of roots in the water. These results can be seen in Figure 95.

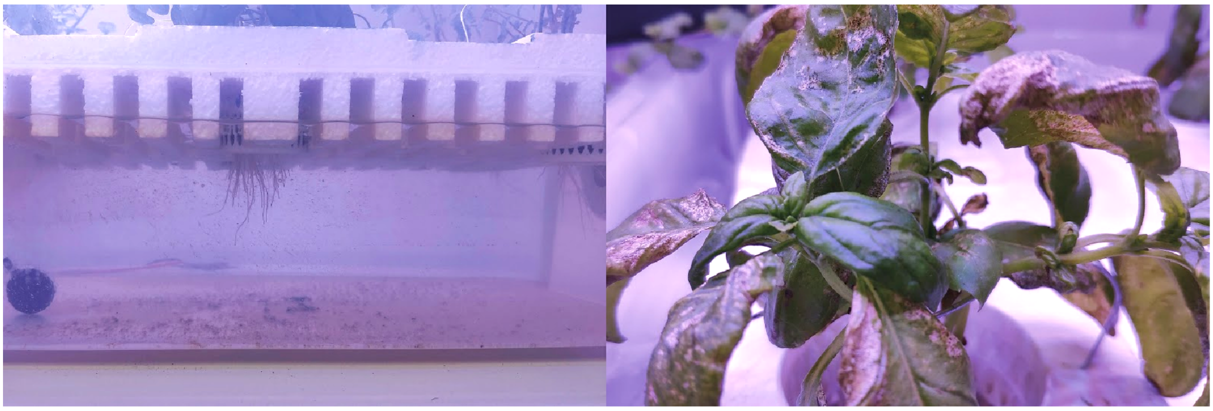


Figure 95 DWC plant growth.

5.5 Perch feeding adaptation

Reason of testing
The three perch that were caught from the sea needed to have their feeding changed from living organisms to artificial food. This is because they needed to be fed with the automatic fish feeder eventually. Putting living worms into the feeder would not be practical, so having them eat artificial food was crucial.

Desired result
A schedule has been proposed to perform such an adaptation, shown in Table 21. The proposal went over the course of two weeks, going from 100% living worms to 100% artificial bloodworm discs. The desired result was that the perch would have made this switch by the end of the semester.

Table 21, proposed conversion plan for perch from living to pelleted feed.

Days	Living worms %	Artificial fish feed %
1-3	100	0
4-6	75	25
7-10	50	50
11-13	25	75
14-…	0	100

Issues
The perch seemed to like the bloodworm discs a lot when they were in the tank with the Malawi, reacting actively to it. Later, they were separated from them and put in a separate tank to really get them to change to the discs properly. When they were fed the mixture of worms and discs in a dough-like mix, they always managed to pick out the worms. This was however not a big problem, because they would at least get used to the taste of it. Later on, they started to get very inactive in this separate tank and did not really eat anymore. They were not properly adapted to the discs, but because they did not eat at all anymore, they were put back with the malawi cichlids. Then, they were exclusively fed the bloodworm discs. Because the tank was so big, it was hard to monitor if they ate it or not.

Actual results
The bloodworm discs were finally crushed and put together with the flakes for the malawi fish in the fish feeder. This was done quite late in the semester, so it is yet to be seen if they will survive on this.

5.6 Fish feeder

Reason of testing
The fish feeder needed to be tested with flakes because its reliable operation is crucial for the survival of the fish.

Desired result
A fish feeder that operates reliably, without jamming or feeding at the wrong moments.

Issues

1. The first funnel part of the feeder that was 3D printed, shown in Figure 96, caused the food to jam at a certain point. Luckily, the Thingiverse model provided an anti-jamming funnel as well.

Figure 96 Normal and anti-clogging funnel.

2. After installing the feeder at its final location and connecting it to the arduino with the real-time clock, the feeder would not perform the feeding action anymore. The issue here was most likely the overload of data that the Arduino has to send as it is also connected to the LED lights. After disconnecting the LED strips for the plants (replaced by already programmed growing lights), the Arduino performed the expected actions.

Actual results
After printing and installing the anti-jamming funnel, the food did not get stuck anymore. The rotating part inside the funnel made sure the food got mixed each time the servo motor turned on. After modifying the code and the wiring multiple times, the fish feeder was able to feed the fish on the desired schedule.

5.7 Settling tank

Reason of testing
It is essential that the settling tank works, to keep the water clean. Otherwise, the dirt would start dissolving in the water, making the water cloudy.

Desired result
A settling tank where dirt accumulates on the floor of the tank, making it easy to clean.

Issues
The tank seemed to work from day one, but when it was not cleaned for more than three weeks, the water would get cloudy. This happened two times, it might have had something to do with the fact that there were no plants present in the system at that point to filter the water. A comparison between the cloudy and clear water while changing the water is shown in Figure 97. The solids can be seen on the left side of the picture, in the settling tank.

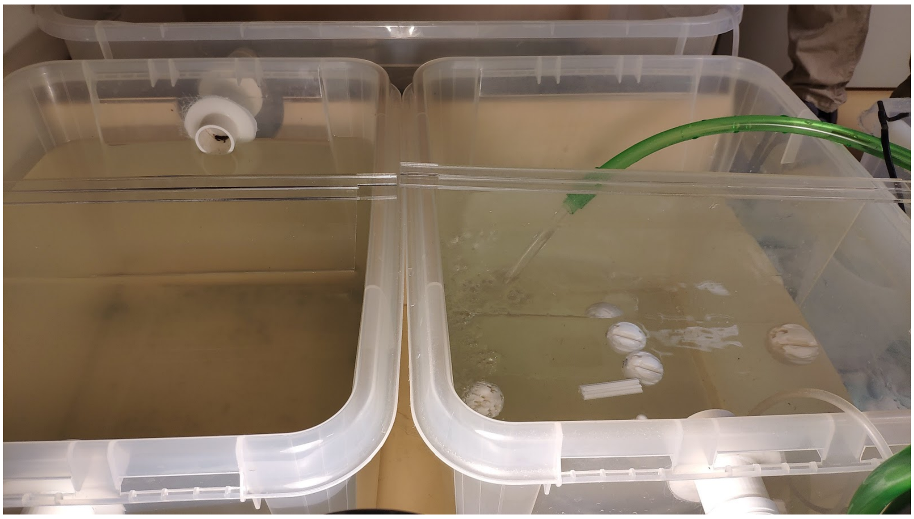


Figure 97 Cloudy water compared to clean water while changing the water.

