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OF OULU**

FACULTY OF TECHNOLOGY

**TECHNICAL AND ECONOMICAL STUDY OF
AQUAPONICS FEASIBILITY IN NORTHERN
FINLAND**

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ABSTRACT FOR THESIS

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Abstract			
<p>The reutilization of waste products is an important matter where world view is focusing. The most common liquid waste is waste water coming from organic processes that carries an overdose of organic compounds, usually nontoxic. Traditionally this organic contaminants have been ignored and just pumped out to the environment, or in the best case neutralized into less contaminant forms. But during the past years eutrophication (overfertilization of aquatic ecosystems) has led to many environmental problems, pushing forward more active measures for removing such contaminants from water.</p> <p>One of the most promising ways of doing it is aquaponics, a soilless crop growing that uses waste water as fertilizer, solving two big problems: it cleans the waste water coming from fish factories and reduces the consume of fertilizer which is a product harmful to the environment in its production and use. This farming technique is really young but is gaining more popularity each year.</p> <p>This work is the study of the viability of implementing an aquaponics waste water treatment in a future fish farm in Oulu, on the north of Finland. Finland is a country with hard conditions for producing vegetables so most of them are imported. All the efforts made into not relying so much in external imports are welcomed and aquaponics was one of the options taken into account when deciding how the waste water cleaning process would be.</p> <p>The calculus process has been made step by step stating from the desired fish production and from there calculating how much vegetables would be produced and the amount of space it takes. In the economic aspect, it has been proved that the factor that caused most of the costs was the weather, as Oulu has a subpolar climate that is not mitigated enough for being a coastal city.</p> <p>The main result of the study has been that aquaponics does not report profits, being the artificial light the most expensive factor. Heat costs can be mitigated importing waste heat from another factories of the area like paper factories, but vegetables need artificial light in winter that has proven to be too much expensive for the benefits the vegetables reported.</p> <p>The study can be used as a basis for other aquaponics studies as it sets a system easy to follow for calculating the different parameters that appear in aquaponics. Also, it stays as an evidence that aquaponics can be hard of implement in extreme weather and other systems may be needed.</p> <p>Keywords: Aquaponics, Aquaculture, Hydroponics, Waste Water treatment, Circular economy</p>			
Additional Information			

PREFACE

This work tries to know the feasibility of implementing an aquaponics system for waste water treatment in a near-to-be-built fish factory in Oulu, on the north of Finland. This master's thesis is the final step of the master of Industrial Engineering from the Polytechnic University of Valencia, Spain, and has been done in the University of Oulu, Finland in the context of the exchange program Erasmus+. It has been done in the spring semester of the year, between February and June of 2017.

The aquaponics project forms part of a bigger study in circular economy funded by the European Union that looks for reutilizing side streams in a future fish farm. As it is in their initial stages, the project forms the first approach to the waste water treatment and has to be developed furtherly. In this sense, I have the feeling that my basis of knowledge in this subject has expand greatly thanks to all the research done. As an industrial engineer, my formation comprises mostly technological subjects, and I'm really happy of being able to apply what I have learnt to more biological processes.

Finally, I would like to thank many people for the support and comprehension I have received during this work. As a stranger who has studied in a different system, many times I have need a complete explanation of simple things. In that sense, I'd like to thank professor Harri Haapasalo for the constant feedback to all my work, and to Saara Väänänen for providing me the starting push into the work of this thesis. Also I would like to thank LUKE members for the external data provided for the work and their help during the meetings, and to the personnel of the Botanical Garden of the University of Oulu for solving the silly but important doubts I had about greenhouses. As an Erasmus student, I would like to thank my family and friends back in Spain that have help me during this time out of home, and I would like to mention also the work of the European Union for allowing me to visit other countries and know other cultures while keeping my studies.

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Andreu Dana Martin

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ABBREVIATIONS

Acronyms

DO	Dissolved Oxygen
DWC	Deep Water Culture
FAO	Food and Agriculture Organization of the United Nations
LUKE	Luonnonvarakeskus; Natural Resources Institute of Finland
NFT	Nutrient Film Technique
NOD	Nitrogenous Oxygen Demand
RAS	Recirculating Aquaculture System

Mathematic expressions

C	Specific heat; water = 4,186 kJ/kg °C
g	Gravity; Earth = 9,81 m/s ²
Ph	Hydraulic power
h	Differential head
Q	Heat added
q	Flow capacity
Δt	Thermic difference between two points
π	Number Pi; $\pi = 3.141592$ (aprox)
ρ	Density of a fluid; water =1000 kg/m ³ (1 atm, 4°C)

1. INTRODUCTION

1.1. Background

In today's world, people are starting to realize on the importance of the concept of sustainability, which was easily explained in the Brundtland Commission: "sustainable development is development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (UN General Assembly, 1987). For accomplish that objective, we must make a rational use of the resources and try to waste as less as possible, achieving a truly circular economy and not prejudice the environment in the process.

In all the history of humanity the aquatic resources have usually come from wild sources, as opposite to the other sources of food, farming and agriculture; where the exploitation of wild resources has moved during the ages towards the domestication of the species and growing them independently from their wild counterparts.

In the past, without having modern advances in boats and fishing, humans were not able of harvesting aquatic resources faster than they grew; but nowadays wild aquatic resources are almost in all cases overexploited, and there appears the need for the farming of fish in captivity as a way of freeing the wild from the pressure (Hishamunda & Subasinghe 2003). The vision of the society is changing among the needs, for example in 2010, total worldwide aquaculture production amounted to approximately 77 million tonnes. This volume was roughly 50 percent of the total world fish and seafood production for human consumption compared to about 25 percent a little over a decade earlier (Aquaculture Sustainability Reporting Initiative, 2012).

Aquaculture also play an important role in developing countries, as small-scale plants employ 41 million people worldwide. Usually fish is the cheaper source of protein to be grown, and so it forms an important part of the diet of most of the world's population, mainly people living in Africa or Asia. In some coastal or island countries like Indonesia or Sri Lanka, it forms 50% of animal protein consumption, reaching peaks of 62% in Gambia and 63% in Sierra Leona (FAO 2007).

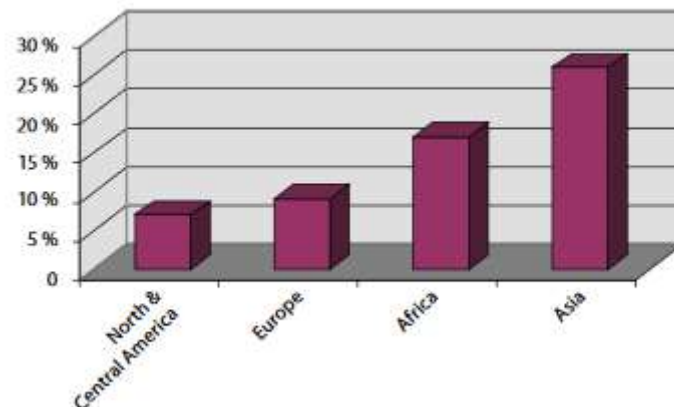


Figure 1. Fish as percent of animal protein on the daily diet of different continents (Delgado et al. 2003)

1.1.1. Environmental impacts of aquaculture

As every living being, fish produce waste that ends up in the water they live in. In the case of the off land aquaculture, fish live in open cages where waste water is mixed with the environment, making it unable to control the resultant contamination. In the case of in land aquaculture fish live in pools where the water gets renovated, being the waste water either thrown to the environment or cleaned and recirculated.

Aquaculture have three major environmental impacts on the media: habitat loss, aquaculture wastes and pollution.

Habitat loss

Primavera (2006) states that fish pens and cages degrade coastal habitats through deposits of feces and solid waste into the bottom of the water or the installations that form the fishing complex itself.

Aquaculture wastes

A big variety of chemicals are used in aquaculture, ranging from construction pigments to disinfectants and antibiotics provided to the fish. This antibiotics probably have a big impact on the microfauna of water environments near aquaculture industries, but still

haven't been properly studied the consequences on the disturbance of this bacterial populations beneficial for the aquatic ecosystem.

What it's proven is that pathogens and infections have been developing resistance to one or even multiple different antibiotics due to the constant contact they are having with the chemicals in the environment (Dixon 1994). In the past years there has been an "arm race" between antibiotic industry and pathogens; laboratories being developing new chemicals as fast as they can and pathogens developing resistance to them even at a faster rate.

Another mayor problem occurs when non-native species are farmed in a certain area. This fish can have already immunity to exotic diseases they are carrying, but can transfer it to the ecosystem and exterminate other animals not used to that disease. Also, escapes may result in a dangerous invasive species interbreeding or successfully outcompeting with native ones and virtually wiping out the original inhabitants of the region. There is little information on how much fish scape from aquaculture farms, but Penczak et al (1982) estimated that about 5% of caged rainbow trout escaped each year.

Pollution

Waste water produced by organic processes always carry a elevate amount of nutrients like nitrogen, phosphorus, potassium, etc. If continuously discharged into the environment can result in an "overfertilization" of the ecosystem, especially in aquatic ecosystems where the main growing restrains are the amount of nutrients. This problem usually appears in badly managed areas where the water isn't renovated fast enough and can result in an explosive grow of certain plants and algae that can cause serious problems:

- The elevate number of nutrients attract big decomposing operations that need huge quantities of oxygen for operating, but this oxygen is already being blocked by the algae bloom so the total oxygen dissolved into the water sinks heavily.
- The algae bloom or eutrophication intercedes with the usual functioning of the environment previously to it: it changes energy and nutrient fluxes, accumulates many of the biomass of the system in one place causing sedimentation and erosion

problems and the oxygen depletion can cause the death of the aerobic aquatic organisms (including all the animals) that effectively destroys the ecosystem nutrient cycle (Gregory & Zabel 1990, Fang et al. 2004).

- In this scenario of high mortality and small circulation of the resources diseases and pathogens may flourish.
- In a human perspective, inadequate waste water handling causes serious problems for human health and development. It contaminates water supply and can extend to groundwater and other near ecosystems not affected by the waste water pollution in first place. (Enelld & Lof 1983).

1.1.2. Environmental solutions to aquaculture

Off-land aquaculture is hard to regulate due to its open nature. Most of the environmental problems it has can't be completely cut off without changing drastically the way open cages are designed. Some problems like escaped alien species could be restricted with more hard control on the net building, but there is always going to be a percentage of breakouts. Uneaten food deposits can be partially resolved using food distribution procedures that focus more on optimizing the quantity of food given.

Other problems like antibiotics and chemicals given to the fish can't be cut out without losing production. There is an open debate on how much complex medicaments should be given to fish, with detractors arguing that these compounds don't decompose easily and end up accumulating in the body of the marine wild species and causing a full range of hormonal and enzymatic problems like strange growth periods, sterile broods, malformations, etc. Supporters claim that these substances are necessary for keeping the industry running at the current cost, otherwise a much higher percentage of fish would die and thus would make fish aquaculture costs non-competitive with wild fishing costs, putting more pressure on wild species and extending overexploitation.

In-land aquaculture can solve these problems more easily, because all the water is in a closed controlled environment, easier to manage and be cleaned. The forms of achieving

this cleaning depends on which contaminants waste water has in it, usually the living beings wastes (from fish to humans) are composed of: solids, greases, ammonia and sometimes pathogens (like virus) and complex organic compounds (like antibiotics); it almost never has important concentrations of heavy metals or toxins, so it's not planned the need of removing them.

Solids and greases can be removed with physical filters, ammonia has to be degraded using a biofilter (made of denitrifying bacteria or plants), pathogens get killed with ultraviolet light or chlorine and complex organic compounds can be degraded with H_2O_2 or O_3 , although those are expensive substances so they only get applied if truly needed.

As an ending thought for this introduction just say that in-land aquaculture has the ways of not being so harmful to the environment without reducing the amount of fish produced, and during the past 20 years many companies had started looking forwards that form of business. This work tries its best to explain the benefits of the aquaculture over the typical RAS (essentially, plants over denitrifying bacteria) and calculates the economic feasibility of both. It has to be taken in account that both systems report less benefits than just not cleaning the water and discharging it into the environment, but if the cost of the consequences of that pollution after discharging it is included into the business model, recirculating always wins. This is because avoiding the contamination is always cheaper than cleaning it, by some orders of magnitude.

1.2. Objectives

The main objective is to provide a work method in order to calculate the feasibility of an aquaponics structure for an in-land fish farm in northern Finland and apply that method to a real example, the company Laitakarinen Kala OY.

For achieving that, that objective is going to be divided into three main questions that are going to be answered in the different chapters of this work. These three questions are:

1. What are the different ways aquaponics can be implemented?

2. How can its technical feasibility be calculated?
3. Is Aquaponics economically feasible? What parameters are related with its feasibility?

