Designing aquaponic production systems

Ragnar Ingi Danner

Faculty of Life and Environmental Sciences
University of Iceland
2016
Ragnar Ingi Danner

90 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Biology

Advisors
Ragnheiður Inga Þórarinsdóttir
Kesara Anamthawat-Jónsson

Faculty Representative
Kesara Anamthawat-Jónsson

External Examiner:
Sveinn Aðalsteinsson

Faculty of Life and Environmental Sciences
School of Engineering and Natural Sciences
University of Iceland
Reykjavik, May 2016
Designing aquaponic production systems
90 ECTS thesis submitted in partial fulfillment of a Magister Scientiarum degree in Biology

Copyright © 2016 Ragnar Ingi Danner
All rights reserved

Faculty of Life and Environmental Sciences
School of Engineering and Natural Sciences
University of Iceland
Sturlugata 7
101, Reykjavik
Iceland

Telephone: 525 4000

Bibliographic information:
Ragnar Ingi Danner, 2016, Designing aquaponics production systems, Master’s thesis, Faculty of Life and Environmental Sciences, University of Iceland, pp. 59.

Printing: Háskólaprent
Reykjavik, Iceland, May 2016
Abstract

Aquaponics is a method of producing food in a sustainable manner where fish and plants are grown together in a closed loop of nutrients. An aquaponics system is comprised of fish rearing tanks, mechanical- and biological filtration and hydroponics units in a closed loop of nutrients. Fish waste produces nutrients for the plants in the hydroponic unit consequently removing nutrients from the water column to make the culture water more suitable for fish. The purpose of this research was to evaluate and calculate the production of tilapia and different aquaponic vegetables through a study period of two years. The suitability of locally available feed and the selection of plant species were assessed. Effects of water flow on plant growth and nutrient utilization were measured. In this study, six aquaponics systems were built in four different places. One of the systems was a nutrient film technology system whereas four were deep water cultures. Moreover, a flood and drain system was built and tested. One system was built within an industrial building and received artificial lighting while the others were all located inside greenhouses. Tilapia, which is one of the most popular fish in aquaculture, was reared in all systems while different leafy green and fruiting plants were grown. The fish were fed commercial aquaculture feed for cod and charr. The feed conversion ratio is used to assess how effective the fish’s growth is, typical FCR for tilapia is between 1.0 and 1.8 depending on the feed quality and environment. The FCR observed in this research was between 0.9 and 1.5. Leafy green plants especially pak-choi showed similar yield to other research, expected approximately four times the production of fish in mature systems. Fruit ing plants did not do as well as leafy greens in this experiment.
Útdráttur

Samrækt er sjálfbær ræktunaraðferð þar sem fiskur og grænmeti er ræktan í lokaðri hringráð næringarefna. Samræktarkerfi samanstendur af fiskitönnum, fastefnaslí, lifshreinsi og vatnsræktarkerfi. Úrgangur físksins losar næringarefni sem plönturnar nýta sér til vaxtar, við það lækkar styrkur næringarefnanna og kerfið verður vistlegra fyrir fískinn. Tilgangur rannsóknarinnar var að bera saman ræktun á mismunandi tegundum grænmetis, meta hentuleika íslensks fískeldisfrøðurs til ræktunar á beitarfíski og meta hvaða plöntur henta best í framleiðslu með samrækt. Sex mismunandi kerfi voru byggð í rannsókninni og mælingar framkvæmdar á þeim til að meta samspil þattra innan kerfisins og áhrif þeirra á stöðu kerfisins. Eitt kerfið var NFT kerfi, fjögur voru svoköllud DWC kerfi og eitt var flood and drain kerfi. Eitt DWC kerfið var byggt í íðnaðarhúsnæði, þar sem notast var við raflýsingu. Tilapia eða beitarfískur er einn vinsælasti eldisfrøður í heimi og var ræktuður í öllum kerfum á meðan plöntuval var misjafnt milli kerfa og samanstóð þæði af bláðgrænmeti sem og ávaxtaplötum. Fískarnir voru fóðraðir á eldisfróðri fýrri sjófísk og bleikju og fódurstúull þeirra reiknafur. Fódurstúull er mælikvarði á hversu vel fískurinn vex og er jafnan á bilinu 1,0 og 1,8 fyrir beitarfísk. Í þessari rannsókn var fódurstúullinn á bilinu 0,9 til 1,5. Bláðgrænmeti, sérstaklega pak-choi skilaði góðum niðurstöðum í kerfunum, sambærílegum við aðrar rannsóknir. Ávaxtaplötur skiluðu ekki eins góðum árangri.
# Table of Contents

List of Figures ........................................................................................................... viii  
List of Tables ............................................................................................................. x  
List of Equations ....................................................................................................... xi  
Abbreviations ............................................................................................................ xii  
Acknowledgements .................................................................................................... xiii  

1 Introduction ............................................................................................................ 1  

2 Background ........................................................................................................... 3  
  2.1 Aquaponics .......................................................................................................... 3  
  2.2 Nitrification ......................................................................................................... 4  
  2.3 Hydroponic system types ................................................................................... 6  
  2.4 Fauna & Flora .................................................................................................... 7  

3 Materials and methods ......................................................................................... 11  
  3.1 Systems ............................................................................................................... 11  
    3.1.1 System 1: Show case setup ........................................................................... 11  
    3.1.2 System 2 – 4: Greenhouse setup ................................................................. 13  
    3.1.3 System 5: Industry building setup ............................................................... 15  
    3.1.4 System 6: Commercial Pilot setup .............................................................. 17  
  3.2 Fauna .................................................................................................................. 18  
  3.3 Flora .................................................................................................................... 18  
  3.4 Lighting and electrical appliances ................................................................... 19  
  3.5 Statistical analysis ............................................................................................. 19  
  3.6 Water sampling and Chemical analysis .......................................................... 20  

4 Results .................................................................................................................... 21  
  4.1 System 1 ............................................................................................................. 21  
  4.2 Systems 2-4 ....................................................................................................... 21  
  4.3 System 5 ............................................................................................................ 25  
  4.4 System 6 ............................................................................................................ 33  

5 Discussion .............................................................................................................. 37  

6 Conclusions and recommendations ..................................................................... 41  

References ............................................................................................................... 43  

Appendix A feed and additive ingredients ............................................................... 47  
Appendix B Posters and other material .................................................................... 51  
Appendix C Test kit user manuals .......................................................................... 57
List of Figures

Figure 2.1 Typical setup of an aquaponic system modified from Thorarinsdottir, et al.
2015......................................................... 4

Figure 2.2 An illustration of a decoupled aquaponic system, modified from
Thorarinsdottir et al. 2015......................................................... 7

Figure 3.1 A schematic illustration of the showcase system.............................. 12

Figure 3.2 A photograph of System 1......................................................... 12

Figure 3.3 System 2, the arrows indicate the flow of water through the system........ 13

Figure 3.4 A photograph taken of System 3 while it was operative, system 1 can be
seen in the background......................................................... 14

Figure 3.5 System 3, the arrows indicate the flow of water through the system.......... 14

Figure 3.6 Schematic overview of System 4.................................................... 15

Figure 3.7 The layout of System 5.................................................................. 16

Figure 3.8 A schematic overview System 6. Arrows indicate the course of water
through the system 1A-1C are fish tanks. 2A is the drumfilter, 2B is the
solids collection tank. 3 is the sump 4A is the biofilter, 4B is the trickling
tower and 5 is the hydroponic unit.............................................. 17

Figure 3.9 The hydroponic part of the system.................................................... 18

Figure 4.1 Nitrogen data from System 2.......................................................... 22

Figure 4.2 Nitrogen data for System 3............................................................. 22

Figure 4.3 pH and conductivity data for System 2............................................. 23

Figure 4.4 pH and conductivity data for System 3 in the greenhouse..................... 23

Figure 4.5 Basil (near) and mint (far) in System 3............................................. 24

Figure 4.6 Rucola plant shows deficiency symptoms, healthy basil plant in the back. .. 24

Figure 4.7 Tomato plants in the growbed in System 4........................................ 25