Actual results
After changing the water two times, the water did not get cloudy anymore. At this point plants were present in the DWC, maybe influencing the cleaning of the water. It can be concluded that the settling tank works as it should, but cleaning the tank should happen every two weeks to prevent cloudy water.

5.8 Water evaporation

Reason of testing
The water level in the whole system is influencing the functionality of the self moving water cycle with one pump. If the water level falls below the minimum, the whole system stops working. The minimum is characterized by the fittings between the tanks whereby still a flow of water is possible. A loss of water is always given by evaporation. Therefore it is necessary to add water to be above the minimum. The air flow for the oxygen supply, room temperature, ventilation of the room, atmospheric pressure and humidity have the biggest influence on the amount of evaporated water. Also the plant species and the used system with different open surface areas and different water distribution systems could have a high influence. The water evaporation could be used to compare the designed aquaponic system to the water evaporation in Finish green houses.

Desired result
In the literature and forums can be found numbers for the water evaporation during the whole year for different seasons. This ranges between 5 % in winter and 15 % in summer *(Editors, n.d.).* Another value which could be used for a general calculation is 1 % per day *(Love, et. al., 2015).*

Issues
Because of a relatively low temperature for an aquaponic system of 19 degrees and a moderate ventilation, low humidity has the highest influence. The water evaporation was only tested with the DWC system and half used area of the rafts the plants. With using the towers and 3D-ponics the evaporation is likely to increase a lot as these systems provide much more surface for evaporation and a thin film of water provides the best evaporation.

Actual results
Two consecutive measurements show that the water evaporation is 11.5 liters per week. With using the other systems it could increase to 15 liters per week. This should be regularly checked and considered for the maintenance.

5.9 Hydroponic systems

Reason of testing
A comparison between the three main types of hydroponic plant growing system was necessary to give recommendations to next semesters' group on what system to use.

Desired result
Three running hydroponic systems to compare operating performance with each other. This would mean observing the plant grow and maintenance issues for each system.

Issues

Comparison between the three systems was not really possible in terms of operation performance as the towers and 3Dponic systems were both only completed in the last week before handing in the report. This was mainly due to a long research period and many problems and difficulties that were faced in acquiring materials as well as in building the setup itself. Many of these difficulties were discussed in the building and testing chapters.

Actual results

Comparison results can be divided into ease of building and system performance.

1. Ease of building:
    - Deep water culture: This system was very straightforward to build. The only difficulty was the designing and 3d printing of connection parts between the tanks, but this could easily be overcome by buying them. Furthermore it was just a matter of cutting the rafts and making holes in the and adding the water distribution and drain system. Plant pots were printed quite easily as well.
    - Towers: Building the pipes themselves was really easy, as it was just a matter of cutting the PVC pipe to length, making holes and putting the foam in. Finding a mounting system was somewhat harder and more time consuming, but the biggest issue was the water supply. Getting the pumping system to work was a real challenge because of the height to which the water had to be pumped.
    - 3Dponics: This system was extremely easy to build, but shares the main issues of the towers: water supply. Creating a mounting system for each separate plant bottle was also quite time consuming, but luckily the process was speeded up by not creating the dripping nozzles with 3D-printing.
2. System performance:
    - Deep water culture: This is the only system of which results could be observed. Plants grew new leaves and roots and no major issues were faced other than a leakage due to the 3D printed connection parts. This system ran stabilly, without any pump failures or clogged pipes.
    - Towers: No results could be gathered.
    - 3Dponics: No results could be gathered.

5.10 Housing

The thickness of insulation was tested on 50mm, 100mm and 150mm. The results of these tests are shown in Figure 98.

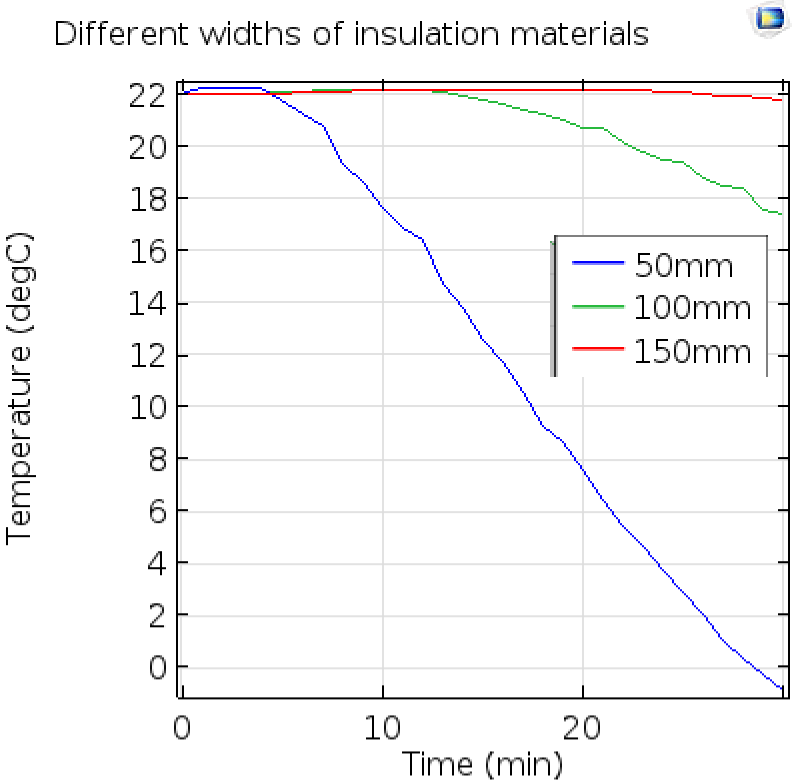


Figure 98 Difference between temperature development through time relative to the thickness of the insulation material

Since 150mm thick insulation material works the best, this thickness has been chosen for the setup. Since the red line loses little temperature through 30 minutes, another simulation has been conducted to see how the insulation material performs further in time, see Figure 99.