The objective of the work is to give a scientific base for aquaponics to work with, later focusing in how the process work and its different parts correlated and finally ending with just a set of relations, equations and parameters that can easily be converted into numbers for achieving a comparison of economic viability between this system and others similar.

1.3. Research process

The research process started at the first meeting, where it was presented the necessity of reevaluating side waste streams for industrial processes. In this case the process was a fish farm that cares from the stage of small fish to the already processed fish meat. Many side streams were proposed, and one of the most promising was the conversion of waste water into market vegetables.

Once stated the objective of the work, it started with a literature research. The process of utilizing waste water into vegetables is called aquaponics, and is a relatively “new” process. Started to be theorized in the 70’s, it wasn’t until the 90’s where the first economic feasible processes were standardized. It is not until the 2010, after the global crisis, where this kind of production systems are becoming more popular. This is because the world is starting to be in a climate of scarce of all finite natural resources, so efforts are being taken into forming a circular economy. Being aquaponics one easy way to promote it and having a simple yet effective concept is becoming more popular each year.

As aquaponics is so young and unexplored, this work was a good opportunity of trying to implement it in a Nordic climate; it is probably the biggest (in volume of production) aquaponics project at a so high latitude in all the world.

The research done for this work can be separated into two groups, the theory and the practical. The theory research matches more or less the chapter of the literature review

and was relatively easy to gather. Since its born in 1980's, many experiments and research have been done in the field of recirculating waste water and soilless plant grow conditions, so there was a enough pool of data for doing a proper research on the theory area.

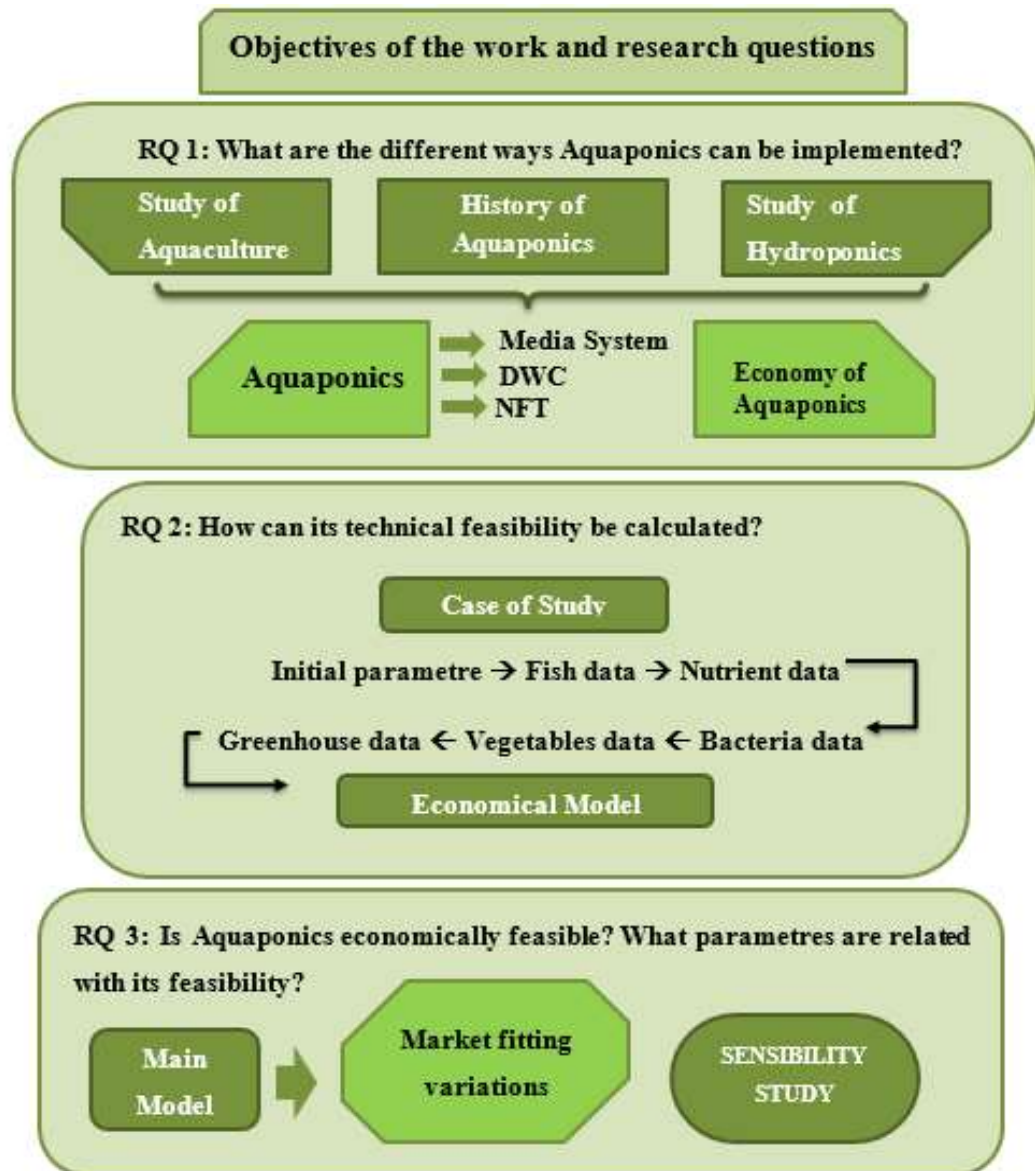


Figure 2. Research process

But in the practical area, where that processes had to be converted into numbers, the work was more difficult. There is a small handful of aquaponics companies working in the world, and most of them keep their ratios and parameters for them. As it will be explained later, aquaponics is a really complex organic balance between fish, plant and bacteria; too much complex for being worth of mathematically modelling it so most of the estimations are made using empirical data, usually gathered by the farmers by try and error and kept for themselves.

Since most of the sources are farmers and small business and therefore non-scientific, it has been tried to avoid them in order to keep the sources contrasted and trusted. The most important source for data for the practical calculus has been the Food and Agriculture Organization, an organism part of the UN that distributes methods of sustainable agriculture among others, and has a really complete guide on aquaponics.

During next meetings with LUKE personnel it was discussed the parameters of the process, like the amount of fish, the type of systems and vegetables grown and parameters related with the climate of Finland. As the work progressed, it was being more clear that aquaponics would not be a good solution for the fish farm. The third question, answered in the last part of the work, explain the changes that need to happen for aquaponics to be feasible in the future.

Finally, it is worth saying that during the last part of the work other models appeared that can fit in the waste water cleaning and plant production that are not pure aquaponics processes, like decoupled aquaponics which relies in anaerobic processes for compressing the space needed by the vegetables reducing costs. This other systems may be the best alternative for the project, but due to using complete different systems apart from aquaponics, can't really be condensed in a work with just aquaponics and need a more exclusive work just for themselves.

2. LITERATURE REVIEW

Aquaponics in its actual stage is an area of farming relatively new, with its scientific and methodological research properly starting around 1980. The word aquaponics is a mixture between aquaculture and hydroponic. Thus, aquaponics can be described as the farming of fish and vegetables in an interrelated environment emulating the natural cycles of nutrients for a more sustainable agriculture, what nowadays is called permaculture.

Taking apart the ancient techniques developed by different cultures at the length of the History, modern aquaponics began in 1977 with studies about the options for removing nitrates from waste aquaculture water which would be recirculated again (Bohl 1977). Among the different options, it was tried the removal of nitrates using plants as a biofilter (Collins et al. 1975, Lewis et al. 1978) which led to the born of aquaponics. Another options were found without relying on plants, mainly bacteria-adsorbent biofilters that led to the RAS, the modern recirculating aquaculture.

Aquaponics as an independent technique born in the 80's with the works of Mark McMurtry and Professor Doug Sanders (McMurtry et al. 1990) who created the first looped system that fully relied in the interaction between fish, vegetables and bacteria. They also adopted the flood drain methods in a sand bed for this system, in which the plants are grown in a porous and loose media that is flooded and drained systematically permitting the roots of the plants to receive both water and air.

At the same time, investigators from the University of the Virgin Islands began to work on commercial profit of interrelated systems of fish and vegetables (Rakocy 1984, Watten & Busch 1984). On mid 90's they adopted the deep water method from hydroponics, which consist on floating rafts for the plants with the roots submerged in an aerated water media.

This both options, and also the recent channel lanes imported from hydroponics, are the most common forms of aquaponics nowadays.

2.1. Aquaculture

2.1.1. Brief History

Aquaculture has been done in different parts of the world at different ages. The first important use it had was in China around 2000 BC. What started with farmers feeding fish trapped in ponds during the dry season rapidly developed into a well-studied method of farming. Around 500 BC Fan Lai wrote his book “The Classic of Fish Culture” which is the earliest record we have of fish culture. During the Tang dynasty (618-906 AD) it happened that the family name of the dynasty was Li, which was also the popular name of the most widely cultivated carp. The emperor banned the culture of that carp, so the farmers had to look upon new species of fish to grow. This led to an explosion on the aquaculture, adding dozens of new species to the stock and developing new methods like mixing different species in the same pond, each one occupying one niche and improving the overall productivity. (Rabanal 1988)

In Europe, apart from ancient Romans, the aquaculture started in small ponds or lakes of monasteries that grew their own fish. This technique became popular in the areas without lakes or sea because it provided fresh fish without relying on salting it for avoiding rotting (Jhingran 1987). With the appearance of train transport on the 19th century, aquaculture was abandoned in favour of traditional fishing. During late 19th century and early 20th century, the focus of aquaculture was changed into the domestication of marine species and growing them into controlled environments near water resources (Rice 2010), this led to the creation of aquaculture companies and the arriving to the modern aquaculture as it's understood nowadays.

During all these period of time the waste water produced in aquaculture was just released into the environment and exchanged for fresh water. It wasn't until the 1970's that began the first efforts for creating an aquaculture process capable of clean its own water and reuse it again. Eventually, this efforts ended in the creation of the RAS and the aquaponics. For the rest of this chapter we are going to talk about only the RAS system

all the time, because is the only technique of aquaculture that shares things in common with aquaponics

2.1.2. How it works

RAS stands for Recirculating Aquaculture System. It was a method developed in order to recirculate the waste water from aquaculture, allowing reducing waste of water and contamination of the environment (Timmons & Ebeling 2013).

The processes occurring in RAS can be separated into three categories: solid removal, ammonia removal and reaconditionation.

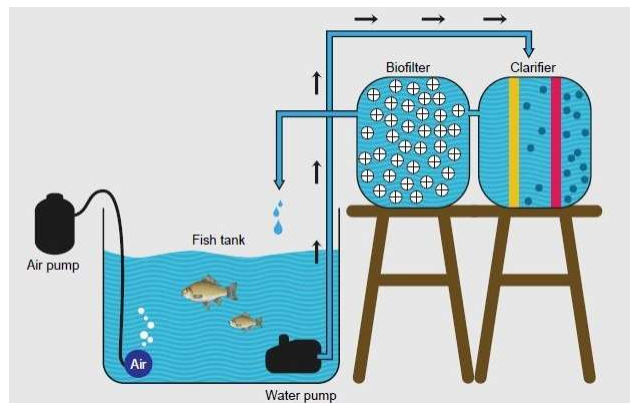


Figure 3. Simplified scheme of a typical RAS process (Somerville et al. 2014)

1. Solid removal focuses on the removal of every substance that is not dissolved into the water. It can be accomplished using big surfaces where the fluid loses speed and the solids either sink to the bottom (sands and feces) or float (fats) and can be flushed out. Other system more commonly used in RAS is forcing the waste water to cross a series of filters in order to remove all particles. Later that filters can be regenerated using clean water (Summerfelt & Penne 2005).

2. The removal of ammonia and other substances dissolved into the water (phosphates, salts, etc) can only be achieved in commercial scales using a biofilter. It essentially consists on a tank full of bacteria that eats every chemical substance available in the water, cleaning it in the process. Later, the excess of bacteria and the dead ones can be removed by filtration and form a sludge, which can be used after an inertization as a fertilizer or solid waste.

3. The reaconditionation consists in the optimization of pH, temperature, dissolved oxygen and elimination of pathogens (if needed) after the cleaning treatment. Usually consists in the dilution of lots of oxygen into the water that have been consumed in the last anaerobic process of the biofiltration and the rectification of the pH because, as it will be explained now, the biofiltration process generates acids that would sink the pH of the water if let them accumulate.

2.1.3. Chemical Reactions

The chemical process taking place in the RAS system have two steps: nitrification and denitrification.