Figure 4.8 Peppers in System 4.................................................................... 25
Figure 4.9 A graph showing the mass of edible greens produced in each bed between runs. ................................................................. 26
Figure 4.10 Nutrient concentrations in Pair A in Trial 1. ................................................................. 27
Figure 4.11 Nutrient concentrations in Pair B in Trial 1. ................................................................. 28
Figure 4.12 Nutrient concentrations in Pair C in Trial 1. ................................................................. 28
Figure 4.13 Conductivity (EC) TDS and pH for the system in Trial 1. ................................. 29
Figure 4.14 Photos of bed B1 taken 9 days in between showing rapid growth in pak-choi. ................................................................. 29
Figure 4.15 Nutrient concentration in Pair A in Trial 2. ................................................................. 30
Figure 4.16 Nutrient concentrations in Pair B in Trial 2. ................................................................. 30
Figure 4.17 Nutrient concentrations in Pair C in Trial 2. ................................................................. 31
Figure 4.18 Conductivity (EC) TDS and pH for the system in Trial 2. ................................. 31
Figure 4.19 Beds in Trial 1 at the day of harvest. ................................................................. 32
Figure 4.20 Tomato plants in System 6, bearing many fruit. ......................................................... 34
Figure 4.21 Okra plants in System 6. A seed pod and a flower can bee seen at center-left of the image. ................................................................. 35
List of Tables

Table 2.1 Different kinds of plants grown in aquaponics. ................................................................. 8
Table 3.1 Systems and system types in the research. ........................................................................... 11
Table 3.2 plants grown in the research ................................................................................................. 19
Table 3.3 Electrical appliances used in the systems ............................................................................... 19
Table 3.4 Locations of sampling and number of samples taken from System 5 ................................. 20
Table 4.1 Results from the survey of public opinion on aquaponics. .................................................. 21
Table 4.2 Growth of fish and vegetables in the greenhouse systems ..................................................... 23
Table 4.3 FCR and total plant to feed conversion ratio for the trials .................................................... 26
Table 4.4 Hydraulic loading rate (HLR) for each pair of beds ................................................................. 26
Table 4.5 Results of ANOVA for plant yield between pairs in Trial 1 ..................................................... 27
Table 4.6 Results of ANOVA for plant yield between pairs in Trial 2 ..................................................... 27
Table 4.7 Results of Nested ANOVA for effects of trials, weeks or HLR on TAN removal .................... 32
Table 4.8 Results of Nested ANOVA for effects of trials, weeks or HLR on NO₂–N removal ................. 32
Table 4.9 Results of Nested ANOVA for effects of trials, weeks or HLR on NO₃–N removal ................. 32
Table 4.10 Results of Nested ANOVA for effects of trials, weeks or HLR on PO₄–P removal .................. 33
Table 4.11 Growth of fish in System 6. .................................................................................................... 33
Table 4.12 An explanation of plant biomass for System 6. ..................................................................... 33
Table 4.13 EROI results for the first 10 years of systems compared (Atlason et al., n.d. Table 2 included with authors permission) ................................................................. 33
List of Equations

Equation 1 The nitritation process (Sultana, 2014) .................................................. 5

Equation 2 The process of nitratation (Sultana, 2014) ............................................. 5
Abbreviations

ANOVA – Analysis of variance

DWC – Deep Water Culture

FAO - Food and Agricultural Organization of the United Nations

FCR – Feed Conversion Ratio

F&D – Flood-and-drain

HLR – Hydraulic Loading Rate

MBB – Moving Bed Biofilter

NFT – Nutrient film Technique

RAS – Recirculating Aquaculture System

TAN – Total Ammonia Nitrogen
Acknowledgements

First I want to thank The University of Iceland, Svinna Engineering, Rannís and the Ecoponics project for funding the research. Landsbankinn and the Organic farm Akur receive gratitude for providing housing for the systems. And the following people for their part in making this happen; Svanhvíð Viðarsdóttir and Marvin Ingi Einarsson for their part in building the systems and assisting with measurements. Ísak M. Jóhannesson, Ólafur P. Pálsson, Rúnar Unnþórsson and Soffía K. Magnúsdóttir for their assistance with measurements. Hermann D. Guls for assisting me with statistical analysis. Utra Mankasingh for invaluable help with laboratory analysis. I also want to thank my advisors, Ragnheiður Þórarinsdóttir and Kesara Ananthawat-Jónsson for their guidance and for giving their time to make this project come true and last but not least I want to thank Snæfríður Pétursdóttir for moral support during the stressful times of putting all of this together.
1 Introduction

Aquaponics is a developing sustainable food production method coupling aquaculture and horticulture together in one circular system mimicking nutrient and water cycles from nature. Aquaponics has gained increased interest in recent years and the number of aquaponic practitioners has increased greatly since 2007 (Love et al., 2014). Most aquaponic practitioners are hobbyist mostly interested in making their own food and in environmental issues (Love et al., 2014). However, a few startup companies in Europe have taken the step towards commercial production (Thorarinsdottir et al., 2015). By using renewable energy sources and abundant clean water in Iceland, aquaponic production could develop into commercial scale production being environmentally friendly as waste from the aquaculture and fertilizer use is minimized in aquaponics.

This study was done in cooperation with Svinna Engineering Ltd. as background studies for establishing commercial scale aquaponic production in Iceland. The main goals of this research were to evaluate and calculate the optimal production of different aquaponic vegetables in different production systems and troubleshooting their design through a study period of two years. The suitability of locally available feed for rearing tilapia was evaluated as no special tilapia feed is produced in Iceland, and emphasis was put on selecting suitable plant species for the production. Also the effects of water flow on plant growth and nutrient utilization were measured, hypothesizing that plants in slower flow would show increased growth and more nutrient removal.

The thesis is divided into five chapters. Chapter 1 is this introduction, Chapter 2 covers the present knowledge within aquaponics and the results from other related studies. Chapter 3 presents the materials and methods used in the study, where system design, fauna and flora of the systems, chemical and statistical analyses are described. Chapter 4 presents the results from the experiments followed by the discussion in Chapter 5. Finally Chapter 6 contains the conclusions made from the experimental work and recommendations regarding system design, feed and plant selection.
2 Background

2.1 Aquaponics

Aquaponics is a combination of recirculating aquaculture system (RAS), that is farming fish in circulating systems, and hydroponics, that is growing plants in a solution of nutrients and water (Rakocy, 1988). An aquaponic system consists of a fish rearing tank, mechanical, and biological filtering, a hydroponic growbed and optionally a sump (Rakocy, 1999). Figure 2.1 shows a typical setup of an aquaponic system. The fish produce, with their waste, nutrients that with time, would become detrimental to the fish’s health. The water from the fish rearing tank is therefore mechanically filtered to remove suspended solids from the water. The solids consist of the fish excrement, uneaten feed and other undissolved matter. The filtration mechanism optimally removes all of these solids to where they can be utilized further or disposed of. After solids removal the water is then filtered through bioworks where nitrification takes place. From the biofilter the water flows through the hydroponic troughs where the plants remove nutrients from the water by utilizing them for growth. Depending on the system type the water flows to a sump where water volume in the system is controlled and from the sump the water is then pumped into the fish tank again, creating a closed loop of nutrients in the system. Aquaponics may help minimizing environmental impacts of aquaculture such as eutrophication. Eutrophication can lead to imbalances in ecosystems such as algal blooms and changes in local fauna (Lekang, 2007). Small crustaceans are often related to increased planktonic algae. These crustaceans can have detrimental effect on opportunistic feeding fish because of their poor nutritional content (Lekang, 2007).
After removal the solids are often composted, either as fertilizer for conventional agriculture or mineralized in water (Lekang, 2007) where the nutrients released may be to further use in the aquaponic system itself (Thorarinsdottir et al., 2015). It is necessary to remove the solids as they will adhere to plant roots (Rakocy, 1999) and could cause negative changes to rhizosphere conditions. Accumulated solids can lead to depleted oxygen content due to a high biochemical oxygen demand (BOD) and elevated ammonia levels (Rakocy, 2007). BOD and chemical oxygen demand (COD) are measurements of how much oxygen is needed to break down waste materials. As solids within a system decompose, the bacteria consume oxygen from the water. Without removing the solids from the system, the BOD of the system remains high, lowering oxygen concentration and reducing the effectiveness of the biofilter (Graber et al., 2010). COD is the same as BOD with the exception that COD includes decomposable organic matter that cannot be decomposed with biological functions (Lekang, 2007). Mineralization is an essential process in aquaponics. Mineralization is the process of releasing nutrients bound in solid waste into their dissolved mineral phase.