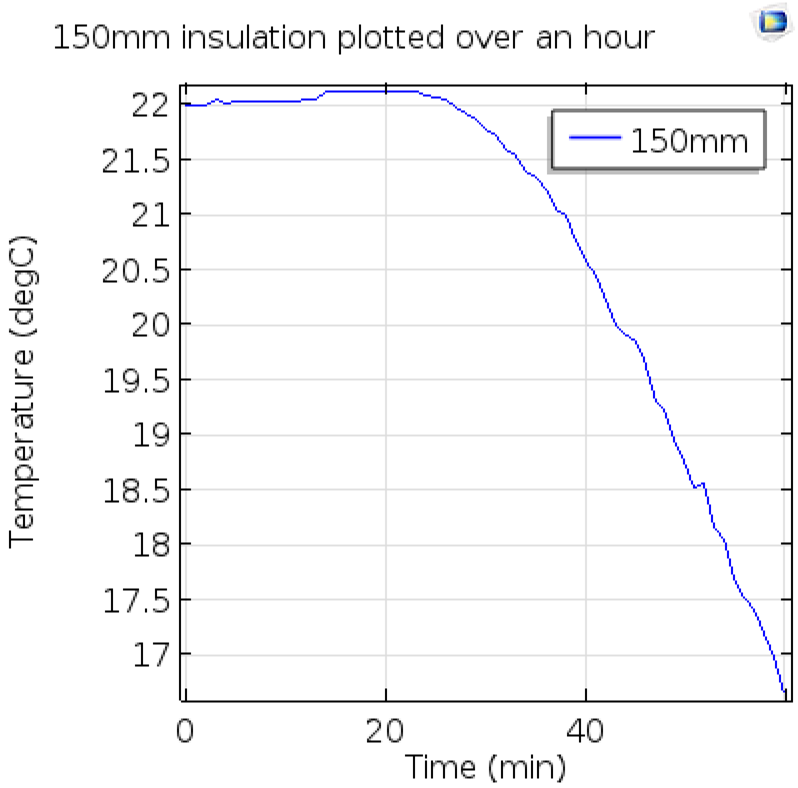


Figure 99 150mm thick insulation material simulated for an hour

After calculating the heat loss and discussing the results in ‘Handoff package/06. Housing/ 06. Housing’, the heat loss is estimated to be around $Q/t \simeq 200\ J/s$.

6 Conclusion and Recommendations

6.1 Conclusion

The project goal was to successfully complete the design and construction of a functional and attractive aquaponic setup to present to the stakeholders. This included making a handoff package to show students the exact procedures carried out to make an aquaponic system.

A design has been made for an experimental aquaponic setup, it has been constructed and all the steps, choices and decisions were carefully documented in a thought out handoff package. Unfortunately there was no time at the end of the project to entirely test the setup, so there is no saying if the setup will be functional in all of its subsystems.

The final conclusion is that we did not reach our project goal completely since there is no telling if the setup is functional in its entirety. However, there is a well documented handoff package and a designed & built aquaponic setup.

6.2 Recommendations

In this chapter, recommendations will be given on the most crucial aspects of building and running an aquaponics setup. These are supported by the research, building experiences and testing results. All of this is useful for the team who will be building the container setup in the second semester. Recommendations of other aspects like controlling or housing that are useful to know can be found in the handoff package.

6.2.1 Fish

The main recommendation for fish is on how to get them. The team advises to get fish from freshwater farms in Finland or other Scandinavian countries. In these farms, fish are grown in different stages, making it possible to get middlesize fish. These fish will also be trained to be fed with artificial food, which is an enormous benefit, because converting the fish from living to artificial food turned out to be very difficult and time consuming in this project. The team has found that it is not easy to get into contact with these farms, so a possible option is to talk to people at agricultural associations. Furthermore, Tilapia or any other warm water fish are not recommended, because of the water temperatures they require and the difficulty of getting them in Finland. Cold water fish like trout or carp on the other hand are recommended. Carp would be the ideal fish for an aquaponic system in Finland because of the ease of feeding (herbivore), resistance to water quality and parameter changes and ability to be grown in high density.

Besides fish, shrimp or prawns could be a very smart and convenient option to use as a natural cleaner of the system. They can be acquired from some pet stores, but asking in advance is recommended, as they are not present all year around.

6.2.2 Plants

Plants are the second crucial aspect of an aquaponic system and should have great attention. The team recommends to start seeding plants in the beginning of the semester, to ensure there are beautiful plants growing in the container setup at the end of the semester. The most important aspect of growing is the light supply. Be sure to have plenty of light, taking inspiration from the test setup that was built, as the light supply here should be considered as a minimum. Another difficulty to keep in mind is the low humidity in the air in the university building. This makes it hard to grow the plants as they will dry out in a day. Watering twice a day, including weekends, is recommended. Something that was not done and should be done in the next semester, is using another growth medium like rockwool. This will make the growing and transplantation process easier. Finally, it is not recommended to buy plants from gardening or any other store, because of the unknown diseases or parasites that can be present. This is something that should be avoided at all cost, because it is bad for the looks of the system.

6.2.3 Filtering

Settling tank

The settling tank has definitely got to be implemented in the container setup as it is the key to keeping the water in the system clean. The design that was presented in the test setup worked, but was extremely inconvenient to clean out. It is highly recommended to look into cylindrical barrel designs with an outlet at the bottom of the tank. Other designs will also work, as long as the dirt is collected in one central spot.

Biofilter tank

Using bioballs as a growing medium for bacteria is great, except for the extremely long process of 3D printing them. As for many aspects of the system, replacing 3D printed parts by parts that can be made in other ways or simply bought can significantly save time and 3D printing material. That is why the team recommends to buy extra bioballs on top of the existing bioballs that were printed this semester. Additionally, there is no need to buy extra bacteria, as plenty is left in the box that was received. There are also a lot of bacteria present in the testing system, so when building the container setup, water from this system can simply be transferred. This way not only bacteria, but also nutrients are put in the water of the container setup.

6.2.4 Hydroponic systems

Finally, when designing the container setup, a choice of hydroponic plant growing system has to be made. Based on all of the research and findings in building and testing, the team recommends to implement deep water culture and vertical towers in the system.

Deep water culture is an obvious choice, because it is easy to build and maintain. It is very safe to run as it is resilient to fluctuations in parameter changes and in case of a system failure, plants will still survive for some days. Using the water distribution is definitely an added value. An adaptation that could be made is to have slightly lower tanks, to avoid having unnecessary amounts of extra water. Something to also be cautious of, is making sure the rafts are made of food safe material, like the fishboxes that were used in the testing system.

Reasons to choose for the vertical towers include visual appeal, high density of plants compared to 3Dponics and the possibility to clean it in case of solids accumulation. Although there were a lot of problems with using the airlift as a pumping device, it is still recommended to use an air assisted pump, as it can generate the necessary water flow of 1 liter per hour for one tower. However, other solutions besides 3Dponics airlifts have to be explored, because of the many problems that were faced with it. Hiding transparent tubing from light is also a good idea if the setup is running for a longer time, as it can cause unwanted algae growth.

6.2.5 General recommendations

As some concluding recommendations, the team wants to emphasize the importance and difficulty of getting fish, as it is absolutely crucial and not something which can be done last-minute. Another recommendation is to not overuse 3D printing. It can be a very useful tool for some complex and specific parts, but if it is used in too many parts it becomes a time and energy consuming and expensive production tool. Finally, it is crucial to design. Find materials and start building as fast as possible, because an aquaponics setup is something that is not built in a couple of weeks. Real setups take more than a year to get functioning properly, therefore three months is already very little time.