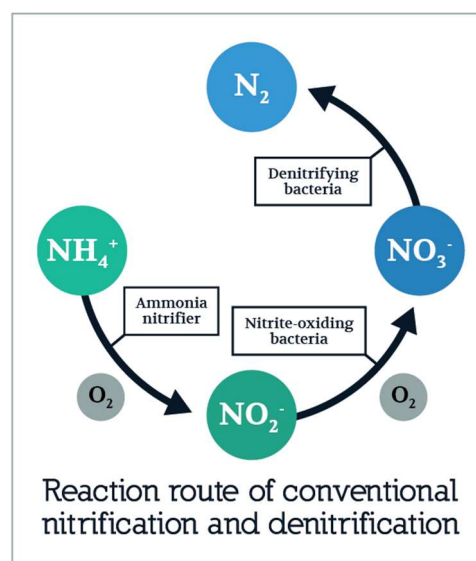


Figure 4. Nitrifying-denitrifying process in biofiltration (Maryland Biochemical, 2017)

Nitrification

In this process the nitrifying organisms transform the ammonia in the water in nitrates with two different processes implying two families of different organisms, nitrosomes and nitrobacter; both processes consume oxygen, the so called NOD (Nitrogenous Oxygen Demand). For this purpose, the process has to happen in an aerated chamber with plenty of space for the oxygen to mix with the water and the bacteria for lie in it.

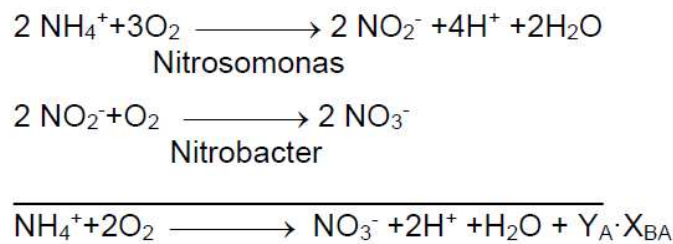


Figure 5. Nitrifying reaction (Ortega 2014)

Ideally, all the NH_4 gets converted into NO_3 in this process, which is a less toxic form than the NO_2 , but there can appear some amounts of NO_2 as nitrobacter usually are not so active or there is shortage of oxygen.

In numbers, we get 1 gram of nitrates for each gram of ammonia using 4,57 grams of oxygen dissolved. (Mosig & Fallu 2004, Larrea 2014).

Denitrification

The next step in the process is to eliminate this less toxic form of nitrogen, the nitrates. The denitrifying process occurs using heterotroph organisms evolved for taking the oxygen necessary to the respiration from sources apart from the air, in this case, nitrates (NO_3). For this bacteria to appear, there has to be an anaerobic media where they can live as opposite with the nitrification, where the bacteria needed a rich-in-oxygen media.

As all respiration processes, the organisms take oxygen and carbon for making energy plus CO_2 . The process in this case is more complex, as there is nitrogen in it, but the general idea can be that this bacteria use the nitrates with organic matter available for producing N_2 and CO_2 , both in its gaseous form that can be removed easily from water

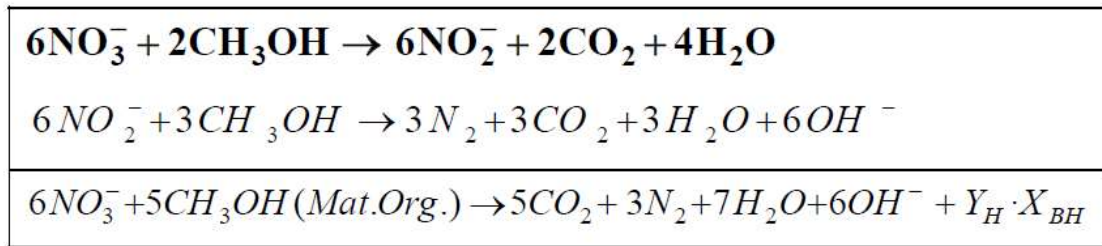


Figure 6. Denitrifying reaction (Ortega 2014)

In this way, the nitrates end finally converted into “neutral” gasses (CO₂ may be considered as a pollutant or not) that escape from the system.

Acidity and Alkalinity of the processes

Nitrifying process produce acids (H⁺) and denitrifying process produce bases (OH⁻); both are related with the pH of the water.

We are going to use the calcium carbonate (CO₃Ca) as the main unit of alkalinity, understanding it as the quantity of this substance you need to counteract in the acid processes and the equivalent of this substance produced in the alkaline processes:

- In the nitrifying process is CONSUMED the equivalent as 7,14 mg/l units of alkalinity for each mg of ammonia nitrogen degraded. (Larrea 2014)
- In the denitrifying process is PRODUCED the equivalent of 3,57 mg/l units of alkalinity for each mg of nitrate decomposed. (Larrea 2014)

As we see, the overall process is more acid than basic, so the addition of basic salts would be necessary for regulating the pH. It is recommended that the alkalinity in the biofilter never goes down of 40 g/l (CO₃Ca) but usually for being in the side of security is used 100 g/l (Ortega 2014).

2.1.4. RAS and Aquaponics

As it is said (McMurtry et al. 1990) aquaponics born as a more productive variation of the typical RAS. In the normal RAS, all the nitrogen introduced in the system in form of fish food that is not used in building fish mass gets wasted in form of N_2 or sludge. Aquaponics otherwise uses all the waste nitrogen left from the fish food and transforms it into plant mass, from what most of it will be sold for profits. Looking at both systems, it can be said is simplicity (RAS) versus full exploitation (aquaponics).

RAS systems are simpler and smaller than aquaponics. The solid filters and bioreactors in RAS occupy relatively small space compared with all the surface plants need in order to clean the same amount of water. Building cost and investment are always higher in aquaponics as it usually needs most of the frame of RAS plus own equipment and, as bacteria tend to be easy to manage and work as planned, RAS needs less specialized handwork compared with aquaponics; where managing properly crops requires a good knowledge on them . On the other hand, it wastes more than half the nitrogen introduced in the system as fish food and the sludge stabilization process can be either expensive or really complex.

Aquaponics otherwise is more complex than RAS and requires much more space in form of greenhouse space, that increases hugely initial costs. On the other hand, a properly designed (or even better, oversized) aquaponics system doesn't need solid filter and solid removal as the solids and dead bacteria mineralize in the medium and get removed by the plants, removing the need of sludge stabilization. In any case, if solid removal is needed, it produces much less solids than RAS because most of the organic matter is being used in growing the plants. Finally, it is a more profitable system because it produces vegetables in exchange of "nothing". As a rule of thumb, 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).

2.2. Hydroponics

2.2.1. Brief history

The very first use of hydroponics can be traced until the Babylon gardens or the “chinampas” used by the Aztecs. The Hanging Gardens of Babylon were considered one of the seven wonders of the ancient world, there doesn’t remain any physical evidence of them; but many ancient sources describe them as a sort of wonderful gardens of trees and other plants that grow on top of a ziggurat (a terraced step pyramid) continuously being irrigated by water from aqueducts. (University of Chicago 1993)

The chinampas otherwise are rafts of packed earth that float in shallow lakes where the vegetables grow and let their roots float in the nutrient rich water below the raft. They have been used in the Mexico area for eight hundred years and still have an important role in the Mexican agriculture. Chinampas are infamous for permitting growing up to 7-8 crops per year, more than any other terrain, and are called “the most productive grounds on Earth” (Vulling 2007). As an example of its productivity, they were the responsible of maintaining easily a population of 200.000-300.000 people living on top of a lake in Mexico-Tenochtitlan city, at a time where the biggest city in Europe, Paris, didn’t reach the 200.000 people (De Rojas 1986, Moctezuma 2006)

Modern hydroponic studies start with Francis Bacon in 1627 who worked on how to grow terrestrial plants without soil (Bacon 1670). It rapidly generated expectations and in the next three hundred years was a popular field of study, leading to better understanding the process on how plants take nutrients and which substances are needed by the plants to grow.

In 1929 William Frederick Gericke began publicising that soilless culture can be a revolution to ordinal agriculture. It caused controversy, amplified by the fact that Gericke was really closed with his methods on how he was achieving such big production rates. Dennis R. Hoagland and Daniel I. Arnon were assigned resources by Gericke’s University for proving or refuting his theory.

Gericke published his book in 1940 in a climate of controversy (Gericke 1940). Hoagland and Arnon published their own research in 1938 where they refuted Gericke's theory arguing that both traditional agriculture and hydroponics had the same production rates on optimal conditions (Hoagland & Arnon 1938). What they underestimate was the fact that optimal conditions are much easier to achieve in hydroponics. Parameters like nutrient intake were similar in both systems, but others like achieving the correct amount of water and air for the roots, (like preventing drying due to too much air/water ratio or anaerobic conditions due to flooded roots) can only be achieved by expert farmers in traditional soil agriculture as opposed to hydroponics, where those ratios are easy to manage for everyone. In fact, the Hoagland and Arnon works are the basis where modern hydroponics exists, being the "Hoagland solution" one of the most popular solution composition nowadays (Hoagland & Arnon 1950).

One of the earliest commercial uses of aquaponics occurred in Wake Island in 1930. It was a refuelling station used by Pan American Airlines in a rocky island in the Pacific Ocean where fresh vegetables were grown for the passengers of the planes. Due to the rocky nature of the ground, there was no soil suitable for agriculture so hydroponics had to be used (Taylor 1939). During the WWII in the Pacific Ocean, American troops stationed in small unfertile islands often depended on hydroponic vegetables for food. For example Iwo Jima island, rocky and inhabitable, was transformed after the famous battle into a hydroponic vegetable production compound for the front troops.

In the 60's two major revolutionary systems were invented, the Drip Irrigation Systems and the Nutrient Film Technique. The DIS allowed the nutrients to be delivered directly into the roots drop by drop. The NFL, otherwise, used a really thin layer of water as a form of irrigation (NFL technique will be explained more widely later in the aquaponics section). With these inventions, modern hydroponic agriculture consolidated as it is nowadays.

2.2.2. How it works

Hydroponics is a type of horticulture that grows plants in a medium without soil, providing the necessary nutrients in the form of nutrient solutions in a water solvent. Terrestrial plants can be grown with their roots floating freely in the nutrient solution or in a bed of an inert substance like gravel or sand.

In the vegetal kingdom, among green terrestrial plants we can find two types, vascular and non-vascular plants. Non-vascular plants (like moss) doesn't have specialized cells and every cell of the plant has to procure its own source of nutrient, water, air, etc. Vascular plants otherwise have specialised parts that carry different tasks. Nutrients and water for example are taken in the roots from the medium by capillarity, then pumped up to the rest of the plant through the xylem using difference of pressures created by the evapotranspiration in the leaves. Once transformed into organic compounds by the photosynthesis in the leaves, it goes again down to the roots through the phloem.

Almost all terrestrial vascular plants use this process. Also, usually in the roots of all plants lives bacteria with which the plants have symbiotic relations, being bacteria the responsible of decomposing the nutrients in its first stage before entering the root, much like humans have bacterial flora in their intestines that help with digestion. This bacteria does need air for breathing, and usually the supervivence of the plant depend on the supervivence of its roots bacteria.

This both concepts are important in order to know why plants need nutrient, water and air at the same time in their roots. In basic hydroponics, this three substances are given to the plant by a water solution with nutrients that has been aerated. Usually this nutrients come in form of chemical fertilizer because they are easy to work with and solution composition can be much more precise allowing the farmer choose a specific composition for each variety of plant.

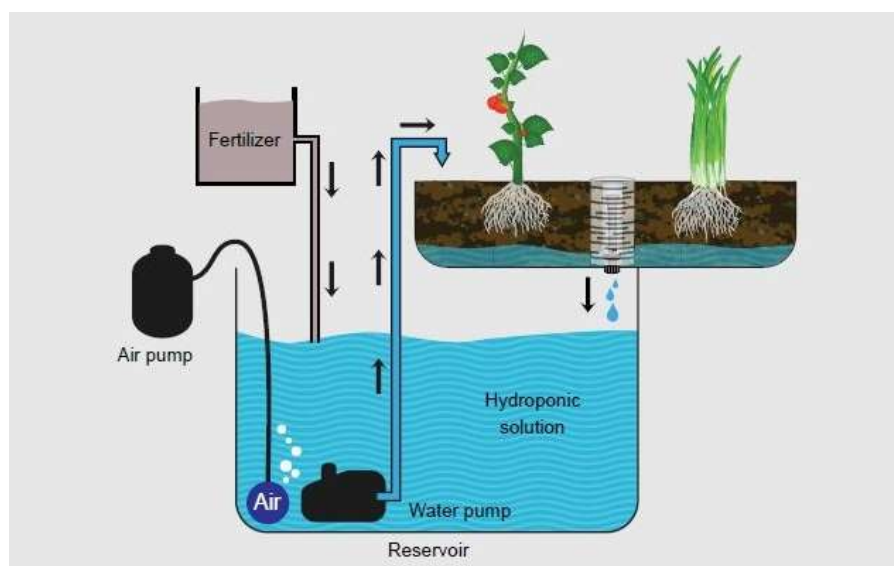


Figure 7. Simplified process of an hydroponic system (Somerville et al. 2014)

2.2.3. Hydroponics and Aquaponics

Aquaponics and hydroponics share much of its vegetal way of working. Both deliver the nutrient into the water from an external source instead of using soil with nutrients that get diluted into water. Both also use aerated water or non-continuous water delivering in order to let the roots get the air their symbiotic bacteria need.