### 2.2 Nitrification

Nitrification is an essential function in the system. As the fish excrete ammonia, the water would soon become toxic without water exchange or microbial action. Nitrification is the process of oxidizing ammonia to nitrate. Ammonia and nitrite, the first products of the nitrification process are toxic to aquatic animals (Jensen, 2003; Kroupova et al., 2005). Nitrite is formed through a process called nitritation (Sultana, 2014) described in Equation 1
\( \text{Equation 1 The nitritation process (Sultana, 2014).} \)

\[
\text{NH}_4^+ + 1.5 \text{O}_2 \rightarrow \text{NO}_2^- + 2\text{H}^+ + \text{H}_2\text{O}
\]

Nitrite is oxidized further to nitrate via nitratation (Equation 2; Sultana, 2014) which is less harmful but becomes toxic at higher concentration (Cheng & Chen, 2002; Jensen, 2003).

\( \text{Equation 2 The process of nitratation (Sultana, 2014).} \)

\[
\text{NO}_2^- + 1.5 \text{O}_2 \rightarrow \text{NO}_3^-
\]

For the nitrifying bacteria to thrive in the system, a large surface area for them to grow on is needed. This is done with a biofilter which is filled with media where the water flows through. Nitrifying bacteria come from several genera, however, species of three genera are the most important when it comes to nitrification in an aquacultural system, \textit{Nitrosomonas}, \textit{Nitrococcus} and \textit{Nitrospira} (van Kessel et al., 2010).

Nitrification can be described as two processes, nitritation, performed by \textit{Nitrosomonas}, and nitratation performed by \textit{Nitrococcus} and \textit{Nitrospira}.

TAN or total ammonia nitrogen consists of two compounds; ammonia NH\(_3\) and ammonium NH\(_4^+\). Biological membranes are highly permeable for NH\(_3\) while being impermeable to NH\(_4^+\) (Randall & Tsui, 2002). The form in which TAN is present is related to environmental pH with NH\(_3\) being more present in higher pH (Randall & Tsui, 2002). At high pH 7.8-9.0 environmental Ca\(^{2+}\) can protect fish from toxic effects of ammonia by reducing elevation in cortisol levels (Wicks et al., 2002; Wilson et al., 1998). Ammonia toxicity in fish is related to extracellular glutamate concentration in the brain, excessive NMDA glutamate receptor activation and neuronal cell death, likely caused by NH\(_4^+\) depolarization on neurons, leading to convulsions and death (Wicks et al., 2002).

Nitrite toxicity is connected with its affinity to the Cl\(^-\) binding mechanism in fish’s gills (Jensen, 2003). Freshwater fish with more active Cl\(^-\) binding are more vulnerable to nitrite toxicity whereas environmental chloride levels in marine environments make nitrite less toxic to marine life. Nitrite oxidizes iron in haemoglobin, turning it into methaemoglobin which does not have the ability to carry oxygen causing methaemoglobinemia. Also nitrite has an effect on osmoregulatory and endocrine systems in fish (Deane & Woo, 2007). Nitrite can be detoxified in aquatic animals at high environmental oxygen concentrations. Rainbow trout have shown tolerance to a long exposure of moderate levels of environmental nitrite by conversion to nitrate (Doblander & Lackner, 1996).

The mechanism for nitrate toxicity is the same as for nitrite, e.g. conversion of haemoglobin to methaemoglobin but the higher tolerance levels for nitrate are due to the impermeability of gill membranes to nitrate (Jensen, 1996). Ingested nitrate is also considered as a factor in infant methaemoglobinemia in humans (Fewtrell, 2004). Nitrogen removal is therefore an important factor in the success of recirculating aquacultural systems.


2.3 Hydroponic system types

There are various types of hydroponic system setups: Deep water culture (DWC), nutrient film technique (NFT) and flood-and-drain (F&D) systems being the three most common types used in aquaponics. They differ mostly in the method of irrigation.

DWC works by the plants growing in rafts floating in or being suspended over a watertight growbed with their roots suspended in the nutrient solution that flows continuously. DWC also adds a body of water where other organisms can be cultured. Sometimes microfauna such as small crustaceans like ostracods and copepods, planarian flatworms and mosquito larvae, can flourish in these conditions. Some species can be harmful to plants, but can be remedied by introducing small predatory fish to the DWC bed (Rakocy et al., 1997).

NFT allows water to flow at a constant level through the rhizosphere of the plants, which are grown in a vertical or horizontal tube. There is only a thin layer of nutrient solution that continuously flows over the roots. It is essential to remove all solids in this kind of a system as they will build up on the plant roots with detrimental causes for the plant’s health.

F&D systems utilize a bed of a porous medium for the plants to grow in, usually expanded clay or pumice. The bed slowly fills up with water, when a certain maximum is reached a simple device drains the bed for the cycle to start again. The media in the bed also serves purposes other than just being a surface for the plant roots to stick to. The porous nature of these materials also provides a large surface area for the essential nitrifying bacteria to thrive on and therefore serves as a biofilter for the system, negating the need for a separate biofilter in a well-balanced system, thus improving spatial utilization. The flushing of the bed gives the bacteria highly oxygenated conditions that optimize their growth and nitrification. F&D systems are however prone to solids buildup in the media. This can be remedied by using a good solids remover or by manually removing and rinsing the media which is labor intensive.

A new version of aquaponic systems is being developed by the Ecoponics team and by IBG (Kloas et al., 2015; Thorarinsdottir et al., 2015). Decoupled systems vary from the traditional system in that the aquacultural and hydroponic parts of the system are not joined in a closed loop (Figure 2.2). Instead the fish are raised in traditional RAS manner with optimized conditions for the fish’s growth. Water is exchanged in the system typical of RAS systems but instead of disposing of it, the water is used for irrigation in a traditional hydroponic unit. This decoupling allows for optimization of each individual production part of the system and gives the freedom of selecting fish and plant species that have separate needs (Kloas et al., 2015; Thorarinsdottir et al., 2015).
2.4 Fauna & Flora

Tilapia (*Oreochromis niloticus*) is one of the most popular fish in aquaculture and in aquaponics systems. This is due to its omnivorous nature, rapid breeding and fast growth which make it an ideal fish for aquaculture. Utilization of YY-chromosome males in the brood stock has allowed for all-male cultures to be used leading to higher productivity (Baroiller et al., 2009). The Food and Agricultural Organization of the United Nations (FAO) has even suggested that aquaculture of tilapia should replace agriculture of livestock in poorer regions because it has lower feed conversion ratio (FCR), using similar feed as used for livestock, i.e. 1.6 for tilapia vs 8.8 for cereal fed beef (FAO, 2006; Wilkinson, 2011) while FCR and product quality is highly dependent on feed composition (Jatta, 2014). Tilapia is also very hardy and tolerant of a wide range of water quality and parameters, making it a suitable species to grow in an aquaponics system that is still maturing. The traits that make tilapia a popular aquacultural species have also led to them
colonizing new waters outside their natural range, through escapes from fish farms or being released into the wild. Being a prolific and aggressive breeder, tilapia has become invasive in many parts of the world. This, however, should not be a hazard in Iceland because tilapia will not survive in temperatures below 10°C (Rakocy, 1989).

Other species of fish have also been tested in aquaponics systems. Rainbow trout (Oncorhyncus mykiss) for example, is already a popular, dominant aquacultural species in Europe and is being cultured in a test aquaponics system in Norway (Thorarinsdottir et al., 2015).

Various species of plants have been tested with success in aquaponics systems (Table 2.1). Many studies show that leafy green plants such as various cultivars of lettuce (Latuca sativa), basil (Ocimum basilicum) give very good yields in aquaponic systems (Rakocy et al., 2003; Savidov et al., 2007; Trang et al., 2010).

Table 2.1 Different kinds of plants grown in aquaponics.