7 Bibliography

3dponics.com. (2015). 3d-printing-Hydroponics - 3Dponics. Retrieved October 1, 2019, from https://www.3dponics.com/blog/how-to-grow-herbs-indoors-hydroponics/3dponics-3d-printing-hydroponics/

3Dponics.com. (n.d.). 3Dponics | 3D Printing + Hydroponics. Retrieved September 16, 2019, from https://www.3dponics.com/

Adreco Plastics.co.uk. (2018). ABS Plastic Properties. Retrieved September 17, 2019, from https://www.adrecoplastics.co.uk/abs-plastic-properties-and-application/

AeroFarms. (2019). Retrieved 1 October 2019, from https://aerofarms.com/

All3DP. (2019). 2019 PLA Filament Guide – All You Need to Know. Retrieved September 30, 2019, from https://all3dp.com/1/pla-filament-3d-printing/

Allthat3D.com. (n.d.). PETT Filament: Strength, Properties, and Tips for Better 3D Printing. Retrieved September 17, 2019, from https://www.allthat3d.com/pett-filament/

AlShrouf, A. (2017). Hydroponics, Aeroponic and Aquaponic as Compared wit conventional farming (pp. 247-255). Abu Dhabi: American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS).

Alsteen, P. (2019). Best Aquarium Air Pumps in 2019 for a Quiet Fish Tank. Retrieved October 2, 2019, from https://petsnerd.com/best-aquarium-air-pumps/

Aqualogue.org. (n.d.). Minimal Vertical Aquaponics Garden DIY: 6 Steps (with Pictures). Retrieved September 24, 2019, from https://www.instrucTables.com/id/Aquaponics-Minimal-Apartment-DIY/

Aquaneo-Techna. (n.d.). The Feed Conversion Ratio and other Performance Indicators in Farmed Fish. Retrieved October 21, 2019, from https://www.aquaneo-techna.com/en/productivity/experts/feed-conversion-ratio-farmed-fish

Aquaponics Grow Bed. (2016). Best Fish For Aquaponics. Retrieved October 16, 2019, from https://aquaponicsgrowbed.com/best-fish-for-aquaponics/

Aquaponics Iberia. (2019). Retrieved 1 October 2019, from https://www.aquaponicsiberia.com/?lang=en

Aquaponics.com. (n.d.). Methods of Aquaponics • Nelson & Pade Aquaponics. Retrieved October 1, 2019, from https://aquaponics.com/methods-of-aquaponics/

Aquaponics.fandom.com. (n.d.). Nutrient Film Technique. Retrieved September 13, 2019, from https://aquaponics.fandom.com/wiki/Nutrient_Film_Technique

Aquaponicsexposed.com. (n.d.). Nutrient Film Technique In Aquaponics. Retrieved September 13, 2019, from https://aquaponicsexposed.com/nutrient-film-technique-in-aquaponics/

Aquariumadviser.com. (n.d.). Best Cichlid Food for Color & Growth 2019. Retrieved November 23, 2019, from https://aquariumadviser.com/best-cichlid-food/

Aquasi. (2019). Carp aquaponics - Excellent species choice for large UK systems. Retrieved October 15, 2019, from https://aquapona.co.uk/carp-aquaponics/

Aqueon.com. (n.d.). Designing an African Rift Lake Cichlid Aquarium. Retrieved November 22, 2019, from https://www.aqueon.com/articles/designing-an-african-rift-lake-cichlid-aquarium

Avooq.com. (n.d.). Cascaqua - Cascading Aquaponics System. Retrieved September 16, 2019, from https://avooq.com/product/cascaqua/

Baguley, R. (2017). 3D Printing Materials: The Pros and Cons of Each Type. Retrieved September 23, 2019, from https://www.tomsguide.com/us/3d-printing-materials,news-24392.html

Barbara Project.eu. (2017). Bioplastics: Towards new advanced green materials. Retrieved September 23, 2019, from https://www.barbaraproject.eu/bioplastics-towards-new-advanced-green-materials

Bengtson, H. (2019). Use of Excel Spreadsheets to Calculate Forced Convection Heat Transfer Coefficients. Retrieved October 3, 2019, from Bright Hub website: https://www.brighthubengineering.com/hvac/91056-calculation-of-forced-convection-heat-transfer-coefficients/

Böer, K. (n.d.). Solar Cells - Chemistry Encyclopedia - structure, metal, equation, The pn Junction. Retrieved September 9, 2019, from http://www.chemistryexplained.com/Ru-Sp/Solar-Cells.html

Brooke, N. (n.d.-a). Building A Vertical Aquaponics System | How To Aquaponic. Retrieved September 24, 2019, from https://www.howtoaquaponic.com/designs/vertical-aquaponics-system/

Brooke, N. (n.d.-b). Freshwater Shrimp and Prawn Aquaponics. Retrieved October 16, 2019, from https://www.howtoaquaponic.com/fish/freshwater-aquaponics-shrimps/

Brooke, N. (n.d.-c). Swirl Filter for Aquaponics. Retrieved December 2, 2019, from https://www.howtoaquaponic.com/designs/swirl-filter/

Bundschuh, J., & Chen, G. (2014). *Sustainable energy solutions in agriculture* (8th ed.). Retrieved from https://books.google.fi/books?id=hQDOBQAAQBAJ&pg=PA111&dq=%22heat+pump%22+%22heat+sink%22+opposite+direction&redir_esc=y&hl=nl#v=onepage&q=%22heat pump%22 %22heat sink%22 opposite direction &f=false

BusinessDictionary.com. (n.d.). What is a parameter? definition and meaning. Retrieved October 10, 2019, from http://www.businessdictionary.com/definition/parameter.html

Carruthers, J., Longstaff, B., Dennison, W., Abal, E., & Aioi, K. (2001). Global Seagrass Research Methods (p. 369-392). Elsevier Science.