The mayor difference exists in the way nutrients end in the solution. As it was said, in hydroponics the nutrient solution are really controlled in order to achieve maximum productivity, usually using chemical fertilizers which its composition is known (Hoagland & Arnon 1938). In aquaponics, there is impossible to know the exact composition of the solution at each moment because of the organic source of the nutrients that can vary over the time. So, usually aquaponics systems are not working at maximum productivity. On the other hand, as the source of the nutrients are organic wastes and much cheaper, aquaponics systems compensate their lack of productivity with lower costs of nutrient source.

Other mayor variation are the bacterial colony. Hydroponic plants only need a small bacterial colony that can easily live in their roots because the nutrients come to them almost in its final form thanks to the precise composition and chemical source.

Aquaponics nutrients come almost always in its primitive form, and need a strong processing before being capable of being used by the plants. This strong processing is made by a big colony of different specialized bacteria that need more space than merely the plants roots, that's why aquaponics systems always need a solid porous bed for allowing the bacteria to live in. Also, this specialized bacteria is not the same that lives in the plants roots, and usually has a different needings of temperature and pH than the roots.

So, hydroponic systems have a higher productivity due to its measured solution proportions but also require more expensive fertilizer. On the other hand, aquaponics does not work at maximum productivity due to its variable solution and not perfect pH and temperature, but compensates it using a much cheaper source of nutrients. Also, hydroponic crops are much more fragile to changes because they grow at maximum capacity all the time while aquaponics crops can withstand major variations on the system as they are never working at truly 100%. Their big bacterial colony also helps absorbing much of the damage of this variations, like excess of nutrients or pH peaks.

2.3. Aquaponics

2.3.1. How it works

Aquaponics systems rely on a mutual beneficial symbiosis between fish, bacteria and plants that can live together in a closed aquatic ecosystem as long as fish food is provided and fish and plants get harvested.

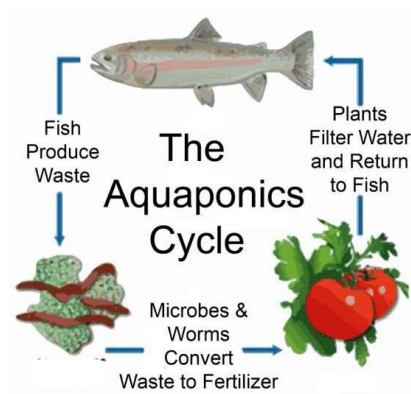


Figure 8. The triple symbiosis between fish, bacteria and plants in aquaponics (Aquadesk, 2017)

In the system there are two main chains of resources moving around, the nutrients and the water:

- Nutrient chain starts in form of fish food provided to the fish. They use some of it in growing, throwing the rest into the water. Once there, it is used by the bacteria living in the porous media that transforms it into simpler forms of nutrients and assimilates a small portion for growing. The simpler nutrients are absorbed by the roots of the plants that use it for growing. More complex and bigger solids would need more processing, usually made by earthworms and other types of bacteria that need more time for processing them. If given enough time for decompose complex solids (in form of enough space in the porous bed in order to process all the solids without clogging the filter) plants don't need an extra income of

nutrients, otherwise extra nutrients will need to be added and the solid waste removed.

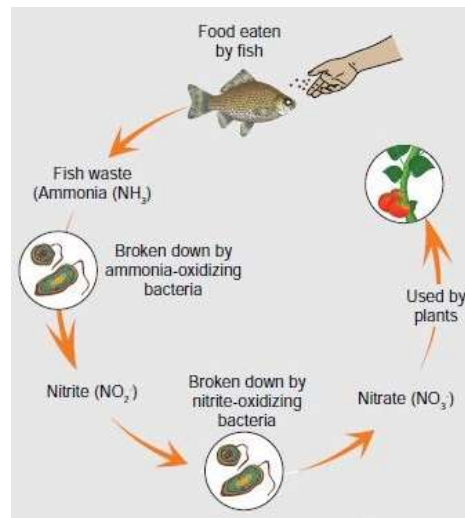


Figure 9. Nitrifying-filtration process in biofiltration with plants (Somerville et al. 2014)

- Water chain can be considered better a water circle. Water starts clean in the fish pools. There, gets aerated in order to provide air for the fish. The waste water goes later through the biofilter and the plant roots being cleaned in its way from ammonia and solid wastes and finally arrives back at the fish pool. If the biofilter and the plant roots are continuously underwater, extra air will need to be added because both bacteria and roots need oxygen; if the system works as a flooding/drying system, the dry periods between floods are designed to be enough to provide the necessary oxygen.

2.3.2. Types

There are lots of different solutions to aquaponics, but the best three for commercial use are the next ones. The major variation between the three are the place where the bacterial bed is placed in the system and how are growing the roots of the plants. (FAO 2015).

Media Filled Bed

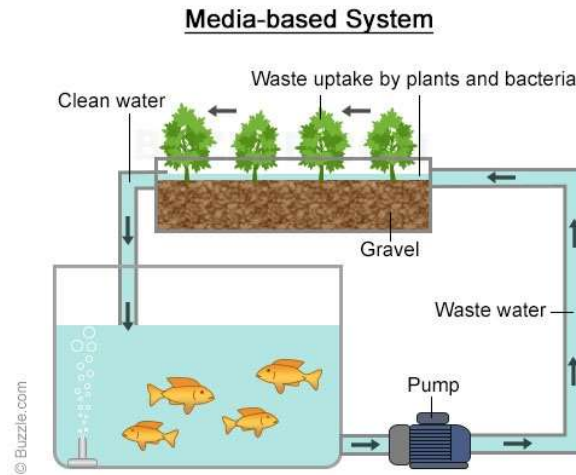


Figure 10. Simplified scheme of a Media based system (Chavan 2016)

Media filled bed is an aquaponic system that consist in a grow bed filled with an inert media as clay, gravel or sand where the roots are. The water is circulated from the fish tank to the bed where live both bacteria and plants and then returned to the fish tanks once is clean.

The medium is used as support for the roots of the plants and also functions as a filter, both mechanical (mineralization) and biological (bacterial biofiltration). The material that compose the medium has to accomplish a list of characteristics: it has to have high surface area while remaining highly permeable for water and air, has to be inert and pH neutral, not dusty and non-toxic. The most commonly used media for aquaponics are volcanic gravel, expanded clay, river gravel and sand.

Water can be delivered to the bed in different ways depending on the degree of technology desired. The easiest way is simply distribute uniformly thorough the medium using pipes with holes and is a perfectly acceptable design. The preferred method for ensuring a good ratio of air and water into the system is the flood-and-drain method.

It consists in plumbing water until the media bed is flooded and then don't plumb it again until the level of water has drained until certain high. This allows the existence of three areas or micro-ecosystems in the beds, the dry zone, the wet zone and the flooded zone. Each area hosts a different group of organisms that participate in the process of water cleaning depending on their preferences of humidity and air. The most important section, the wet zone, retain always the humidity necessary for roots and bacteria to live but ensures an air flow once per cycle when the water gets drain, allowing roots and organisms to breathe. From this organisms the most important are the nitrifying bacteria that process NH_3 into nitrates, but other notable mentions can be fungus and earthworms that contribute in the degradation of the solid wastes.

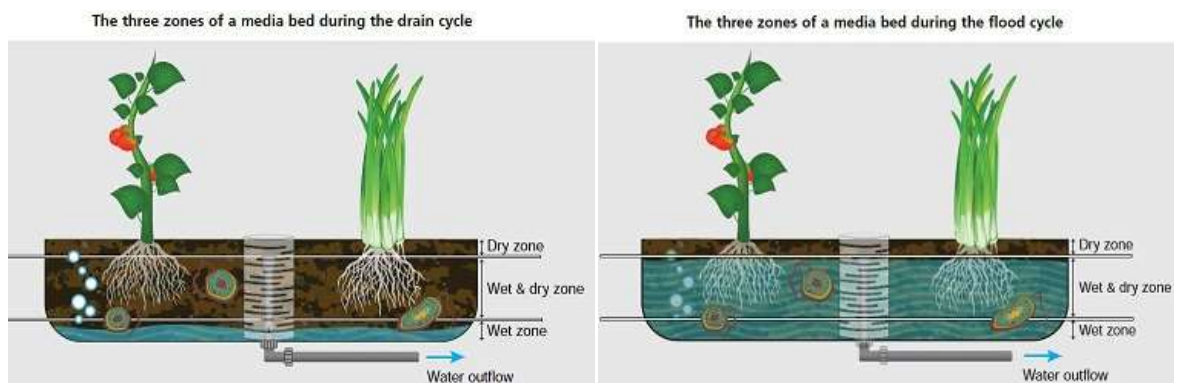


Figure 11. Comparison of the different areas of the bed during dry periods and flood periods (FAO 2015).

Deep Water Culture

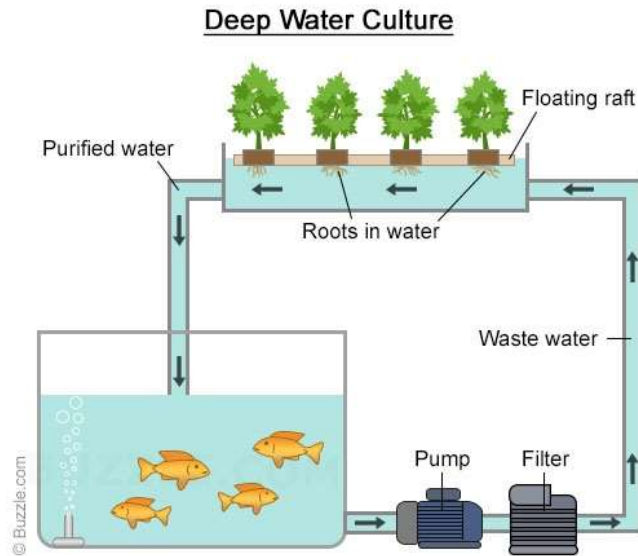


Figure 12. Simplified scheme of a Deep Water Culture system (Chavan 2016)

Deep water culture (DWC) or floating raft method consists in circulating the waste water through an external mechanical and biological filter and later through long canals with rafts floating on top. Plants live in pots within holes on the rafts and their roots hang down into the nutrient rich water, absorbing that nutrients and cleaning it.

This is the method preferred in large scale aquaponics, usually monoculture crops like leafy vegetables with high stocking fish density.

The biofilter before the canals can be removed if the stock density is low. In this case, the bacteria living in the canal walls and the bottom of the raft can be enough for decompose the NH_3 and the solid waste. Only a small mechanical filter should be used for the big solids.

In the rest of cases, a special filtration unit should be implemented. It would usually consist in two stages, the mechanical and the biological. In the mechanical stage, a series of physical barriers each one with smaller holes than before are used for trapping all the solids. The barriers should be periodically cleaned with clean water for removing the

solids. The second stage consists in an aerated chamber filled with high surface materials for allowing a colony of nitrifying bacteria to live in. As opposite with media bed systems, this high surface materials doesn't have to sustain weigh roots so light cheap plastics can be used like nets or bottle caps.

Canals are made of strong and inert materials with their interior layer appropriate for food production. The water inside them should have a retention time between one and four hours for allowing an adequate replenishment of nutrients. Higher water speeds allow more nutrients to come in contact with the roots, so narrower canals are preferred to "squarish" ones because they allow higher speeds without changing the retention time (the extreme situation of this can be found in the next method, NFT).

Finally, aeration is an important feature happening in the canals. Roots need to breathe and all the DO in the water will probably be consumed in the biofiltration process. Thus, an artificial aeration system is needed along the canal for provide enough DO in the water for the roots.

A method for improving aeration (that doesn't exclude the need of aeration) can be to let a space between water and raft. This allows a portion of the plant rootsto be in contact with oxygen, and the air to dissolve in the water. This is knew as the Kranky method and has proven beneficial in order to prevent diseases in the collar zone.