<table>
<thead>
<tr>
<th>Species</th>
<th>Scientific name</th>
<th>Reference</th>
<th>Yield (kg/m²/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basil</td>
<td>Ocimum basilicum</td>
<td>(Rakocy et al., 2003; Savidov et al., 2007)</td>
<td>13-42</td>
</tr>
<tr>
<td>Lettuce</td>
<td>Latuca sativa</td>
<td>(Savidov et al., 2007; Trang et al., 2010)</td>
<td>30</td>
</tr>
<tr>
<td>Pak-choi</td>
<td>Brassica campestris. var. chinensis</td>
<td>(Hu et al., 2015; Trang et al., 2010)</td>
<td>3.8 (plant:feed ratio)</td>
</tr>
<tr>
<td>Choy sum</td>
<td>Brassica campestris. var. parachinensis</td>
<td>(Trang et al., 2010)</td>
<td></td>
</tr>
<tr>
<td>Tomato</td>
<td>Solanum lycopersicon</td>
<td>(Graber &amp; Junge, 2009)</td>
<td>128</td>
</tr>
<tr>
<td>Water spinach</td>
<td>Ipomoea aquatica</td>
<td>(Liang &amp; Chien, 2013; Savidov et al., 2007)</td>
<td>60</td>
</tr>
<tr>
<td>Chives</td>
<td>Allium schoenoprasum</td>
<td>(Savidov et al., 2007)</td>
<td>14</td>
</tr>
<tr>
<td>Spinach</td>
<td>Spinacia oleracea</td>
<td>(Savidov et al., 2007)</td>
<td>15</td>
</tr>
<tr>
<td>Egg plant</td>
<td>Solanum melongena</td>
<td>(Graber &amp; Junge, 2009; Savidov et al., 2007)</td>
<td>32.9</td>
</tr>
<tr>
<td>Parsley</td>
<td>Petroelenium crispum</td>
<td>(Savidov et al., 2007)</td>
<td>20</td>
</tr>
<tr>
<td>Cucumber</td>
<td>Cucumis sativus</td>
<td>(Graber &amp; Junge, 2009; Savidov et al., 2007)</td>
<td>29.2</td>
</tr>
<tr>
<td>Watercress</td>
<td>Nasturtium officinale</td>
<td>(Savidov et al., 2007)</td>
<td>10</td>
</tr>
<tr>
<td>Okra</td>
<td>Abelmoschus esculentus</td>
<td>(Rakocy et al, 2004)</td>
<td>13.4</td>
</tr>
</tbody>
</table>

Staggered vegetable production seems to be favored over batch production. In Staggered production the plants of the system are of different growth stages at all times, from seedlings to harvest size plants allowing labor to be managed. Growing all of the plants in the same growing phase can lead also to nutrition deficiencies while plants of different growth stages have different nutritional requirements therefore moderating the nutrient uptake (Rakocy et al., 2003).
The balance between the nitrogen waste produced in the system and plant uptake is of a large importance, as described in section 1.2. Nitrogen metabolites carry a toxicity risk for the animal life in the system. Plants utilize nitrogen mostly as ammonium (NH$_4^+$) or as nitrate. Some co-influences on nutrient uptake are known such as uptake of ammonium hinders the uptake of other cations from the substrate whereas nitrate uptake can impair the uptake of phosphorus. (Haynes & Goh, 1978; Riley & Barber, 1971). Balance in the concentrations of macronutrients N, P and K is therefore of utmost importance to keep the nutrient use efficiency balanced (Janssen, 1998).

Nitrate removal through utilization is the most important function to the aquaponic system. Plants assimilate CO$_2$ and nitrate for the production of carbohydrates and amino acids that will construct the body of the plant (Foyer et al., 2001). For efficient energy use during photosynthesis a large amount of light harvesting chlorophyll proteins is necessary. The protein that plays the major role in this is Rubisco. Rubisco is a catalyst and has a low catalytic rate per mass of protein, therefore, for fast photosynthesis, Rubisco is needed in large amounts. If nitrogen supply is low during the growth of the leaf, less amount of Rubisco is formed leading to lower photosynthetic productivity in the leaf (Lawlor et al., 1989). Rubisco also has a low affinity for CO$_2$ therefore by increasing the concentration of CO$_2$ in the atmosphere, faster photosynthesis can be reached (Drake et al., 1997). However high CO$_2$ content in the culture water are detrimental to fish health, therefore measures have to be taken to minimize the CO$_2$ content.
3 Materials and methods

3.1 Systems

The work was carried out during a two years period from spring 2014 until spring 2016. Aquaponics systems were developed in four different places during the development; a show case system for visitors at Iceland Ocean Cluster House in Reykjavik; developing units in a greenhouse in Kopavogur; and in an industry building in Reykjavik; and a small scale commercial unit at the greenhouse farm Akur in Laugaras, South Iceland (Table 3.1). The show case system in the Ocean Cluster House has been operational from January 2014. It has served well as an educational and presentation unit for a large group of visitors from many different countries. In the greenhouse in Kopavogur, three systems were built in June 2014 and operated until October the same year when they were moved to the industry building in Reykjavik for further development. During spring 2015 the small scale commercial unit was started in the greenhouse in Laugarás, South Iceland.

<table>
<thead>
<tr>
<th>System number</th>
<th>System type</th>
<th>Housing</th>
<th>Location</th>
<th>Artificial lighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F&amp;D</td>
<td>Office Building</td>
<td>Reykjavik</td>
<td>12 hours</td>
</tr>
<tr>
<td>2</td>
<td>DWC</td>
<td>Greenhouse</td>
<td>Kópavogur</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>DWC</td>
<td>Greenhouse</td>
<td>Kópavogur</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>F&amp;D</td>
<td>Greenhouse</td>
<td>Kópavogur</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>DWC</td>
<td>Industrial building</td>
<td>Reykjavik</td>
<td>12 hours</td>
</tr>
<tr>
<td>6</td>
<td>NFT</td>
<td>Greenhouse</td>
<td>Akur</td>
<td>No</td>
</tr>
</tbody>
</table>

3.1.1 System 1: Show case setup

The show case systems were built for education purposes and as demonstration units for the general public and others interested in the functions and the principles of aquaponic systems. The hydroponics systems were built with raft beds and flood-and-drain media beds filled with pumice. To begin with there was no means of separating solids other than the media in the bed, but in the summer of 2015 the systems were combined turning one of the growbeds into a solids separation tank through which half of the water volume was
pumped to catch some of the solid waste. Red-claw crayfish (*Cherax quadricarinatus*) were reared in the solid separation tank to aid mineralization of nutrients by ingesting fish waste and stirring up the sediment preventing anaerobic conditions from developing within the sediment. Many different kinds of plants have been tested in this system, fruit bearing plants, e.g., different cultivars of tomato, paprika and okra. Leafy green vegetables such as lettuce, pak-choi, malabar spinach (*Basella alba*), spinach beet (*Beta sp.*) and watercress were also tested. A schematic illustration and a photograph of the system can be seen in Figures 3.1 and 3.2.

![Figure 3.1 A schematic illustration of the showcase system.](image)

![Figure 3.2 A photograph of System 1.](image)
3.1.2 System 2 – 4: Greenhouse setup

During the summer of 2014, three aquaponics units were developed in a greenhouse in Kopavogur, two of which were DWC systems and the third one was a F&D system. This part of the experiment was mainly intended to calculate mass balances and FCR for tilapia on commercial and locally available char feed (protein 45%, fat 23% for other ingredients see Appendix A) and to monitor the nitrogen cycle in an aquaponic system.

The smallest system (Figure 3.3) had a 0.65 m$^3$ fish tank, a 0.1 m$^3$ sedimentation tank and a 0.1 m$^3$ biofilter with 0.05 m$^3$ of biomedia (YULONG MMBR). The two raft beds had a volume of 0.3 m$^3$ each, adding up to a total system volume of 1.1 m$^3$. Each bed had 48 plants.

Nitrogen compounds were measured daily for the first month to monitor the nitrogen cycle. Further information on in-situ chemical analysis can be found in section 3.6.

The largest system (Figure 3.4 and 3.5) was also a DWC. It had a 1 m$^3$ fish tank, a 0.1 m$^3$ sedimentation tank, a 0.2 m$^3$ biofilter and a 0.5 m$^3$ sump tank. There were 3 growbeds in the system each with a volume of 1 m$^3$ and 72 plants on a surface area of 2 m$^2$.

![Figure 3.3 System 2, the arrows indicate the flow of water through the system.](image-url)
Figure 3.4 A photograph taken of System 3 while it was operative, system 1 can be seen in the background.