Chris Goering. (2019). Types of Aquaponics Designs - ECOLIFE Conservation. Retrieved October 1, 2019, website: https://www.ecolifeconservation.org/updates/types-aquaponics-systems-design/

Collos, Y., & Harrison, P. J. (2014). Acclimation and toxicity of high ammonium concentrations to unicellular algae. *Marine Pollution Bulletin*, *80*(1–2), 8–23. https://doi.org/10.1016/j.marpolbul.2014.01.006

ConcernUSA. (2018). The world’s ten hungriest countries. Retrieved September 19, 2019, from https://www.concernusa.org/story/worlds-ten-hungriest-countries/

ConcernUSA. (2019a). 10 Causes of world hunger. Retrieved September 19, 2019, from https://www.concernusa.org/story/top-causes-world-hunger/

ConcernUSA. (2019b). What are El Niño and La Niña – and why do they matter for humanitarian work? Retrieved September 19, 2019, from https://www.concernusa.org/story/el-nino-and-la-nina/

Connolly, K., Trebic, T. (2010). Aquaponics Design. P. 73. Retrieved from https://www.academia.edu/4107785/Aquaponics_Design

Craig, S. (2017). Understanding Fish Nutrition, Feeds, and Feeding. Virginia Tech.

Creative Mechanisms staff. (2016). Everything you need to know about bioplastics. Retrieved October 16, 2019, from https://www.creativemechanisms.com/blog/everything-you-need-to-know-about-bioplastics

Crocker, A., & Student Fletcher Miller, G. (2010). *Status of Solar Thermal Power in California*. Retrieved from www.wikipedia.org

Curran, M. (2006). Life Cycle Assessment: principles and practice. Retrieved 22 October 2019,

Different Light at Different Stages of the Plants Life cycle. (2018). Retrieved 13 October 2019, from https://localharvestorganics.com/blog/f/different-light-at-different-stages-of-the-plants-life-cycle

DIY staff. (n.d.). What Equipment You Need for an Aquaponics System. Retrieved October 4, 2019, from https://www.doityourself.com/stry/what-equipment-you-need-for-an-aquaponics-system

Dunlap, W. C., Williams, D. M., Chalker, B. E., & Banaszak, A. T. (1989). ABSORBING PIGMENTS IN FISH EYE TISSUES*. In *Biochem. Physiol* (Vol. 93).

Dyer, M. (n.d.). Basil Plant Turning Yellow: How To Treat Yellow Leaves On Basil Plants. Retrieved October 15, 2019, from https://www.gardeningknowhow.com/edible/herbs/basil/yellow-leaves-on-basil.htm

Conservation, E. (2016). The Top 5 Aquaponics Fish Species for Your System. Retrieved November 22, 2019, from https://www.ecolifeconservation.org/updates/the-top-5-aquaponics-fish-species-for-your-system/

EDEN ISS | Ground Demonstration of Plant Cultivation Technologies and Operation in Space. (2019). Retrieved 1 October 2019, from https://eden-iss.net/

Editorial S. (2019). What is the Role of Ammonia in an Aquaponics System? Retrieved December 3, 2019, from https://www.leaffin.com/role-ammonia-aquaponics-system/

Editorial Staff. (2019). Best Aquaponic Fish (Top 11 SuiTable Species for every type of System). Retrieved October 14, 2019, from https://www.leaffin.com/aquaponic-fish/

Elieson, M. (2019). Feeding African Cichlids. Retrieved November 23, 2019, from https://www.cichlid-forum.com/articles/feeding_african_cichlids.php

Erwin, J., & Gesick, E. (2017). Photosynthetic Responses of Swiss Chard, Kale, and Spinach Cultivars to Irradiance and Carbon Dioxide Concentration. Hortscience, 52(5), 706-712.

European Commission. (2012). Sturgeon Acipenser Baerii. *Fisheries and Aquaculture in Europe*, *56*, 12. Retrieved from https://op.europa.eu/en/publication-detail/-/publication/312dc873-8a39-43b2-a40a-ac16cbc969d3/language-en

FAO. (2002). Farming freshwater prawns. Retrieved from http://www.fao.org/3/y4100e/y4100e00.htm#TOC

Fao.org. (2015). 7 rules-of-thumb to follow in aquaponics. Retrieved October 10, 2019, from http://www.fao.org/zhc/detail-events/en/c/320156/

FAO: Nutritional requirements. (2019). Retrieved 1 October 2019, from http://www.fao.org/fishery/affris/species-profiles/barramundi/nutritional-requirements/en/

Farm, W. F. & L. (n.d.). Perth Metro Delivery - Woodvale Fish & Lily Farm. Retrieved October 15, 2019, from https://www.woodvalefishandlilyfarm.com.au/product/barramundi/

Fondriest. (2019-a). Emitted radiation frequencies of the sun. Retrieved 13 October 2019, from https://www.fondriest.com/environmental-measurements/parameters/weather/photosynthetically-active-radiation/

Fondriest. (2019-b). Optimal photosynthetically active radiation is the band from 400-700 nm. Retrieved 13 October 2019, from https://www.fondriest.com/environmental-measurements/parameters/weather/photosynthetically-active-radiation/

Frei, W. (2017). Modeling Natural and Forced Convection in COMSOL Multiphysics® | COMSOL Blog. Retrieved October 14, 2019, from https://www.comsol.com/blogs/modeling-natural-and-forced-convection-in-comsol-multiphysics/

Freight Farms. (2019). Greenery Product Booklet August 2019 [Ebook] (p. 10). Boston, Massachusetts. Retrieved from https://www.freightfarms.com/greenery#booklet-download

Friend, S., Mann, T., & Aquaponics, F. (2014). Aquaponics the easy way! 224. Retrieved from https://www.friendlyaquaponics.com/docs/AEWComplete7-23-14.pdf; https://friendlyaquaponics.com/docs/HowManyPrawnsCanISqueezeIn.pdf

Friendly Aquaponics. (n.d.). System Startup , Operation and Maintenance. Retrieved from https://www.friendlyaquaponics.com/docs/System%20Startup3-5-14.pdf

Futuren. (n.d.). How does it work? Retrieved September 13, 2019, from http://www.futuren-group.com/en/lenergie-eolienne/comment-ca-marche

Gary. (2009). The Aquaponic Ecosystem. Retrieved October 1, 2019, from https://www.microponics.net.au/microponics/the-aquaponic-ecosystem/

Ghamkhar, R., Hartleb, C., Wu, F., & Hicks, A. (2019). Life cycle assessment of a cold weather aquaponic food production system. *Journal Of Cleaner Production*. doi: https://doi.org/10.1016/j.jclepro.2019.118767

Gibbens, S. (2018). What you need to know about plant-based plastics. Retrieved September 23, 2019, from https://www.nationalgeographic.com/environment/2018/11/are-bioplastics-made-from-plants-better-for-environment-ocean-plastic/

Goddek, S. (2017). Opportunities and Challenges of Multi-Loop Aquaponic Systems. https://doi.org/10.18174/412236

Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K., Jijakli, H. and Thorarinsdottir, R. (2015). Challenges of Sustainable and Commercial Aquaponics. *Sustainability*.