Nutrient Film Technique

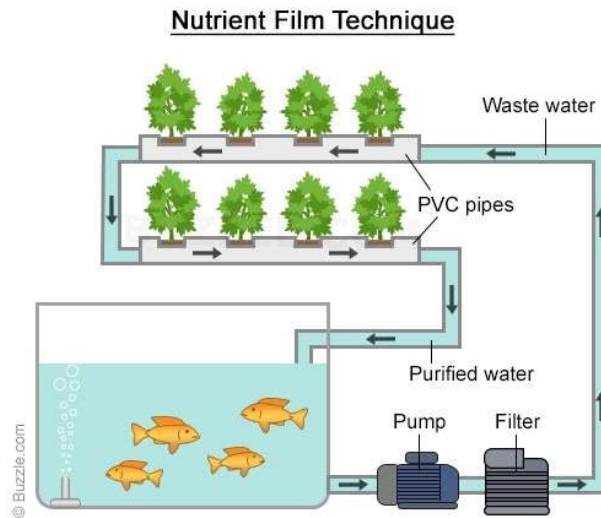


Figure 13. Simplified scheme of a Nutrient Film Technique System (Chavan 2016)

In Nutrient Film Technique (NFT) water from aquaponics is circulated in a thin layer through almost horizontal pipes. Plants grow in pots suspended within holes in the top of the pipes, letting their roots to reach until the bottom and be in contact with the water. The rest of the plant grow up and around the exterior of the pipe.

It always needs an external filtration unit that can be formed by the same components as the filter in DWC described previously.

The technique works as the water, after going through the filter, is pumped into the pipes continuously forming only a shallow stream rich in nutrients that run in the bottom of the pipe. The rest of the pipe is empty with air that lets roots breathe, therefore not being necessary artificial aeration systems. As they have enough air, roots can withstand a nonstop stream allowing a faster nutrient intake and growth of the plants. Water flow should not be higher than 1-2 liters/minute for allowing enough air into the root systems.

In matter of pipes, there are specific pipes for NFT. This pipes have usually a square shape in order to let the maximum amount of water go through the pipe without being too much deep. The width of these pipes usually vary from 11 to 7,5 cm depending on how big are the vegetables that are going to be grown. An important factor to be taken into

account is the type of root system of the plants; plants with dense root systems like tomatoes or mint can clog easily the pipe stopping the water stream. Finally, the length of these pipes should never exceed 12m in order to assure that even the last plant on the row receives enough nutrients.

2.3.3. Bacteria populations

In the nitrification process the reactions are made by autotroph bacteria very specialized from the genera *nitrosomas*, *nitrosocomas* and *nitrobacter*. This autotroph bacteria are different from the typical heterotroph bacteria that degrades organic matter, and is much more sensible to variations in DO, temperature, pH and toxics in the water, so they need a really stable environment in order to work properly.

One important parameter that affect the growing rate of the bacteria (it has to be taken in account that bacteria die and grow continuously, so growing rate is related with productivity) is the pH. Autotroph bacteria have an optimum growing rate with a pH between 7,2 and 8,5, and for a pH of 6,5 (the maximum pH fruit vegetables withstand in aquaponics) the growing rate is half the optimum (Ortega 2014). Biofilter surface will have to be big enough in order to compensate that small grow rate without losing productivity.

Table 1. Tolerance of nitrifying bacteria to different parameters (Somerville et al. 2014)

	Temperature (°C)	pH	Ammonia (mg/litre)	Nitrite (mg/litre)	Nitrate (mg/litre)	DO (mg/litre)
Tolerance Range	17–34	6–8.5	< 3	< 3	< 400	4–8

2.3.4. Additional environmental friendly systems for aquaponics

Aquaponics can be improved by a lot of means, here there is going to be explained two of the most common improvements that also have zero cost for the process.

Duckweed for extra treatment

Duckweed is a primitive water plant that lack of roots and true leaves, and grow on fresh water. It is an excellent nutrient remover from water, it can duplicate its mass each day and the only factor that restrains its growing are the nutrients present in the water source. It can be used as a food source for herbivorous fish and land animals, and excels as a source of vegetal proteins.

It is used in waste water treatment as an extra filtration system. It should be placed after the biofilter (if placed before would eat all the nutrients) and will clean all the rests of nitrogen, phosphorus and other nutrients that the biofilter had let pass. If there is a potential market for this source of food, maybe as source of food of the main fish, it is a perfect way of ending the water treatment process (Somerville et al. 2014)

Seashells to counteract pH

The biofiltration process is slightly acid, and in a close cycling system this can lead to a dangerous increase in the acidity of the water over the time. The only solution for counteracting this is to add a basic substance to the water. One cheap and efficient way of doing it is adding mashed seashells to the flow of water. Seashells are made of carbonates, a soft base, and will dilute over the time in an acid media.

If the factory is near the coast or with an easy source of seashells, this is an easy and cheap way of increasing the pH of the water at a long term. For short term pH variations the adding of a stronger base would be need (Somerville et al. 2014).



Figure 14. Duckweed (left) & a net bag of seashells for pH regulation (right).
(Somerville et al. 2014)

2.4. Economic model of aquaponics systems

As it is said, there is a difference on the economic revenues between traditional RAS and aquaponics. This work is focused on the economics of aquaponics as a waste water treatment, so other production costs of the main fish line will be ignored like fish food.

2.4.1. Costs

Investment costs

In matter of investment, waste water treatment plants are expensive. For both systems; pumps, valves and pipes are needed for regulate the water flow. Waste water pumps are specially designed for working with solids and corrosive substances but they get rusted over the time and have to be changed regularly.

The main difference between RAS and aquaponics is space. RAS occupies low space as the biofilters use to be really compact and most of the time are only a tank filled with high surface materials. Aquaponics needs a huge surface for growing the vegetables, but usually vegetable beds are cheap and don't need much extra investment. The mayor investment on aquaponics happens if the presence of a greenhouse is needed.

Greenhouses building costs depend on the country where the factory is built, so each calculus of investment cost have to be made "on site" by the builder. In warm weather areas greenhouses can be built with just thin layers of plastic film that don't need much of permanent infrastructure, but in cold climates like Finland, in order to reduce heat loss, greenhouses must be built with thick polymers or glass walls that need a good basement and structure, increasing costs.

Operation costs

In the matter of operation costs, four factors have to be taken into account for the process of cleaning water, two common for both RAS and aquaponics and two exclusive (although not compulsory) for aquaponics. This four costs are:

1. Pumping

Water has to be moved between the fish section and the water treatment section. This usually is achieved by pumps working all day or by the method of flooding/drying depending on the needing of air from the biofilter. Usually is the smaller energetic cost of the process.

2. Water warming

In the case of north climate factories, probably region's fish species have to be grown on cold water that usually doesn't go well for large colonies of bacteria. Cold environments slows bacterial production rates, needing an oversizing of the biofilter area. In aquaponics this doesn't have to be a problem because bacterial surface is already oversized for achieving solid mineralization and correct plant growing, but affects plants roots. In RAS, which relies in small high productive reactors, this can be a problem. In both cases, water can't go into the system lower than 10-15°C without affecting ammonia removal greatly. This water heating is costly, but can be reduced using heat exchangers between the cold water that has to be warmed for the biofilters and the warm water that has to be cooled for the fish.

3. Greenhouse heating

Depending on the geographical area, aquaponics vegetables may need a greenhouse for favouring a stable growing climate. Also, if the area is really cold sun may not provide enough heat for the greenhouse, having to rely on commercial air heaters for achieving an optimal weather.

4. Greenhouse illumination

Plants need light for growing, and in high latitudes sunlight hours may not be enough for vegetables. If this is the case, artificial light may be needed, greatly

increasing the operation costs and making aquaponics non profitable for most of the vegetables species.

In traditional RAS and in non-mineralizing aquaponics systems there is still needed a method for stabilizing the sludge generated, that increases costs. The most commonly used methods are:

- Biodigestion

All the waste organic matter generated can be mixed in a big reactor that digest and converts it into biogas (a mixture of CO₂ and methane) and stabilized sludge. This process needs to happen at a continuous 35°C in anaerobic conditions. If the methane produced is enough to maintain heating conditions, the process will be economically profitable generating a surplus of methane that can be used for producing electricity. If it's not enough, the process will require fossil fuels in order to stay at that temperature, increasing costs.

- Aerobic digestion

When the organic matter produced would not be enough for being self-sustainable in a process of biodigestion, usually is preferred a method of aerobic digestion over anaerobic. In aerobic digestion, you inject big quantities of oxygen during a long period of time in the sludge achieving its oxidation and stabilization. This process consumes high quantities of energy in form of aeration, but is still cheaper than burning fossil fuels for biodigest. In aquaponic plants, where most of the organic matter goes out the system in form of vegetables, this process may be the only one feasible.

2.4.2. Incomes

The biggest difference between RAS and aquaponics lies in the extra income the second achieves. This income can be really big taking into account that vegetables can be really expensive and the cost of production of them are low thanks on the free fertilizer coming from waste water.

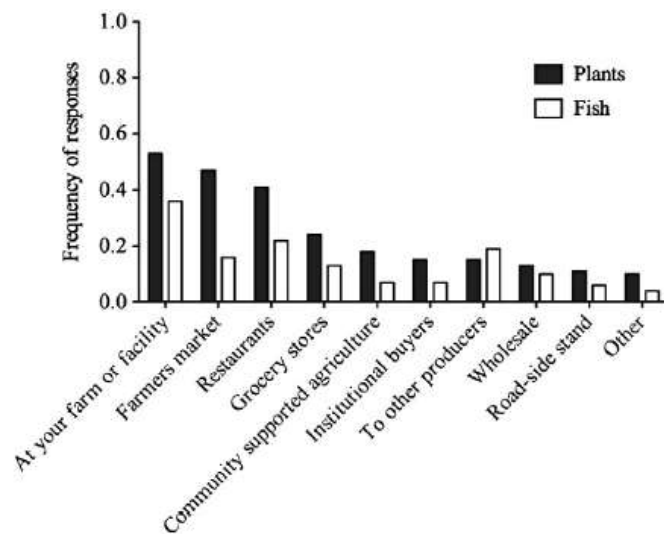


Figure 15. Study of the markets where commercial aquaponics farmers sell their product (Love et al. 2015)

In studies among farmers that had aquaponics in their lands, the results shown that the vegetable market is usually bigger than the fish market, having more potential sales. (Fig 15)

Also states that farmers that produce both fish and vegetables for selling are usually more time in benefit zone than them who just sell one of the two (Fig 16). This can be explained because if you only sell fish you are still losing valuable resources like in RAS without having nothing in exchange, and if you only sell vegetables you are relying in a cheaper source of fertilizer (fish food) that makes your system less efficient than hydroponics without having the extra income from the fish meat.

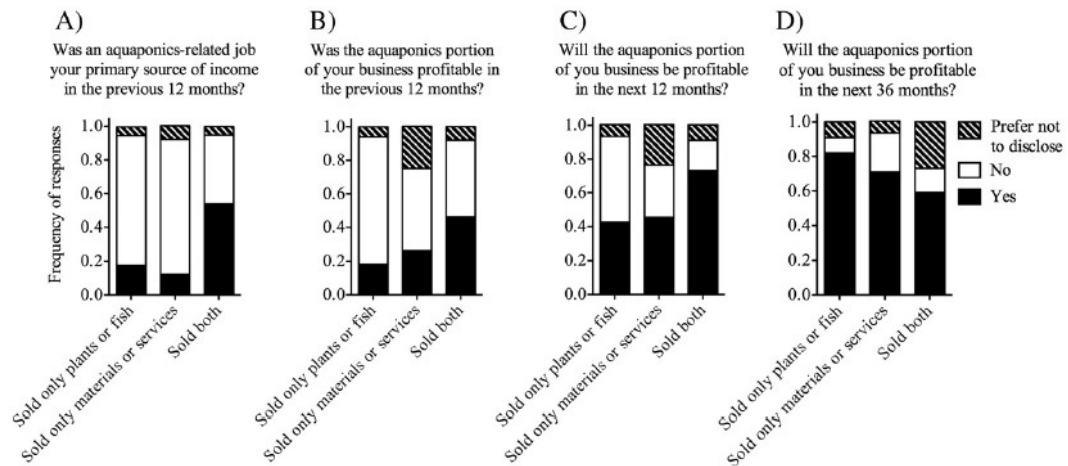


Figure 16. Study of profitability on aquaponics depending on products sold (Love et al. 2015)

Also, another economic benefit of diversifying products is that if your business does not rely on only one market of income (fish or vegetables) but in two different markets it can withstand more easily the fluctuations an eventual economic bubbles that may happen in one of the markets.