Figure 3.5 System 3, the arrows indicate the flow of water through the system.
The last of the greenhouse systems (Figure 3.6) was a F&D system, it had a 1 m$^3$ fish tank, a 0.1 m$^3$ sedimentation tank, a 0.8 m$^3$ sump and two growbeds of 1 m$^2$ each. This system had tomato plants (*Solanum lycopersicum*) and peppers (*Capsicum annuum*) of different varieties.

Fish in the systems were fed daily a 1% of their total biomass. To assess the total biomass the fish were weighed individually on a monthly basis. Plants were harvested at the same time as the fish were weighed to see the monthly output of these systems. These systems relied only on summertime ambient lighting.

### 3.1.3 System 5: Industry building setup

Effects of water flow on plant growth and nutrient concentration with tilapia and pak-choi in a DWC system were performed in this system. The system consisted of a 1 m$^3$ IBC fish tank and 1 m$^3$ IBC sediment filter, a biofilter with 0.2 m$^3$ media in two 0.2 m$^3$ barrels, 6 growbeds 0.3 m$^3$ each and a 0.5 m$^3$ sump tank.

In the test run, the fish were fed on the same charr feed as in the greenhouse systems before (3.1.2). After reviewing the nutritional needs of the fish, the feed was changed to cod feed as it had lower fat than charr feed (51% protein, 17% fat, see appendix A for other ingredients and nutritional value).
The growbeds were set up as pairs (Figure 3.7) where one tank of each pair served as a control for the other, each growbed was 1.2 m² in surface area.

Pair A had the highest flow rate (0.46–0.49 m³* h⁻¹), pair B had medium flow rate (0.144–0.163 m³* h⁻¹) and pair C had the lowest flow rate (0.036–0.040 m³* h⁻¹). This difference in flow rates was the experimental variable.

From the growbeds the water was collected in a sump from where it was pumped back into the fish tank. In each bed 40 pak-choi plants were grown in 50mm net pots.

In trial 1 and 2 water samples were taken weekly from the system in following locations: Fish tank, biofilter part 1 and 2, from the outlet of each bed and the sump. Samples were filtered and frozen. The collected samples were diagnosed for Nitrogen and Phosphorus at the University of Iceland (More information in section 3.6).

Artificial lighting was provided in both trials at 100W/m². In Trial 1 ambient lighting through windows in the building was also present for 22 h/d.

After the initial test run in the system the filtration was modified. The solids separator which was only around 0.1m³ was replaced by the separator described above, the biofilter

Figure 3.7 The layout of System 5.
which was also only 0.1 m$^3$ and contained 0.05 m$^3$ of media was also replaced by the filter described.

### 3.1.4 System 6: Commercial Pilot setup

The NFT system had three fish tanks, each of which had a functioning volume of 2 m$^3$. All of the tanks overflow into the same water pipe which lead to a Hydrotech HDF 501 microscreen drumfilter which separated solids from the water. Solids were gathered in a 0.1 m$^3$ tank from which they were pumped automatically twice daily. The filtered water went into a sump where it was pumped in three directions. One outlet from the pump went to the biofilter, one to the fish and one to the hydroponic unit (Figure 3.8).

The hydroponic unit (Figure 3.9) consists of eight 140 mm PPE pipes each containing 11 net pots of 75mm in diameter. Plants were preplanted in coco husk and put in the pots with pumice for added hydration the reason for this was that the coco husk was easily transferrable from the preplanting tray to the pots. For the first week the pipes were flooded so the plants could sprout roots outside the pots in order to be able to draw water from the bottom of the pipe.

The biofilter is an 1 m$^3$ IBC tank which contains 0.4 m$^3$ of YULONG MMBR biobed. There is constant aeration in the biofilter to keep the media moving. After biofiltration the water overflows into a trickling tower with 2 compartments also filled with the same media. The trickle tower served as additional biofiltration unit as well as a means of aeration and degassing.

![Figure 3.8 A schematic overview System 6. Arrows indicate the course of water through the system. 1A-1C are fish tanks. 2A is the drumfilter, 2B is the solids collection tank. 3 is the sump. 4A is the biofilter, 4B is the trickling tower and 5 is the hydroponic unit.](image)

Energy return on investment (EROI) calculations were carried out for this system, System 5 from section 3.1.3 and a system built by the company BREEN in Hondarribia, Basque Country where they were compared. EROI is the Energy output of the system divided by the energy input in the production of the system, this is used to calculate the energy...
efficiency of a given production system. The results have been presented in an article submitted for publication (see abstract in Appendix B).

Figure 3.9 The hydroponic part of the system.

3.2 Fauna

Tilapia was grown in all systems, in Systems 2-3, fish weighing between 25-100 grams initial weight were reared. In System 4 fish under 20 grams were reared. System 5 had fish between 200-400 grams initial weight and in Systems 1 and 6, fish of mixed size from 1-200 grams were reared. Fish were in all instances fed 1% of initial live weight daily and weighed monthly to assess their growth.

3.3 Flora

Different plants were tested in the systems, all plants were grown from seeds within systems. Table 3.2 shows what plant species were grown in which system. System 1 and 4 were only show case systems to store fingerlings and no measurements were done on plant mass in these systems.
Table 3.2 plants grown in the research.

<table>
<thead>
<tr>
<th>System number</th>
<th>System type</th>
<th>Plants grown</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F&amp;D</td>
<td>Tomato, peppers, basil, watercress, okra, pak-choi, komatsuna</td>
</tr>
<tr>
<td>2</td>
<td>DWC</td>
<td>Basil, coriander, rucola, mint</td>
</tr>
<tr>
<td>3</td>
<td>DWC</td>
<td>Basil, coriander, rucola, mint</td>
</tr>
<tr>
<td>4</td>
<td>F&amp;D</td>
<td>Tomato and peppers*</td>
</tr>
<tr>
<td>5</td>
<td>DWC</td>
<td>Pak-Choi</td>
</tr>
<tr>
<td>6</td>
<td>NFT</td>
<td>Tomato and Okra</td>
</tr>
</tbody>
</table>

*not measured

3.4 Lighting and electrical appliances

Two systems used artificial Lighting (Table 3.1). In these systems a 400W Metal Halide (Powerplant MH SuperVeg) bulb with a Eurowing reflector was suspended over each pair of bed. These bulbs are stated by the manufacturer to have more light in the blue spectrum to support vegetative growth. All Systems had impeller pumps, aerators and electronic heaters, all manufactured by Hailea, further information on the pumps and product names can be seen in Table 3.3.

Table 3.3 Electrical appliances used in the systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Pump</th>
<th>Q (liter/h)</th>
<th>Heater</th>
<th>Aerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HX8830</td>
<td>3100</td>
<td>1x300W</td>
<td>9610</td>
</tr>
<tr>
<td>2</td>
<td>HX8830</td>
<td>3100</td>
<td>2x300W</td>
<td>9610</td>
</tr>
<tr>
<td>3</td>
<td>HX8860</td>
<td>6500</td>
<td>2x300W</td>
<td>9810</td>
</tr>
<tr>
<td>4</td>
<td>HX8830</td>
<td>3100</td>
<td>No</td>
<td>9610</td>
</tr>
<tr>
<td>5</td>
<td>HX8830</td>
<td>3100</td>
<td>3x300W</td>
<td>ACO-009</td>
</tr>
<tr>
<td>6</td>
<td>H18000</td>
<td>18000</td>
<td>No</td>
<td>ACO-009</td>
</tr>
</tbody>
</table>

3.5 Statistical analysis

For System 5 Nested analysis of variance (ANOVA) was used to estimate the effects of HLR, age of the system and trial on nutrient removal and a simple ANOVA was used to compare plant yields between pairs within trials.
3.6 Water sampling and Chemical analysis

Weekly water samples were collected from System 5. Two 100 ml samples were gathered from locations in the system indicated in Table 3.4. One of the samples was acidified for storage, the other was filtered through a 40µm filter to remove any suspended solids. All samples were frozen and then thawed for chemical analysis NO₂ and NO₃ were measured using the method described in Shand et al. (2008) and Phosphorus was determined using the method described in Murphy and Riley (1962). Mg, Ca and K are currently being measured.