Godfrey, M. (2018). The Quick Reference Guide for Hydroponic Farmers - Upstart University. Retrieved October 3, 2019, from https://university.upstartfarmers.com/blog/the-quick-reference-guide-for-hydroponic-farmers

Goering, C. (2019). Types of Aquaponics Designs. Retrieved September 13, 2019, from https://www.ecolifeconservation.org/updates/types-aquaponics-systems-design/

Grove. (2016). 5 Awesome Plants for Aquaponics - The Grove Blog. Retrieved October 3, 2019, from https://blog.grovegrown.com/5-awesome-plants-for-aquaponics-aa90fb205e65

Growtainer - The PorTable Production Facility of the Future. (2019). Retrieved 1 October 2019, from http://www.growtainers.com/

Grunenwald, S. J. (2015). 3Dponics is Modernizing Urban Agriculture Further With New 3D Printed Cube Garden - 3DPrint.com | The Voice of 3D Printing / Additive Manufacturing. Retrieved October 1, 2019, from https://3dprint.com/66460/3dponics-urban-agriculture/

Gsbi.org. (n.d.). How Hunger Differs in Different Places - Feeding the Future World. Retrieved September 19, 2019, from https://sites.google.com/a/gsbi.org/gvc1305/feeding-the-future-world/hunger/how-hunger-differs-in-different-places

Guy-Allen, C. (2014). The world's 10 hungriest countries. Retrieved September 19, 2019, from https://www.globalcitizen.org/en/content/the-worlds-10-hungriest-countries/

HambreyConsulting. (2013). *Aquaponic Research Project*. Retrieved from https://www.mfat.govt.nz/assets/Aid/Aid-approach-aquaponics-Pacific-report-2013.pdf

Heatsink - Design and Selection, Fin Arrangements. (n.d.). Retrieved September 27, 2019, from https://www.abl-heatsinks.co.uk/heatsink/heatsink-selection-fin-arrangements.htm

Helmenstine, A. M. (2019). pH Definition and Equation in Chemistry. Retrieved October 11, 2019, from https://www.thoughtco.com/definition-of-ph-in-chemistry-604605

Higgins, M. (2016). Understanding Ultraviolet LED Wavelength - UV+EB Technology. Retrieved September 30, 2019, from https://uvebtech.com/articles/2016/understanding-ultraviolet-led-wavelength/

Home Aquaria. (2014). Retrieved 14 November 2019, from http://homeaquaria.com/aquarium-fish-food-types-nutrition/

Hoopes, B. (2015). 3DPonics introduces the first 3D prinTable hydroponics system. *The Hemp Connoisseur*. Retrieved from https://issuu.com/thcmag/docs/thc_august_15_issuu_e11a74d8e94c55/50

Hunt, A. (2016). Grow Veggies & Fish in Your 3D Printed Aquaponic Home | All3DP. Retrieved 18 October 2019, from https://m.all3dp.com/grow-veggies-fish-in-your-3d-printed-aquaponic-home/

Hyperphysics. (2019). Light Absorption for Photosynthesis. Retrieved 13 October 2019, from http://hyperphysics.phy-astr.gsu.edu/hbase/Biology/ligabs.html

Ilmatieteenlaitos.fi. (n.d.). Seasons in Finland. Retrieved September 27, 2019, from https://en.ilmatieteenlaitos.fi/seasons-in-finland

Jamet, J. (1994). Feeding activity of adult roach (Rutilus rutilus (L)), perch (Perca fluviatilis L.) and ruffe (Gymnocephalus cernuus (L)) in eutrophic Lake Aydat (France). Aquatic Sciences, 56(4), 376-387. doi: 10.1007/bf00877183

Junge, R., König, B., Villarroel, M., Komives, T., & Jijakli, M. H. (2017). Strategic points in aquaponics. In *Water*. https://doi.org/10.3390/w9030182

JYSK.fi. (n.d.-a). Retrieved October 19, 2019, from https://jysk.fi/sailytys/korit-jne/muovi-sailytys-0/sailytyslaatikko-basic-box-80l-kannella

JYSK.fi. (n.d.-b). Retrieved October 19, 2019, from https://jysk.fi/sailytys/korit-jne/muovi-sailytys-0/sangynaluslaatikko-basic-box-30l-kansi

Kim, H. (2018). Aquaponics basics. 1–16. Retrieved from https://ag.purdue.edu/hla/fruitveg/Presentations/Aquaponics%20Basics_February%2013,%202018_Hye-Ji%20Kim.pdf

Kim, H., Goins, G., Wheeler, R., & Sager, J. (2004). Green-light Supplementation for Enhanced Lettuce Growth under Red- and Blue-light-emitting Diodes. Hortscience, 39(7), 1617-1622.

King, R. (n.d.). White Sturgeon - National Maritime Historical Society. Retrieved October 15, 2019, from https://seahistory.org/sea-history-for-kids/white-sturgeon/

Kishor. (2018-a). Best Plants for Aquaponics System – Which Aquaponics Plants to Grow | High Desert Farming. Retrieved October 1, 2019, from https://www.highdesertfarming.org/best-plants-for-aquaponics-system/

Kishor. (2018-b). Which Fish Should You Grow in Aquaponics | High Desert Farming. Retrieved October 1, 2019, from https://www.highdesertfarming.org/aquaponics-fish-how-to-select-and-maintain-good-fish-for-aquaponics-system/

Kulkarni, S., Abraham, P. S., Mohanty, N., Kadam, N. N., & Thakur, M. (2018). Sustainable Raft Based Hydroponic System for Growing Spinach and Coriander. In Techno-Societal 2016 (pp. 117–125). https://doi.org/10.1007/978-3-319-53556-2_13

Lark, R. J. (2004). Proceedings of the Institution of Civil Engineers. *Bridge Engineering*, *157*(2), 103–110. Retrieved from https://www.icevirtuallibrary.com/doi/10.1680/bren.2004.157.2.103

Laylin, T. (2016). 3D-printed Aquaponic Homes grow their own veggies and fish. Retrieved September 16, 2019, from https://inhabitat.com/3d-printed-aquaponic-homes-grow-their-own-veggies-and-fish/

Lennard, W. (2012). Aquaponic System Design Parameters : Fish to Plant Ratios (Feeding Rate Ratios). *Aquaponic Solutions*, *1*(1), 1–11. Retrieved from http://www.aquaponic.com.au/Fish%20to%20plant%20ratios.pdf

Live Aquaponics. (n.d.). Live Prawns 1-2.5 inch. Retrieved October 17, 2019, from https://www.liveaquaponics.com/Prawns-In-Aquaponics-s/176.htm