At last, it is worth say that although stabilized sludge from RAS can be a potential source of income as fertilizer, reality has proven that even if that product works really well as a long lasting non concentrated fertilizer, farmers don't use it in most of the crops. As an example, in Spain the price of that product varies between zero to five euros the ton, charging the transportation on the buyer. Usually, waste water treatment plants give it for free as long as you take it out from them.

2.5. Synthesis

In this chapter there has been discussed the different ways aquaponics can be implemented. There has been shown that aquaponics is not the only option for a recirculating water system, but can be the most profitable if exploited correctly.

Also, there has been shown that aquaponics is not just a single technique, but a bunch of different ways of growing plants soilless perfected by different people at different places and times that share some of their processes, but each one are designed for some specific plants and situations

It has been shown how flexible is aquaponics, being able of being specifically designed for a lot of situations. But even in the situations that aquaponics is not enough, it still has flexibility of being in a process mixed with another techniques allowing for more personalization of the processes.

Finally, it is worth to mention than as a matter of the economic part, if a system is designed to grow both fish and plants it will be most of the time more profitable to choose plants and fish species able of being sold that relying in less demanding but with no market value species. Generally, the profits of one branch of aquaponics can't compensate the cost of the whole system.

3. PRACTICAL IMPLEMENTATION OF AQUAPONICS

3.1. Case environment

In this work it will be studied the case of the company Laitakarin Kala OY. This company operates a series of seawater fish factories around the coast of Oulu, Finland; and wants to build a fish farm that grow salmon from its earlier stages until full developed.

The future factory has an objective of producing up to 1000 tons of fish per year. It will have an early stage of freshwater for the young fish and an ending stage of seawater cages for the adult fish. During all the process of growing there will be efforts of taking maximum profit of every byproduct or waste generated from the main fish grow chain, trying to achieve the most closed possible circular economy. The main efforts will be focused in searching for second uses for fish fat, guts and bones, energy efficiency and waste water reutilization. In this matter, at first sight aquaponics looks the most attractive option for reusing waste water. It will provide a second product for the company and a source of vegetables near the consumers in a country like Finland that imports most of its vegetables.

Oulu is situated in the north of Finland, in a coastal area. Its climate is subarctic, with cold long winters and short warm summers. The average temperature is 2,7°C ranging from 21°C in warm summer days to -13,5°C in cold winter nights. Its subarctic climate means Sun rises every day of the year, but during the winters it doesn't provides enough light for the typical vegetables to grow. All this factors may not affect a cold weather fish like salmon but will be really important in order to determine if vegetable growing is profitable.

3.2. Process data

In this part of the chapter there is going to be explained how to size and calculate the amount of resources going around the system. In order to get that, it is important to have a starting point, an objective to accomplish and seize the rest of the system around it. It could be amount of fish grown, amount of vegetables grown, surface of the greenhouses or even energy used in pumping.

Once this objective is established, the rest of parameters are interdependent so everything can be disclosed from it. In this case the starting point is the amount of fish produced by the factory. The company has established a quota of one thousand tons of grown fish per year. LUKE has estimated that the fish will grow 30% of their mass in the freshwater pools, so the maximum amount of fish mass at the same time on the pools will be of 300.000 kg. From there; waste water, vegetable grown and the rest of parameters can be estimated.

3.2.1. Calculus simplifications

In the process of making all the calculus, some simplifications have been made that later are corrected by a factor. All the parameters of the process can be separated into two groups, depending if they use as reference point the maximum mass of fish or the accumulated mass of fish (the product of the fish mass and the time it is in the system).

An example of maximum mass parameter can be the size of the pools. Pools are dimensioned thinking in the maximum stock density is going to be reached, because they can't grow in size with the fish. In the next graphic you can see the relation: in order to simplify the process, the pool seizing is made like the mass of fish is constant in a year and tops 300.000kg (grey area), but the truth is that the fish mass grows 1% each day, reaching 300.000kg the last day of the year (blue area). The ratio between black and grey area is 26,8% and will be used for correcting some calculations like the energy applied to the water.

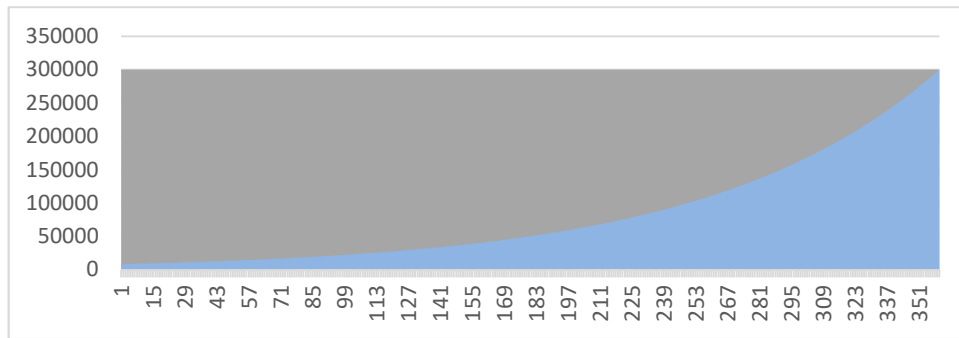


Figure 17. Comparison between a full year at full capacity (grey) and the true growth as a 1% per day during a year (blue)

On the other side; most of the calculations are related with the amount of fish and the time it is in the system. This is represented graphically as the surface of the blue area. In order to simplify the vegetable production, this area is divided equally in the days of the year, resulting in the grey area that has the same surface as the blue area.

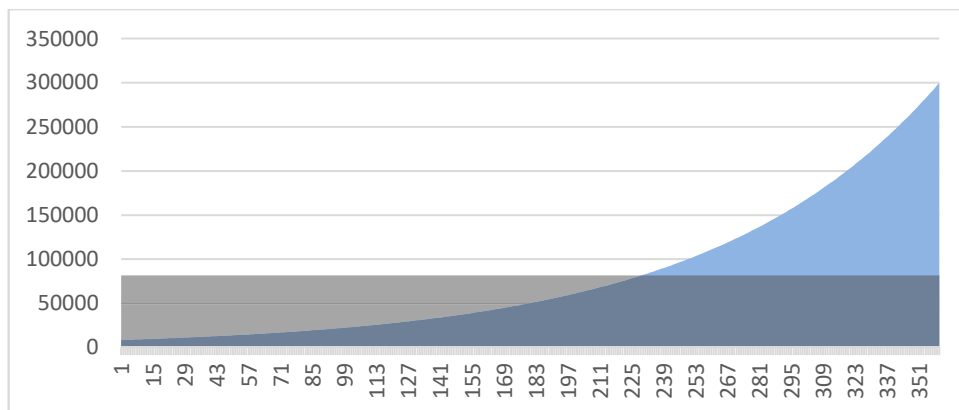


Figure 18. Comparison between distributing the mass over the year (grey) and the real mass growth (blue)

This model is way simple and perfect for having an estimation of the vegetable production in a year, but is impossible to achieve technically because fish has to grow and be harvested. In commercial systems fish don't use to grow all in one but in "packs" over the year, at each moment of the year there are pools for small, medium and big fish separated one from another. Each number of months, biggest fish get harvested or in this case moved to seawater cages. As an example, if we divide the 300.000kg of fish in three

rows of 100.00kg with 4 month separation between them, growing 1% of its mass each day over a year span we get a graphic that still is not constant but is much more similar to the approximation and is commercially feasible.

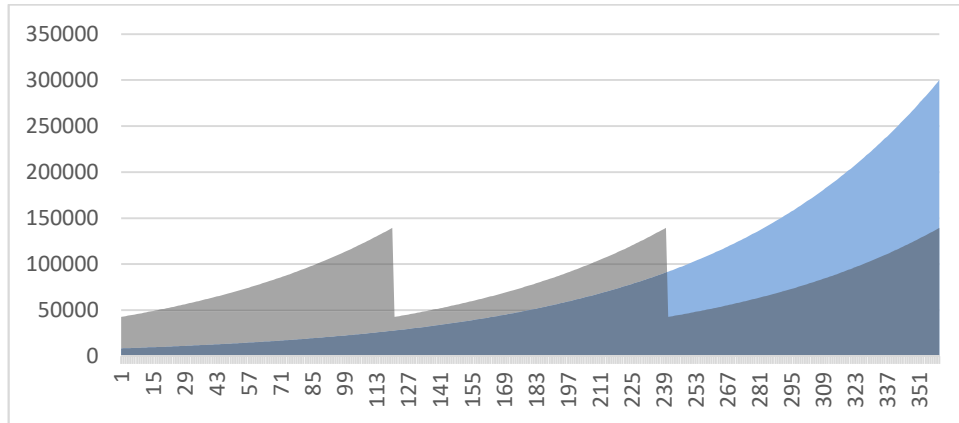


Figure 19. Comparison of the same mass of fish distributed between 1 brood per year (blue) and 3 broods per year (grey)

The more rows done, the less variation there is in the system and more perfect it will be, having also more constant nutrient intake by the plants and better crops.

3.2.2. Fish

Once having the objective of 300.000kg of fish in the pools, we have to select a fish/water ratio, the so called stock density. For salmonids in freshwater it is recommended a maximum of 30kg/m³ of water (RSPCA 2010)

Fish growth

Salmons can spend from months to 2 years between fry (tiny fish out of hatchery) and smolt (young adult ready to go to seawater). In this work it is estimated they will be 1 year in the freshwater pools, growing 1% each day as it is the normal ratio in aquaculture. As it has been explained before, it is better for the system that all the fish don't grow all in one row in order to have more constant productions of vegetables.

Pools

Once having the stock density and the maximum mass of fish, the water volume can be calculated. Setting a number of pools and a parameter either depth or diameter the geometry of the cylindrical pools can be calculated:

$$Volume = Radius^2 * Depth * \pi$$

NH₃ production

In order to estimate the maximum NH₃ production of the fish, first is important to know how much fish food (main source of nitrogen) we are introducing in the system and how much of that quantity ends in the water.

The fish feed can be made between 5 and 50% of proteins (proteins are the source of nitrogen), the normal level at which studies work is with 32% of proteins (McMurtry et al. 1990). Proteins contain 0.16g of Nitrogen for each gram of protein. Somerville et al. (2014) establishes that 55% of nitrogen end up in the water in form of urea and 6% in form of undigested food, having so a 61% of nitrogen rejected. Finally, it is produced 1,2g of ammonia per each gram of nitrogen rejected.

Taking all this chain of conversion into account, and having in mind that fish get feed 2% of their weight (if you want that they build 1% of mass each day, and 61% of food ends up out of the body, more or less you have to give twice the food than the mass) we can calculate the amount of ammonia created as a peak, in this case 225kg/day.

3.2.3. Bacteria

The amount of ammonia calculated before needs to be degraded into nitrates in order to be removed by the plants. Bacterial activity (the efficiency at which they decompose) is related to pH, temperature, light... but usually varies between 0,2-2 g NH₃/m² surface/day (Somerville et al. 2014). For being on the side of security it is going to be used 0, 57.

With that correlation can be calculated the minimum surface bacteria need to colonize in order to be enough for decomposing all the ammonia. As a bed for live bacteria in it is often preferred to use media with high relation surface/volume for reducing the space of the bed. In this case, the calculus is going to use volcanic gravel (an inert, pH neutral high porosity rock with affordable price) with a specific surface of $300\text{m}^2/\text{m}^3$.

As the company wants to plant fruit vegetables (tomatoes or cucumbers) that require a Media Bed with at least 0,4m depth for their roots, this is the media where the bacteria is going to live, instead of in a separate chamber as in Deep Water Culture and NFT. Setting the depth of the beds at 0,4m it is need at least 3300m^2 of bed in order to decompose the ammonia.

3.2.4. Plants

There are many methods that calculate the ratio between nutrient intake and plant growing using different correlations and factors. This is like this because mathematically modelling complex reactions in organic beings can be extremely complicate and time consuming, and the ending result may only vary slightly with the empirical relations used by farmers. As a preliminary estimation for production or surface needing, those ratios are more than enough.

In this case, there is going to be calculated the total mass of the vegetables and the space they are going to need for growing by two different methods, and the result is going to be mostly the same.

Fish/vegetable mass ratio

The first method is going to use an estimated ratio between the amount of fish and vegetables produced and from there calculate the rest of the parameters. Empirical studies show that vegetables growing in an aquaponics system produce from 0,5 to 10 kg of vegetables for each kg of fish grown, but usually this ratio is higher than 5.

So, being on the security side, we are going to work as if we are going to produce at the end of the year 5 times more vegetables than fish, this is 1.500 tons. LUKE studies predict the production of the cucumber in 120kg/m²/year (Kaukoranta et al. 2014) which sounds really feasible (author's personal experience). If we estimate that the area of the greenhouse must be twice the needed for the plants in order to have corridors, storing space, pumps...it results in an area of greenhouses of 2.5 ha.