<table>
<thead>
<tr>
<th>Location</th>
<th>Samples</th>
<th>Filtered</th>
<th>Acidified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sump</td>
<td>2x 100 ml</td>
<td>100 ml</td>
<td>100 ml</td>
</tr>
<tr>
<td>fish tank</td>
<td>2x 100 ml</td>
<td>100 ml</td>
<td>100 ml</td>
</tr>
<tr>
<td>Biofilter 1</td>
<td>2x 100 ml</td>
<td>100 ml</td>
<td>100 ml</td>
</tr>
<tr>
<td>biofilter 2</td>
<td>2x 100 ml</td>
<td>100 ml</td>
<td>100 ml</td>
</tr>
<tr>
<td>Bed A1</td>
<td>2x 100 ml</td>
<td>100 ml</td>
<td>100 ml</td>
</tr>
<tr>
<td>Bed A2</td>
<td>2x 100 ml</td>
<td>100 ml</td>
<td>100 ml</td>
</tr>
<tr>
<td>Bed B1</td>
<td>2x 100 ml</td>
<td>100 ml</td>
<td>100 ml</td>
</tr>
<tr>
<td>Bed B2</td>
<td>2x 100 ml</td>
<td>100 ml</td>
<td>100 ml</td>
</tr>
<tr>
<td>Bed C1</td>
<td>2x 100 ml</td>
<td>100 ml</td>
<td>100 ml</td>
</tr>
<tr>
<td>Bed C2</td>
<td>2x 100 ml</td>
<td>100 ml</td>
<td>100 ml</td>
</tr>
</tbody>
</table>

In-situ chemical analysis were performed using Multitest NO₂/NO₃, Multitest Ammonia and Multitest Phosphate also produced by Seachem Laboratories following the instruction manuals (Appendix C). Conductivity, TDS and pH were measured using PCSTestr 35 multi-Parameter device from Eutech Instruments. Dissolved oxygen was monitored with CyberScan DO300 manufactured by Eutech Instruments and maintained over 4mg/l. Iron was measured with HI checker colorimeter iron from Hanna Instruments. Iron was maintained at 0.3 mg/l in all systems by adding Aqualron DTPA Iron Chelate.
4 Results

4.1 System 1

A survey was done on public opinion on aquaponics (Table 4.1). 43 people of the age between 19 and 65 years answered the survey, 32 of which were female and 11 male. 16 of the people had a Bachelors degree whereas 8 had a diploma or lower education and 12 had a higher education level. 5 people did not answer. As seen in Table 4.1 most of the participants showed a positive attitude towards aquaponic production methods and products.

Table 4.1 Results from the survey of public opinion on aquaponics.

<table>
<thead>
<tr>
<th></th>
<th>I Strongly disagree (%)</th>
<th>I mildly disagree (%)</th>
<th>Neutral (%)</th>
<th>I mildly agree (%)</th>
<th>I strongly agree (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I would prefer aquaponic fish</td>
<td>2</td>
<td>7</td>
<td>30</td>
<td>26</td>
<td>35</td>
</tr>
<tr>
<td>I would prefer aquaponic vegetables</td>
<td>2</td>
<td>7</td>
<td>35</td>
<td>33</td>
<td>23</td>
</tr>
<tr>
<td>I would not eat aquaponic products</td>
<td>79</td>
<td>7</td>
<td>12</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>I want to know where my food comes from</td>
<td>2</td>
<td>5</td>
<td>9</td>
<td>35</td>
<td>47</td>
</tr>
<tr>
<td>Aquaponics is ecological</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>37</td>
<td>53</td>
</tr>
<tr>
<td>Aquaponics is sustainable</td>
<td>2</td>
<td>0</td>
<td>7</td>
<td>35</td>
<td>53</td>
</tr>
<tr>
<td>Aquaponics supports better use of resources</td>
<td>2</td>
<td>0</td>
<td>5</td>
<td>30</td>
<td>63</td>
</tr>
</tbody>
</table>

4.2 Systems 2-4

As can be seen in Figure 4.1 the nitrifying bacteria took a month to establish in System 2. This can be seen in the initial TAN spike around week one followed by a decline in TAN concentration and increase in NO₂ which was subsequently exhausted in the system after four weeks, indicating that sufficient amount of nitrifying bacteria had colonized the system to instantly remove TAN and NO₂ as they formed in the system, leaving only NO₃.
System 3 showed the same trend as System 2, with the exception that a spike in TAN concentration never occurred in the system (Figure 4.2). The NO₂ peaked at 5mg/l and was maintained at that level with water exchange seen by a drop in NO₃ concentration at 18.07 and another 2 days later.

Conductivity was measured as an indicator of accumulation of nutrients within the system as the conductivity increases with the addition of ions to the water. Nitrification is an acidifying process and therefore pH should decrease as time progresses. This can be seen in Figures 4.3 and 4.4 where pH decreased by time except for two spikes probably caused
by a malfunction in the measuring equipment. As expected the conductivity of the water increased by time as ions from waste products accumulated in the system.

Figure 4.3 pH and conductivity data for System 2.

Figure 4.4 pH and conductivity data for System 3 in the greenhouse.

Table 4.2 shows how much feed the fish were fed, how much biomass they added, the FCR of the fish and the yield of plants in the system. The fish had an FCR around 1 and the plants grew at a ratio of 1.31 kg plant wet weight per kg of feed input.

Table 4.2 Growth of fish and vegetables in the greenhouse systems.
<table>
<thead>
<tr>
<th>System</th>
<th>Feed (kg)</th>
<th>Fish biomass increase (kg)</th>
<th>FCR</th>
<th>Plant yield (kg)</th>
<th>Plant to feed conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>System 2</td>
<td>2.9</td>
<td>3.2</td>
<td>0.92</td>
<td>3.8</td>
<td>1.31</td>
</tr>
<tr>
<td>System 3</td>
<td>4.0</td>
<td>3.8</td>
<td>1.05</td>
<td>3.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Basil and mint were the only plant species that produced any considerable biomass so the yield numbers are yields for those two species, the plants looked very healthy as can be seen in Figure 4.5. Rucola did very poorly and showed signs of nutrient deficiency (Figure 4.6).

![Figure 4.5 Basil (near) and mint (far) in System 3.](image)

![Figure 4.6 Rucola plant shows deficiency symptoms, healthy basil plant in the back.](image)

Even though no measurements were done in System 4 plants did remarkably well in the System with the plants growing very fast and sprouting numerous fruit (Figure 4.7 and 4.8).
4.3 System 5

Figure 4.9 shows the yield of all runs of the system. The test run included the establishment of nitrifying bacteria in the system and was not expected to give any considerable yield. As can be seen in the Test run and Trial 1, Pairs B and C gave the highest yields, this difference however was not significant (Tables 4.6 and 4.7).
In Trial 2, the temperature in the industrial building decreased and the electronic heating elements did not suffice to heat the system. The temperature was stable at around 17°C. At such low temperatures tilapia stop feeding which is evident in the high FCR shown in Table 4.3. Trial 1 showed good plant to feed conversion of 2.96 kg plant biomass per kg feed.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Feed (kg)</th>
<th>Fish biomass increase (kg)</th>
<th>FCR</th>
<th>Plant biomass (kg)</th>
<th>Plant to feed conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>10.6</td>
<td>9.2</td>
<td>1.2</td>
<td>4.8</td>
<td>0.45</td>
</tr>
<tr>
<td>Trial 1</td>
<td>5.97</td>
<td>4.4</td>
<td>1.4</td>
<td>17.7</td>
<td>2.96</td>
</tr>
<tr>
<td>Trial 2</td>
<td>4.5</td>
<td>0.4</td>
<td>11.1</td>
<td>7.3</td>
<td>1.7</td>
</tr>
</tbody>
</table>

HLR was calculated to show the difference between the pairs, HLR is calculated as flow rate (Q) divided by the surface area of the bed. This is shown in Table 4.4.

<table>
<thead>
<tr>
<th>Location</th>
<th>Q (m$^3$/day)</th>
<th>HLR (m$^3$/m$^2$/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair A</td>
<td>11.76</td>
<td>9.8</td>
</tr>
<tr>
<td>Pair B</td>
<td>3.9</td>
<td>3.26</td>
</tr>
<tr>
<td>Pair C</td>
<td>0.96</td>
<td>0.8</td>
</tr>
</tbody>
</table>

ANOVA was performed to see if there was any significant difference in plant yields within trials, as shown in Table 4.5 and 4.6 the pairs did not differ significantly from each other within trials.
Table 4.5 Results of ANOVA for plant yield between pairs in Trial 1.