Love, D. C., Uhl, M. S., & Genello, L. (2015). Energy and water use of a small-scale raft aquaponics system in Baltimore, Maryland, United States. *Aquacultural Engineering*, *68*, 19–27. https://doi.org/10.1016/j.aquaeng.2015.07.003

Luv2garden. (n.d.). Hydroponic Mint - Growing Quality Mint Leaves Hydroponically. Retrieved October 15, 2019, from https://luv2garden.com/hydroponic_mint.html

Mann, T. (2015). Feeding The Fish And Making Your Own Fish Food - Friendly Aquaponics. Retrieved October 1, 2019, from https://www.friendlyaquaponics.com/2015/08/19/feeding-the-fish-and-making-your-own-fish-food/

Martin, A. D. (2017). Technical and economical study of Aquaponics Feasibility in northern Finland. (June), 73. Retrieved from http://jultika.oulu.fi/files/nbnfioulu-201708022724.pdf

Martineau, V., Lefsrud, M., Naznin, M., & Kopsell, D. (2012). Comparison of Light-emitting Diode and High-pressure Sodium Light Treatments for Hydroponics Growth of Boston Lettuce. Hortscience, 47(4), 477-482.

Maucieri, C., Forchino, A., Nicoletto, C., Junge, R., Pastries, R., Sambo, P., & Borin, M. (2018). Life cycle assessment of a micro aquaponic system for educational purposes built using recovered material. *Journal Of Cleaner Production*, *172*, 3119-3127. Retrieved from https://www.sciencedirect.com/science/article/pii/S0959652617327634

MaximumYield. (n.d.). Induction Grow Lights. Retrieved September 26, 2019, from https://www.maximumyield.com/definition/3102/induction-grow-lights

Nelson and Pade Aquaponics. (n.d.-a). Retrieved October 1, 2019, from https://aquaponics.com/aquaponics-overview/

Nelson and Pade. (n.d.-b). Methods of Aquaponics. Retrieved September 14, 2019, from https://aquaponics.com/methods-of-aquaponics/

Nelson and Pade. (n.d.-c). What is Aquaponics? Retrieved September 8, 2019, from https://aquaponics.com/aquaponics-information/

Nelson, Pade, & Inc. (2010). Recommended Plants and Fish in Aquaponics. Retrieved October 3, 2019, from https://aquaponics.com/recommended-plants-and-fish-in-aquaponics/

Nieuws - Action Power. (n.d.). Retrieved September 27, 2019, from https://actionpower.eu/nl/nieuws/

Petrea, S. M., Coadă, M. T., Cristea, V., Dediu, L., Cristea, D., Rahoveanu, A. T., ... Mocuta, D. N. (2016). A Comparative Cost – Effectiveness Analysis in Different Tested Aquaponic Principles of Remote Sensing. (2019). Retrieved 13 October 2019, from https://crisp.nus.edu.sg/~research/tutorial/optical.htm

Ragheb, M. (2014). *OPTIMAL ROTOR TIP SPEED RATIO*.

Rakocy, J. E., Masser, M. P., & Losordo, T. M. (2006). Recirculating aquaculture tank production systems: Aquaponics-Integrating fish and plant culture. Retrieved October

22, 2019, from https://www.researchgate.net/publication/284496499_Recirculating_aquaculture_tank_production_systems_Aquaponics-Integrating_fish_and_plant_cultur

Rakocy, J., Masser, M. and Losordo, T. (2016). *Aquaponics - Integrating Fish and Plant Culture*. Oklahoma: Oklahoma State University.

Ritchie, H. and Roser, M. (2019). Co2 and Greenhouse Gas Emissions. *Our World in Data*. Retrieved from https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Rivera-Mendes, Y., & Romero, H. (2017). Fitting of photosynthetic response curves to photosynthetically active radiation in oil palm. Agronomía Colombiana, 35(3), 323-329.

Rizal, A., Dhahiyat, Y., Zahidah, Andriani, Y., Handaka, A., & Sahidin, A. (2018). The economic and social benefits of an aquaponic system for the integrated production of fish and water plants. IOP Conference Series: Earth And Environmental Science, 137(012098).

Robert, J. (2019). Best LED Grow Lights] an Ultimate Guide for Growing Plants In 2019. Retrieved 13 October 2019, from https://consumercure.com/best-led-grow-lights/

Russell, S. (2014). Everything You Need to Know About Agricultural Emissions. Retrieved 20 October 2019, from https://www.wri.org/blog/2014/05/everything-you-need-know-about-agricultural-emissions

Sallenave, R. (2016). *Important Water Quality Parameters in Aquaponic Systems*. Retrieved from https://aces.nmsu.edu/pubs/_circulars/CR680.pdf

Schubert, D., Bamsey, M., Zabel, P., Zeidler, C., & Vrakking, V. (2018). Status of the EDEN ISS Greenhouse after on-site installation in Antarctica.

Sean, B. (2019). Designing Your Aquaponics System | The Aquarium Adviser. Retrieved October 3, 2019, from https://theaquariumadviser.com/designing-your-aquaponics-system/

Short-day & Long-day Plants: Photoperiodism. (2019). Retrieved 13 October 2019, from https://myperfectplants.com/2017/11/03/photoperiodism-day-length/

SimplyHydro. (2008). Basic Hydroponic Systems and How They Work. Retrieved October 4, 2019, from https://www.simplyhydro.com/system.htm

Snabel_a. (2019). Hydroponic on a string planter by Snabel_a - Thingiverse. Retrieved October 1, 2019, from https://www.thingiverse.com/thing:3790451

Somerville, C., Cohen, M. (2014). Small-scale Aquaponic systems - Annexes. 139–172. Retrieved from http://livefreeaquaponicsllc.com/wp-content/uploads/2017/07/UN-Part-10.pdf

Somerville, C., Cohen, M., Pantanella, E., Stankus, A. and Lovatelli, A. (2014). *Small-scale aquaponic food production*. Retrieved from http://www.fao.org/3/a-i4021e.pdf

STATE-OF-THE-ART | meaning in the Cambridge English Dictionary. (2019). Retrieved 18 October 2019, from https://dictionary.cambridge.org/dictionary/english/state-of-the-art

Sterzelecki, F., & Tidwell, J. (2012). Aquaculture Production Systems (p. 421). P. 421. Retrieved from https://www.academia.edu/36260785/Aquaculture_Production_Systems

Storey, A. (2016-a). Growing or selling Basil? Retrieved Dezember 03, 2019, from https://university.upstartfarmers.com/blog/hydroponic-basil