NH₃ root cleaning area (Rakocy et al. 2006)

The second method will work with a ratio used by farmers in order to estimate easily the surface needed for aquaponics. It states that the efficiency on cleaning NH₃ of a surface of vegetal roots is between 60-100 gr fish food/m²/day. This is a very gross approximation because it ignores things like bacterial efficiency, fish food composition and different fish metabolism but it gives reasonable results.

Salmonids will need between 1-1,2 times its final weight in fish food (RSPCA 2010), knowing that they grow 300.000kg each year we can calculate the amount of food given daily. From there, using 80 gr fish food/m²/day as the ratio, the surface of greenhouses is calculated; in this case 2.47 ha. Using the LUKE ratio for cucumbers the amount of vegetables produced is mostly the same than with the other method: 1.480 ton/year.

3.2.5. Water related costs

Those are the costs associated with the energy spent in pumping and heating the water from the fish ponds, and then cooling it again. Water in aquaponics systems with high stock density like this must be circulated through the system at least two times per day (Somerville et al. 2014). Having a stock density of 30kg fish/m³ the flow of water through the pipes will be 20.000 m³/h

Pumping

The energy consumption of a pump responds to the next formula:

$$Ph = \frac{q * \rho * g * h}{3,6 * 10^6}$$

Being the meaning of the letters:

- Ph → Hydraulic power (kW)
- q → Flow capacity (m³/h)
- ρ → Density of the fluid (water = 1000kg/m³)
- g → Gravity (Earth = 9,81 m/s²)
- h → Differential head (m)

As the system doesn't have important loss of energy, with a differential head of 5 meters is more than enough. Assuming a pump working all day with 60% of efficiency the calculus gives 10.900 kWh/day of energy consumed in pumping at peak stock density. This sums up to 1000 MWh/year when scaled with the accumulated amount of fish (26,8%).

Water heating

As it is said in the literature, water must be up of 10°C in order to no affect significantly to the cleaning process. Salmon in fresh water need to be at no more than 8°C (RSPCA 2010), so water must be heated before the bacteria and cooled before returning to the pools. In this case, we are going to work with 8°C as cold temperature and 12°C as warm temperature.

Such amount of water needs lots of energy for warming just a few degrees, so an option is to input a heat exchanger between the in and out pipes in order to recycle that heat. Using a properly sized heat exchanger we can get up to 95% of efficiency easily. This means that cold water temperature is really of 11,8°C so the thermic difference is of 0,2°C.

The formula that rules heat transferences is the next one:

$$Q = c * \rho * \Delta t$$

The letters stay for:

- Q → Heat added (kJ/h m³)
- C → Specific heat (water = 4,186 kJ/kg °C)
- ρ → Density of the fluid (water = 1000kg/m³)
- Δt → Thermic difference (°C)

Assuming an efficiency of the boiler of 85%, working all day consumes an amount of 131.325 kWh/day of energy in heating that 0,2 degrees at peak stock density. This sums up to 13.000 MWh/year when scaled with the accumulated fish mass (26,8%).

3.2.6. Greenhouse

In order to calculate the energy consumption of heating the greenhouse and the electric light is going to need in winter, it is necessary to know the climate of the region where the greenhouse is going to be. As those are complex calculus specialized from Finland, LUKE centre proportionate the estimations of energy consumption (Kaukoranta et al. 2014); those are:

- Heating: 0,4 MWh/m² greenhouse/year
- Illumination: 1,4 MWh/m² greenhouse/year

As the space of greenhouse is 2,5 ha, the energy consumption of this part is:

- Heating with gas: 10.000 MWh/year
- Illumination with electricity: 37.000 MWh/year

Those results take in account that electric lamps have an efficiency of 95% and the losses counts as heating. Also, heating has an efficiency of 85% for using gas but still is cheaper than using electricity with a 100% efficiency (Appendix 2).

3.2.7. Economic model

At this point of the work all the data we need for the economic model is already calculated. The outputs of money will come in form of energy spent as we are assuming a perfect process without needing of external fertilizer (greenhouse root area is 4 times bigger than minimum area for bacterial decomposition, oversized enough for allowing mineralization of the solids and giving up with external fertilizers). The inputs of money will come in form of profit for the vegetables sold.

Operation Costs

There are four main costs in the process, two in form of electricity and two in form of fossil fuel (natural gas):

- Pumping (electricity): 1.000 MWh/year
- Water heating (gas): 13.000 MWh/year
- Greenhouse heating (gas): 10.000 MWh/year
- Greenhouse illumination (electricity): 37.000 MWh/year

In Finland in 2015 the cost of electricity was 0,059€/kWh and the cost of the natural gas was 0,042€/kWh, resulting in a cost of:

- Pumping: 63.000€/year
- Water heating: 540.000€/year
- Greenhouse heating: 417.000€/year
- Greenhouse illumination: 2.174.000€/year

Benefits

During the last years, the sell prices for farmers in Finland of the two main vegetables wanted for the process are the next (the column of 2017 is an estimation using the market tendency):

Table 2. Market variation of cucumber and tomato prices over the past years (Kasvistieto OY 2017)

	2010	2011	2012	2013	2014	2015	2016	2017
Cucumber	1,268	1,261	1,404	1,489	1,381	1,326	1,455	1,5
Tomato	1,576	1,498	1,739	1,766	1,687	1,681	1,693	1,7

So, assuming a vegetable production of 1.500 tons the monetary income would be in 2017 of:

- Cucumber: 2.250.000€/year
- Tomato: 2.550.000€/year

3.3. Synthesis

All this data combined is enough for calculate the economic viability of the project in the next chapter. Also, it provides a step by step guide that can be used for calculating the process parameters in other aquaponics projects.

In order to calculate the parameters of a process and thus its technical feasibility, the most important thing to know are the relations between the different factors that affect the results. For example, the mass of fish is related with the mass of ammonia and therefore the mass of vegetables grown. But this relation is made only thanks to bacterial chemical reactions that have an efficiency dependant on temperature.

This lead to a complex web of interrelationships instead of a simple chain, and in order to know if a project will work the first step is to understand all the factors that are going to participate in the project. Once you know all of them, is easy to pick one and start from there and untie all the web until you have the process modelled.

4. ECONOMIC FEASIBILITY

4.1. Models

The market study of the Finnish vegetable sector was made by other members of the project at the same time than this work. Its preliminary results show that in Finland there is a potential market for local fresh vegetables. From all the vegetables that can be grown in aquaponics (appendix 1) the most desired are tomatoes, cucumbers and lettuce, and only lettuce market is fulfilled by local farmers. So, as the study suggested, in the area of Oulu the market of tomatoes and cucumbers will buy all the locally produced tomatoes and cucumbers at the market price.

The decision can be made on focusing on one type of vegetable or grow both at the same time. As both need a media bed for growing, this decision doesn't affect much the aquaponics system. This will lead to the first basic model of the aquaponics that has been used thorough the work, a system of media beds without filter and sized in order to don't need solid removal.

Another possibility is to have a mixed system. If the market would be more opened and accept leafy vegetables or herbs there would be feasible to grow them at the same time than the tomatoes or cucumber. Aquaponics systems can be mixed without much problem as long as the minimal bacterial surface will be respected. A mixed system could be half Media Bed half DWC but it would be necessary to calculate if the bed surface will be enough for removing solids, otherwise a filter would be necessary and probably mineral supplements for the vegetables.

Aquaponics can be really flexible with the market needs, the fact of using different plant grow systems doesn't affect the productivity and can even be beneficial as some type of plants can compensate the deficiencies of other. In general lines, the more variety of fish and vegetables growing together, the better use of the resources given to the system.

4.2. Final discussion

The amount of money earned and spent are summarized in the next table. This table divides the costs depending on where they come from, the water or the greenhouse. The water costs can be labelled as constants in every system that doesn't dump the waste water in the environment, and so it would not be fair to charge them to aquaponics. The greenhouse costs otherwise are only caused by aquaponics, as traditional RAS uses compact biofilters that don't have any cost associated apart from the water costs.

The benefits are divided between fish and vegetables. The fish benefits are the TOTAL fish benefits, the 1.000 ton, and are calculated assuming a price of 3,6 €/kg (Rakocy et al. 2006). The vegetable benefits are the ones calculated previously.

In order for aquaponics to be feasible over RAS, the vegetable benefit (one of the two, either tomatoes or cucumber) would have to be higher than the greenhouse costs.

Table 3. Comparison of all the incomes and mayor outcomes of money in the process

Cost	Aquaponics	RAS	Pumping	63 .000€/year
			Heat water	540 .000€/year
		Heat greenhouse	403 .000€/year	
		Light greenhouse	2174 .000€/year	
Profit	Fish			3600 .000€/year
	Vegetables	Tomato		2250 .000€/year
		Cucumber		2550 .000€/year

As we can see in the table, it doesn't matter which vegetable we decide to grow, aquaponics can't be profitable on a first sight. Growing vegetables and selling them will be more expensive than just cleaning the water with bacteria and using the sludge for landfilling. There are still some alternatives that can be made in order to achieve a better level of profitability.

4.3. Sensibility study

There are two mayor operation costs in the system, heating and lighting. Heating cost can be reduced using an alternative source than fossil fuels. One option would be to build the factory near a paper factory. Paper factories are really common in the north of Finland and produce high quantities of hot water as a byproduct. Usually this hot water is not used in other processes, so it could be used as a cheap source of heat for aquaponics. This would reduce the costs of heating water and the greenhouse greatly.

Without taking into account heating the greenhouse aquaponics seems viable (planting cucumbers as it is the most profitable crop) but the difference between benefits and costs is so small that any change (like a bad market drop or the dead of a crop caused by a disease) would cause the system to be in losses, even if the company in overall is profitable.

In this case it would not be recommended to implement an aquaponics system if one of this three things don't happen:

- A reduction on the electricity price and therefore a reduction in the illumination cost.
- An augment of the price of vegetables, reporting more benefits
- A government help to reduce CO₂ emissions, as aquaponics is an environmental friendly system. The vegetables grown in aquaponics have less CO₂ emissions than their counterparts grown in traditional farming or hydroponics because fertilizer production industry is a heavy contaminant sector and aquaponics is the only mass scale system that can produce vegetables without it.

4.4. Synthesis

As we have seen in this chapter, at first sight the aquaponics process is not feasible. This is caused mostly by factors related to the extreme climate where the project wants to be done. Cold temperatures during most of the year and not enough light during all the winter requires a special equipment that compromises the results. It is worth to mention that is not fault of aquaponics as a system in particular, as this factors would make difficult all greenhouse farming in such climate.

So, aquaponics as an environmental friendly process of growing vegetables may report profits in countries where vegetables can be cultivated outdoors or easily indoors, and it will probably grow in the future with the needing of a global circular economy.

But, in the north of Finland (and almost every place with 65° of latitude) the costs of fighting against the weather are bigger than the benefits that it reports. As it has been said, there are two big resources that affect the costs, heat and electricity. In order to be economically feasible, both resources should decrease its cost (by reusing waste heat from another factories and a decrease in electricity cost for example) or vegetables should report more benefits (by market prices or government helps for example).

5. CONCLUSION

In this chapter there are presented the conclusions of the work and evaluated if the objectives of it had been accomplished properly, in a reliable way that allows repeatability of the study. The last section proposes some topics that can be studied as improvements of this work or variations that are better in terms of business feasibility.

5.1. Contribution of the Study

The objective of this study has been to find the viability of implementing an aquaculture system in a near-to-build fish farm in the north of Finland, all of this inside a frame of various research paths focused in the reutilization of waste by-product streams in such farm.

The first research question of the project, asking for different ways of implement aquaponics, has been answered in the first part of the work, the literature search. We can find that aquaponics is a mixture of other techniques and can be easily personalized for each business model, thanks to the variety of ways that can be implemented and the possibility of mixing them. This flexibility is essential because the fact of making aquaponics a symbiosis between fish and non-aquatic plants implies taking some compromises between the needs of the fish and the plants; that are not the same. This compromise reduces efficiency of the vegetable production compared with traditional hydroponics, but its flexibility makes it desirable in situations where hydroponic crops are too delicate.

The second research question, the technical implementation of aquaponics, is answered in the empirical parameters chapter. It implies a chain of parameters that are calculated; starting from an objective of production (fish production per year in this case) it can be obtained the rest of the data that allows for the designing, in a future step, of the plant and all the equipment needed.

The last research question, and the most important is the matter of the business, is if aquaponics is economically viable with this criteria. It is hinted during the technical

parameters chapter what seems to be the result of the work; but during the next chapter, the economic model, all the major cost and profits from the process are clearly disclosed. Once all the costs are disclosed and the first solution obtained, it is explained how to change it with the disclosure of the main factors that account for that costs. If this factors would change in a profitable way, the solution may change, in this case the project could be economically feasible.