<table>
<thead>
<tr>
<th></th>
<th>Sum Sq</th>
<th>Df</th>
<th>Mean Sq</th>
<th>F</th>
<th>Pr (&gt;F)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between</td>
<td>2382734</td>
<td>2</td>
<td>1191367</td>
<td>4.77</td>
<td>0.12</td>
<td>NS</td>
</tr>
<tr>
<td>Within</td>
<td>748747</td>
<td>3</td>
<td>249582</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.6 Results of ANOVA for plant yield between pairs in Trial 2.

<table>
<thead>
<tr>
<th></th>
<th>Sum Sq</th>
<th>Df</th>
<th>Mean Sq</th>
<th>F</th>
<th>Pr (&gt;F)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between</td>
<td>62440.33</td>
<td>2</td>
<td>31220.167</td>
<td>0.066</td>
<td>0.94</td>
<td>NS</td>
</tr>
<tr>
<td>Within</td>
<td>1413623</td>
<td>3</td>
<td>471207.67</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N-Species and Phosphate concentration were measured at different locations within system 5. Figures 4.10-4.12 show the trends in nutrient concentration throughout Trial 1. As the figures show the nutrients follow the same main trends. TAN concentration remained high throughout the trial.

Figure 4.10 Nutrient concentrations in Pair A in Trial 1.
Figure 4.11 Nutrient concentrations in Pair B in Trial 1.

Figure 4.12 Nutrient concentrations in Pair C in Trial 1.
As can be seen in Figure 4.13, conductivity, TDS and pH stabilize around Week 4, this plateau is concurrent with a sudden increase in plant growth. Pak-choi did not show even growth throughout all the trials, for the first two weeks there was slow growth after which the plants showed very rapid growth, this is shown in Figure 4.14 where two photos are taken of the same bed 9 days between.

Figure 4.13 Conductivity (EC) TDS and pH for the system in Trial 1.

Figure 4.14 Photos of bed B1 taken 9 days in between showing rapid growth in pak-choi.
TAN remained high throughout the course of Trial 1. In between trials, the amount of biofilters was doubled, resulting in lower TAN than in Trial 1 as can be seen in Figures 4.15 – 4.17 (peaking around 10 mg/l in Trial 1 vs 7 mg/l in Trial 2). The drop in NO₃ concentration between weeks 2 and 3 is likely caused by mistakes made with the automatic feeder.

![Figure 4.15 Nutrient concentration in Pair A in Trial 2.](image1)

![Figure 4.16 Nutrient concentrations in Pair B in Trial 2.](image2)
When looking at pH, conductivity and TDS for the system (Figure 4.18) pH drops between weeks 1 and 3 and rises again from week 3 to 5. This is concurrent with the drop in NO₃ between weeks 2 and 3 (Figures 4.15 to 4.17). The little increase in conductivity and TDS between weeks 2 and 3 is explained by a mistake made with the automatic feeder.
In Trial 1 every bed in the system had good growth as can be seen in Figure 4.19.

A nested ANOVA was performed to see if HLR, week of sampling or Trial had any significant effect on nutrient removal within each bed. As Tables 4.7 through 4.10 show, no significant difference was noticed.

**Table 4.7 Results of Nested ANOVA for effects of trials, weeks or HLR on TAN removal.**

<table>
<thead>
<tr>
<th></th>
<th>Df</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>1</td>
<td>230.1</td>
<td>230.12</td>
<td>3.73</td>
<td>0.63</td>
<td>NS</td>
</tr>
<tr>
<td>Trial:week</td>
<td>1</td>
<td>89.7</td>
<td>89.68</td>
<td>1.45</td>
<td>0.24</td>
<td>NS</td>
</tr>
<tr>
<td>Trial:Week:HLR</td>
<td>2</td>
<td>11.2</td>
<td>21306</td>
<td>0.09</td>
<td>0.91</td>
<td>NS</td>
</tr>
<tr>
<td>Residuals</td>
<td>32</td>
<td>1913.2</td>
<td>61.72</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.8 Results of Nested ANOVA for effects of trials, weeks or HLR on NO₂–N removal.**

<table>
<thead>
<tr>
<th></th>
<th>Df</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>1</td>
<td>35</td>
<td>35.1</td>
<td>0.14</td>
<td>0.71</td>
<td>NS</td>
</tr>
<tr>
<td>Trial:week</td>
<td>1</td>
<td>341</td>
<td>341.5</td>
<td>1.33</td>
<td>0.26</td>
<td>NS</td>
</tr>
<tr>
<td>Trial:Week:HLR</td>
<td>2</td>
<td>208</td>
<td>103.8</td>
<td>0.41</td>
<td>0.67</td>
<td>NS</td>
</tr>
<tr>
<td>Residuals</td>
<td>32</td>
<td>7936</td>
<td>256.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.9 Results of Nested ANOVA for effects of trials, weeks or HLR on NO₃–N removal.**

<table>
<thead>
<tr>
<th></th>
<th>Df</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>1</td>
<td>377</td>
<td>376.9</td>
<td>2.29</td>
<td>0.14</td>
<td>NS</td>
</tr>
<tr>
<td>Trial:week</td>
<td>1</td>
<td>26</td>
<td>25.9</td>
<td>0.16</td>
<td>0.69</td>
<td>NS</td>
</tr>
<tr>
<td>Trial:Week:HLR</td>
<td>2</td>
<td>5</td>
<td>2.3</td>
<td>0.01</td>
<td>0.99</td>
<td>NS</td>
</tr>
<tr>
<td>Residuals</td>
<td>32</td>
<td>5092</td>
<td>164.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.10 Results of Nested ANOVA for effects of trials, weeks or HLR on PO₄-P removal.

<table>
<thead>
<tr>
<th></th>
<th>Df</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>1</td>
<td>94.9</td>
<td>94.91</td>
<td>1.940</td>
<td>0.174</td>
<td>NS</td>
</tr>
<tr>
<td>Trial:week</td>
<td>1</td>
<td>130.7</td>
<td>130.69</td>
<td>2.672</td>
<td>0.112</td>
<td>NS</td>
</tr>
<tr>
<td>Trial:Week:HLR</td>
<td>2</td>
<td>114.7</td>
<td>57.34</td>
<td>1.172</td>
<td>0.323</td>
<td>NS</td>
</tr>
<tr>
<td>Residuals</td>
<td>32</td>
<td>1516.3</td>
<td>48.91</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.4 System 6

Table 4.11 shows the growth of plants and fish in the System 6, in these calculations total plant biomass was used to compensate for vegetative growth which was a big part of the growth in the system.

Table 4.11 Growth of fish in System 6.

<table>
<thead>
<tr>
<th>Feed (kg)</th>
<th>Fish biomass increase (kg)</th>
<th>FCR</th>
<th>Plant biomass (kg)</th>
<th>Plant to feed conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>3.7</td>
<td>1.5</td>
<td>20.6</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Table 4.12 shows what the plant biomass in System 6 consisted of. As vegetative growth was a large part of the overall growth in the system it was calculated into the total mass of plants to compensate for it and to get an idea what the biomass could have been if vegetables had been grown instead of fruit.

Table 4.12 An explanation of plant biomass for System 6.

<table>
<thead>
<tr>
<th>Fruit (kg)</th>
<th>Trimmings (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomato</td>
<td>10.8</td>
</tr>
<tr>
<td>Okra</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 4.13 comes from an unpublished article by Atlason et al. where EROI was calculated for Systems 5 and 6 and another system built by the company BREEN in Spain. As the table shows a very high EROI for Akur (System 6) where no direct heating or artificial light was used in the system in the summer time.

Table 4.13 EROI results for the first 10 years of systems compared (Atlason et al., n.d. Table 2 included with authors permission).