Storey, A. (2016-b). Sizing a Pump for Hydroponics or Aquaponics Retrieved October 15, 2019, from https://university.upstartfarmers.com/blog/sizing-a-pump-hydroponics-aquaponics

Systems. *Agriculture and Agricultural Science Procedia*. https://doi.org/10.1016/j.aaspro.2016.09.034

TechNoLand (n.d.). Retrieved September 27, 2019, from http://chamayou.franck.free.fr/spip/spip.php?article208

Tenningas, M. (2013). Top 5 Benefits of LED Grow Lights for Urban Farming. Retrieved October 4, 2019, from https://www.ledluxor.com/top-5-benefits-of-led-grow-lights-for-urban-farming

The National Oceanic and Atmospheric Administration. (2019). What is aquaculture? Retrieved October 4, 2019, from https://www.noaa.gov/stories/what-is-aquaculture

The Pros and Cons of the Different Types of Grow Lights Available. (2017). Retrieved 13 October 2019, from https://www.maximumyield.com/the-pros-and-cons-of-the-different-types-of-grow-lights-available-for-indoor-agriculture/2/3452

The School of Aquaponics. (2017). Aquaponics Vertical Systems Pros And Cons - YouTube. Retrieved September 24, 2019, from https://www.youtube.com/watch?v=XcxFUOWDSO0

Thescientificfisherman.com. (n.d.). Temperature Classifications of Fish. Retrieved October 10, 2019, from http://thescientificfisherman.com/temperature-classifications-of-fish/

Theaquaponicsource.com. (n.d.). What is Aquaponics? Retrieved September 8, 2019, from https://www.theaquaponicsource.com/what-is-aquaponics/

TheUpstartUniversityTeam. (2017). Everything You Need to Know About Nitrogen in Aquaponics. Retrieved October 11, 2019, from https://university.upstartfarmers.com/blog/nitrogen-in-aquaponics

Thorarinsdottir, R. I. (2015). Aquaponic Guidelines. Retrieved from https://skemman.is/bitstream/1946/23343/1/Guidelines_Aquaponics_20151112.pdf

Tibbitts, T., & Bottenberg, G. (1976). Growth of lettuce (Lactuca sativa) under controlled humidity levels. Retrieved October 15, 2019, from https://www.researchgate.net/publication/233860952_Growth_of_lettuce_Lactuca_sativa_under_controlled_humidity_levels

Tilapia Feed Formulation and Feeding Technique. (2019). Retrieved 1 October 2019, from https://www.fish-feed-extruder.com/Application/Tilapia-feed-formulation-and-feeding.html

Toner, D., & Rougeot, C. (2008). Farming of Eurasian Perch Volume 1: Juvenile production. Aquaculture Explained, 1(24), 34.

Urho, L., & Lehtonen, H. (2008). Fish species in Finland. Retrieved from https://www.researchgate.net/publication/239549476_Fish_Species_in_Finland

US EPA, O. (2017). *Mold Course Chapter 2:* Retrieved from https://www.epa.gov/mold/mold-course-chapter-2

van de Ven, R., Espinal, C. A. (n.d.). *Water quality guidelines for Aquaponics*. Retrieved from http://euaquaponicshub.com/hub/wp-content/uploads/2016/05/Water-quality-guidelines-factsheet.pdf

van Rijn, J. and Hall, S. G. (n.d.). *Aquacultural Engineering*. Retrieved from https://www.sciencedirect.com/journal/aquacultural-engineering

Wijk, A. van, & Wijk, I. van. (2015). *3D printing with biomaterials towards a sustainable and circular economy*. Retrieved from https://books.google.fi/books?hl=es&lr=&id=tEAoBgAAQBAJ&oi=fnd&pg=PA1&dq=bioplastic+3d+printing&ots=nLI-E5tR1d&sig=tsekw4PN09p7oygUJuuLWM0WUqo&redir_esc=y#v=onepage&q&f=true

Woodford, C. (2019). Hydroponics. Retrieved October 4, 2019, from https://www.explainthatstuff.com/hydroponics.html

Woods, R. (2018). The Ultimate African Cichlid Guide. Retrieved November 22, 2019, from https://www.fishkeepingworld.com/african-cichlid/

Yeap, M. (n.d.). Bio Filaments for 3D Printing - Explained and Compared. Retrieved September 23, 2019, from https://all3dp.com/2/bio-filaments-for-3d-printing-explained-and-compared

Yorio, N., Goins, G., Kagie, H., Wheeler, R., & Sager, J. (2001). Improving Spinach, Radish, and Lettuce Growth under Red Light-emitting Diodes (LEDs) with Blue Light Supplementation. Hortscience, 36(2), 380-383.

Zhelyazkov, G. (2018). effect of different diets on growth performance and survival of european perch (perca fluviatilis l.) cultivated in recirculating system during transition from live food to formulated feed. aquatic research, 12-17. doi: 10.3153/ar18002

ZipGrow. (2019). Retrieved 1 October 2019, from https://zipgrow.com/

Zoe. (2015). How to Build a 3Dponics Garden - Step-by-Step Instructions. Retrieved October 1, 2019, from https://www.3dponics.com/wiki/instructions-drip-system/

8 Appendix

8.1 List of chemical compounds

Formula	**Chemical compound**
$CaCO_3$	Calcium Carbonate
$Ca(OH)_2$	Calcium Hydroxide
CH_4	Methane
Cu	Copper
Fe	Iron
KOH	Potassium Hydroxide
Mg	Magnesia
Mn	Manganese
NiCd	Nickel cadmium
NiMH	Nickel-metal Hydride
N_2 (N)	Nitrogen
N_2O	Nitrogen oxide
NH_3	Undissolved ammonia
NH_4^+	Dissolved ammonium
NH_3-N	Undissolved ammonia nitrogen
NH_4^+-N	Dissolved ammonium nitrogen
NO_2^-	Nitrite
NO_3^-	Nitrate
NO_2^--N	Nitrite nitrogen
NO_3^--N	Nitrate nitrogen
O_2	Oxygen

TAN	Total ammonia nitrogen (NH_3-N + NH_4^+-N)
Zn	Zinc

8.2 List of units

Unit	**Meaning**
°C	Grad celsius
%	Percentage
cm	Centimeter
dB	Decibel
ft^2	Square feet
g	Gram
K	Kelvin
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
L	Liter
m	Meter
m^2	Square metre
m^3	Cubic metre
mm	Millimeter
mg	Milligram
ms	Milliseconds / Microsiemens
MW	Megawatt
nm	Nanometer
ppm	parts per million (mg/L)
µs	Microseconds