Once cover all the process, it can be said that aquaponics can be attractive under certain circumstances. Its flexibility and environmental friendliness are the two main features that looks promising as further models of business, but in this case the circumstances of the location where it could be implemented makes it hard to be economically attractive. Probably in other place under other circumstances its features will look more attractive than a simple RAS system of the same size.

5.2. Critical evaluation

Every scientific work has to have two characteristics: it has to be true sustained with facts and has to be reproducible by other people in other places. During this work, this two characteristics have been tried to keep the best possible. Most of the references of the work came from trustworthy sources like scientific works or recognized global organizations. In the literature research most of the sources came from past studies in the fields of aquaculture, hydroponics or aquaponics. The few sources that have a less contrastable origin have only been used in non-critical parts in order to keep trust on the work written.

In the empirical study most of the data come from the Food and Agriculture Organization, and as in theory it is an impartial organism dependent only from the United Nations it can be classified as a trustworthy source. Before finding the FAO data other sources were used for gathering that data, but as they were usually handbooks for farmers most of its information was eventually replaced with the FAO data. One remnant that was used on a minor part is an australian aquaculture guide (Mosig & Fallu 2004).

The economic model may be probably the less contrastable part of all the work. This is because there are few sources that can be used from Finland, having to rely in studies made in other countries, mostly in USA. This studies probably show the reality, but may happen that the conclusions about the productivity of aquaponics are different in two so different countries as USA and Finland.

As in the matter of repeatability, the most important part of the work that would need to be repeated is without doubt all the calculus of the different parameters of the process. In this matter all the calculus process was made from the beginning in a way that helps to easy check steps and reproduce it. It was made like this because it was understood that this work would be the basis for future improvement that would lead eventually to the implementation of an aquaponics system. It was calculated using mostly excel trying to follow a structured order, making use of colours and tables for capitalizing the results and of commentaries explaining the source of each data. The author implemented this way of working following a process learned in previous works in waste water treatment plants, so in that way the project could be easily repeatable.

Some of the critical information of the work came from non-published sources. This is the case of the temperature of the water for the plants (that came from questions made to the personnel of the botanical garden of the University of Oulu). Although the data cannot be contrasted without recurring to the same source, the information came from experts in the area and has been treated as essentially true.

Once the work has been finished, taking a look at the past road it seems that other paths could have been more profitable for the company. The most promising path is the “decoupled aquaponics” a mixture of RAS and hydroponics that don’t rely in a symbiosis between the three main actors like aquaponics. This may be the only solution on growing plants in a hard environment like the north of Finland, but until this work was done it was not known if true aquaponics could also be another option. So, as this project has result in non-profitable for business, it can be used as the example that true aquaponics is not viable in hard conditions and further research must be done in other areas.

5.3. Further research

Further research is needed for the business project and for aquaponics. For the business project, now that aquaponics has proven not economically viable other means have to be found in order to provide environmental friendly uses for the waste water. As it has been said, decoupled aquaponics is a promising subject where the project is now heading that could occupy the niche that pure aquaponics can't.

For aquaponics, as a growing aquaculture method, it has been found that really few research has been done in the past years that lead to business implementation. It is needed more research in methods of optimizing the process in order to make it more competitive against traditional aquaculture because in a world with needs of all resources, aquaponics is a method that is able to grow food for humans that waste much less resources than other methods, and this should be motivation enough for making it more competitive.

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7. APPENDIX

Appendix 1: Different parameters for the most suitable vegetables in aquaponics (Somerville et al. 2014).

		pH	Plants/m ²	Growth time (Herb, head plant or fruit)	Temperature	Light needing
Herbs	Basil	5.5-6.5	8-40	5-6 weeks	18-30°C	Full sun/Slightly shadow
	Parsley	6-7	10-15	20-30 days	15-25°C	Full sun
Leaf and Flower vegetables	Lettuce	6.0-7.0	20-25	24-32 days	15-22 °C	Full sun
	Cauliflower	6.0-6.5	3-5	2-3 months (spring) 3-4 months (autumn)	20-25°C (spring) 10-15°C (autumn)	Full sun
	Broccoli	6-7	3-5	60-100 days	13-18°C	Full sun/Slightly shadow
	Head cabbage	6-7.2	4-8	45-70 days	15-20°C	Full sun
	Swiss chard / Mangold	6-7.5	15-20	25-35 days	16-24°C	Full sun
	Cucumbers	5.5-6.5	2-5	55-65 days	22-28°C day 18-20°C night	Full sun
Fruit vegetables	Eggplant	5.5-7.0	3-5	90-120 days	22-26°C day 15-18°C night	Full sun
	Peppers	5.5-6.5	3-4	60-95 days	22-30°C day 14-16_°C night	Full sun
	Tomato	5.5-6.5	3-5	50-70 days	22-26°C day 13-16°C night	Full sun
	Beans and Peas	5.5-7.0	Bush varieties 20-40 Climbing varieties 10-12	50-110 days	22-26°C day 16-18°C night	Full sun

Basil

Basil is one of the most popular herbs in aquaponics units, given its high market value and the high demand it has in urban areas. Many different varieties of basil have been cultivated in aquaponics, usually in large-scale monocultures; like sweet basil, lemon basil and purple passion basil. Is suitable for all three types of aquaponics, but usually is preferred NFT.

Parsley

Parsley is a very common herb appreciated for its nutritional content (is rich in vitamins A and C, calcium and iron) and high market value. It have low nutrient requirements compared with other vegetables. Is suitable for all three types of aquaponics, but usually is preferred NFT.

Lettuce (Salad Leaves)

Lettuce grows particularly well in water culture like hydroponics and aquaponics due to the optimal nutrient intake through the water. Many varieties have been grown in aquaponics, being the most famous the iceberg, the butterhead, Romanie lettuce and loose leaf lettuce. Is a vegetable that has high demand in urban zones and it is one of the preferred vegetable in large commercial monocultures. Is suitable for all three types of aquaponics, but as it has relatively small area and high demand of nutrients it has been grown easily in large DWC units.

Cauliflower

Cauliflower is a winter crop with high market value. The heads can be a nutritious intake, and so the plant has high nutrient demands. It withstands easily high nitrogen and phosphorus concentrations and may need an extra intake of potassium or calcium for the production of the heads. Cauliflower is sensitive to climate changes, so a stable environment of a greenhouse may be need. The plant need a strong root system so the best aquaponics option would be media beds.

Broccoli

Similar to cauliflower, broccoli is a nutritious winter vegetable with high nutrient demands. It is sensitive to warm temperatures, so a good climate management would be needed. As a large and heavy plant, it needs a strong root system so the best option for growing it would be media beds.

Cabbage

Is a nutritious winter vegetable and with high demands of nutrients in the water. Nevertheless, related with the weigh and space it reaches, has a smaller relative nutrient needing than lettuce or other similar vegetables. Its ability to withstand low temperatures (up to 5°C) makes it suitable for aquaculture with cold weather fish. Its final dimensions and weight can make it too heavy for grow rafts or pipes, so media bed is recommended.

Swiss chard

Swiss chard is a popular vegetable in Mediterranean cuisine with high market value. It has low nutrient requirements and a fast growth rate, together with a not special sensibility on weather makes it a really easy to grow vegetable in aquaponics units. It grows well in all three unit types, but probably the best option would be DWC because is the most suitable for commercial scale aquaponics.

Cucumbers

Cucumbers, along with other members of its family like zucchini and melons are high value summer vegetables. They require big quantities of nutrients, specially nitrogen and potassium, so they are good for high stock density systems. As they have big roots and high mineral nutrient demands, they grow better in media beds with mineralization processes. Cucumbers can also grow in DWC systems, but they can clog easily NFT pipes so they are not recommended for that system.

Eggplant

Like cucumbers, eggplant is a summer fruit vegetable with high nutrient demands. This causes that big stock densities are preferred in order to give all the nutrients needed. Their roots need to grow deep and strong, so media beds with enough depth are advised.

Peppers

Peppers are popular vegetables that can come in a different variety of shapes. From the big sweet belly peppers to the small hot chili peppers, all varieties of peppers are suitable for aquaponics. Although media beds are preferred for their growth, NFT pipes with the maximum width (11cm) can be suitable if given the appropriate structural support.

Tomato

Tomatoes are the most popular summer fruit vegetable with high market value and demand. They require large amounts of nutrients through all their life so a properly balanced system between fish stock density and number of plants is needed. Potassium can be a determining factor in the fruit setting and growth, so maybe an extra nutrient intake should be needed. They can be grown in all three aquaponics systems, but usually is preferred media beds as they require structural support and is easier to set in that system than in another.

Beans and Peas

Both climbing and bush varieties grow well in aquaponics units; but climbing varieties, although needing a special structural support, uses less space and produce more quantity of fruits making them more suitable for aquaponics. Beans have low nitrate and moderate phosphorus and potassium needs. They are susceptible to high nitrogen concentrations, so stock density is preferred low or high quantity of plants per fish. Climbing varieties are more suitable for media beds for the structural support and bush varieties to DWC and NFT.

Appendix 2: Calculus tables

BASIS 1000000 kg fish/year total
 300000 kg fish/year on pools

	Parameters
	Solutions
	Constants

FISH PRODUCTION	Fish/water ratio	30	kg/m ³
	Number of pools	6	pools
	Harvest per year	1	
	Water volume needed	10000	m ³
	Water volume per pool	1667	m ³
	Depth pools	4	m
	Diameter pools	23	m

NH₃ PRODUCTION	Maximum fish weight	300000	Kg
	Fish feed	2	% per day g Prot/g
	Protein fish feed	0,32	feed
	Nitrogen in protein	0,16	g N/g Prot
	Nitrogen not asimilated	61	%
	Ammonia per nitrogen	1,2	g NH ₃ /g N
	Ammonia per day	225	kg/day
	224870	g/day	
BACTERIAL NH₃ DEGRADATION	Bacteria efficiency	0,57	g/m ² /day
	Surface of media needed	394509	m ²
	Material of bed	Volcanic gravel	
	Specific superfice of material	300	m ² /m ³
	Volume of bed	1315	m ³
	Heigh of bed	0,4	m
	Area of beds	3288	m ²

VEGETABLE PRODUCTION	1st METHOD	Vegetable/fish ratio	5	kg veg/kg fish	
		Production per area cucumber	120	kg/m ² /year	
		Multiplier factor	2		
		Vegetable production	1500000	kg/year	
		Greenhouse area	25000	m²	
			2,5	ha	
		2nd METHOD	Feed conversion ratio	1,2	kg food/kg fish
			Feed needing daily	986	kg food daily
			Waste conversion ratio	80	g/m ² /day
			Production per area cucumber	120	kg/m ² /year
			Multiplier factor	2	
		Greenhouse area	24658	m²	
			2,5	ha	
		Vegetable production	1479452	kg/year	

WATER ENERGY CONSUMPTION		Water volume in ponds of fish	10000	m ³	
		Cycles of water per hour	2		
		Flow rate	20000	m ³ /h	
		Correction mass rate	26,8	%	
		PUMPING ENERGY	Density fluid	1000	kg/m ³
			Gravity	9,81	m/s ²
			Diferential head	5	m
			Pump efficiency	60	%
			Time powered	24	h/day
			Hydraulic Power	273	kW
			Shaft Power	454	kW
			Energy consumption	3978500	kWh/year
			True energy consumption	1066238	kWh/year

HEATING ENERGY	Cold temperature	8 °C
	Warm temperature	12 °C
	Heat exchanger efficiency	95 %
	Middle temperature	11,8 °C
	Heating temperature gap	0,2 °C
	Specific heat water (c)	4,186 kJ/kg 4186 kJ/m3
	Time powered	24 h/day
	Heater efficiency	85 %
	Heat added (Q)	16744000 kJ/h 4651,111111 kW
	Heat power	5472 kW
	Energy consumption	47933804 kWh/year
True energy consumption	12846259 kWh/year	
GREENHOUSE HEATING AND LIGHT	Electricity price	0,059 €/kWh
	Natural gas price	0,042 €/kWh
	Greenhouse surface	25000 m2
	Estimated heat necessity	0,4 MWh/m2/year
	Estimated light necessity	1,4 MWh/m2/year
	Lamp efficiency	95 %
	True heat necessity	0,326 MWh/m2/year
	True light necessity	1,474 MWh/m2/year
	Boiler efficiency	85 %
	Heat gas consume	9598 MWh/year 403096 €/year
	Electric radiator efficiency	100 %
	Heat electric consume	8158 MWh/year 481316 €/year
	Illumination consume	36842 MWh/year 2173684 €/year