<table>
<thead>
<tr>
<th>Year</th>
<th>Hondarribia</th>
<th>Sudarvogur</th>
<th>Akur</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.036</td>
<td>0.006</td>
<td>0.085</td>
</tr>
</tbody>
</table>
Plants in the system produced well. A drawback in the system caused feeding to be ceased for 2 weeks. This caused phosphorus to be depleted in the systems and stunted growth in the plants. The fruit that already had formed on the plants all matured normally. Figures 4.20 and 4.21 show the plants in the system around the end of the experiment.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.045</td>
<td>0.007</td>
<td>0.099</td>
</tr>
<tr>
<td>3</td>
<td>0.049</td>
<td>0.007</td>
<td>0.102</td>
</tr>
<tr>
<td>4</td>
<td>0.051</td>
<td>0.008</td>
<td>0.104</td>
</tr>
<tr>
<td>5</td>
<td>0.052</td>
<td>0.008</td>
<td>0.105</td>
</tr>
<tr>
<td>6</td>
<td>0.053</td>
<td>0.008</td>
<td>0.106</td>
</tr>
<tr>
<td>7</td>
<td>0.054</td>
<td>0.008</td>
<td>0.107</td>
</tr>
<tr>
<td>8</td>
<td>0.055</td>
<td>0.008</td>
<td>0.107</td>
</tr>
<tr>
<td>9</td>
<td>0.055</td>
<td>0.008</td>
<td>0.107</td>
</tr>
<tr>
<td>10</td>
<td>0.055</td>
<td>0.008</td>
<td>0.108</td>
</tr>
</tbody>
</table>

Figure 4.20 Tomato plants in System 6, bearing many fruit.
Figure 4.21 Okra plants in System 6. A seed pod and a flower can be seen at center-left of the image.
5 Discussion

System 1. The Showcase system, has been a successful demonstration of the necessity of proper solids removal. For the first year there were no visible effects but early in 2015 fish started showing symptoms of deficiencies and stress. Instability in water conditions was caused by buildup of solids in the system and following a cleaning of the substrate media there was an ammonia spike that had to be remedied by rapid water changes for 3 consecutive days. After the addition of a settling tank a considerable amount of solids has been removed from the system. Worms (*Eisenia fetida*) were added to the media bed to aid with mineralization of the solids accumulating in the media and in the settling tank were seven red-clawed-crayfish that constantly sifted through the accumulated solids. The settling tank where the crayfish lived had a bottom area of around 1m² and was littered with PVC pipes for shelter. Some aggression and cannibalism was noted in the crayfish indicating that they feel confined, this could be remedied by adding more pipes and hiding places for them as stocking densities of up to 60 crayfish per m² should be feasible for breeding them (Barki & Karplus, 2000). Adding more pipes could also aid in catching solids and minimizing direct current within the settling tank. Leafy green plants have performed well in the system especially basil which produced enough to be distributed promotionally. Fruit bearing plants did not thrive as well. Tomatoes rarely flowered with around one flower per month. Okra showed mostly vegetative growth in the system. The low productivity of fruit bearing plants is likely due to the stable warm conditions in the office and unfavourable nutrient profile in the system. In April 2015 plants started showing symptoms of stress again. Chlorosis, often associated with Fe deficiency was noted. Fe was measured at 1mg/L in the water column A thorough cleaning of the media was done revealing large amounts of accumulated solids in the media. Following the cleaning the deficiency symptoms disappeared leading to suspicion of salt stress or other unfavourable conditions forming in the growing medium. Salt stress increases suberization of root endothelium leading to the plants stopping active absorption of nutrients (Barberon et al., 2015).

In Systems 2 and 3 rucola showed purple leaves and stunted growth which are symptoms of phosphorus deficiency (Bradley & Hosier, 1999). When measured, phosphorus was in good supply (3 mg/L) in the water and the water pH was 6.4. Phosphorus uptake is pH sensitive (Bradley & Hosier, 1999) so suspicion rose that the pH within the peat insert was too low. A supporting argument for that was that the plants which showed signs of deficiencies had no roots outside the insert and were therefore not in direct contact with the water. A decision was made to add CaCO₃ additive, Hafkorn (ingredients in Appendix A), to the system. The symptoms of deficiency disappeared partly even though some of the plants did still show stunted growth. Those that did best managed to sprout roots outside the peat and into the water leading to the assumption that the pH in the peat was too low to allow for proper nutrient uptake and healthy growth.

There was a noticeable amount of solids in all of the growbeds in the systems underlining the necessity for better solids removal. In the end the roots on some of the plants in System 2 became clogged and rotted away. In one instance in the greenhouse systems hydrogen sulphide smell was noticed in one of the growbeds indicating anaerobic conditions within
the sediment. This could have been alleviated by both increasing solids filtration and by increasing water movement in the growbeds to keep the solids in suspension instead of accumulating in the beds. Where the hydroponic part of the system is small solids should be removed from the system as they are far in excess of what the plants will manage to regulate (Rakocy, 1999).

After slaughtering fish from Systems 2 and 3 it became evident that the charr feed might not be suitable for them. Tilapia mainly collect fat in visceral adipose tissue (He et al., 2015) in fact the internal organs were all combined in a white mass of fat that had to be removed to view the organs. The decision was made to switch to a lower fat feed than charr feed (17% Cod feed vs 23% Charr feed) this would still be considered a high fat feed for tilapia with 5 – 7.4 % fat being the optimum (He et al., 2015).

In System 5 the beds with the fastest flow showed the least biomass produced and also the most solids buildup. Even though not measured there were visibly more solids that covered the roots of these plants, especially in the Test run and Trial 1. The slower flow beds, pairs B and C, produced more biomass, and had less solids built up on the roots. After officially ending Trial 1 the plants were put back in the system with their protruding roots removed. In a week the plants in all beds showed a minor increase in growth with healthy root growth also, indicating that solids buildup was having negative effect on them.

There was no significant difference found in mass due to HLR in the beds (Tables 5.3 and 5.4). Light and temperature were different between the two trials and made the largest contribution to the difference in mass between those two. Sudden drop in NO₃ between weeks 2 and three in Trial 2 is probably due to a mistake made with the automatic feeder as the feeder looked half full when in fact it was clogged and therefore no feed was added to the system for that week, interestingly, no drop in TAN concentration was observed.

No weekly measurements of plants were made so the contribution of weekly growth on nutrient content could not be evaluated. Plant growth, however, was not linear, the plants stayed small for around 2-3 weeks and suddenly showed a rapid growth. The production cycle of the plants from seed to harvest took 6 weeks and yielded 1.01 (Trial 2) - 2.45 (Trial 1) kg/m². This yield is within the same variable yields found for lettuce in aquaponics (1.4 - 6.5 kg/m²) (Rakocy et al., 1997; Seawright et al., 1998). Pak-choi can be very fast growing and demand after fresh pak-choi has grown with the diversifying population of Iceland. The success of pak-choi also underlines the success of leafy green vegetables grown in aquaponic systems and indicates that even more, commercially valuable, species with similar requirements can be successfully grown in this kind of system. There was no significant difference in plant nutrient removal between trials, beds nor HLR, the largest contributing factor on plant mass was light, as in Trial 1 ambient light was present through windows leading to to the suspicion that the hydroponic part of this system could have been larger with lower HLR rates to support more production than seen in this system. This is further supported by the fact that NO₃ and PO₄ concentrations continued to rise and the nutrient utilization of the plants present in the system was therefore not enough to regulate the nutrient concentrations (Rakocy, 1999).

The statistical tests done in System 5 are of little quality as the sample size (2 trials) was very low. Further research with a larger sample are needed to give conclusive results.
The okra plants in **System 6** could have produced more seed pods than they did. The flowers would close and fall off as expected but the developing pods would die within two days with less than 30% reaching harvest size. There was a drawback in the system where feeding had to be stopped for two weeks and two weeks later the irrigation pipe to the hydroponic unit was clogged for a whole day putting the plants under water stress from evaporation. These drawbacks could have played a role in the plants sacrificing their pods as reduced yield is a consequence of water stress (Gunawardhana & Silva, 2011). At the same time the tomato plants were in full bloom and started showing deficiency symptoms such as stunted growth in the plants themselves along with purple leaves. When water tests were done phosphate was nonexistent in the system which was in accordance with the deficiency symptoms (Bradley & Hosier, 1999). Flowering of the plants promptly halted yet the tomatoes, which had already formed, all matured normally leading to the suspicion that if the irrigation and feeding would have continued as normal the production would have been much better. Also bees were always present in the greenhouse so lack of pollination is an unlikely cause. A decoupled system as described in Thorarinsdottir et al. (2015) would have allowed for treatment of the fish system without negative effects on the plants as they could have been supplemented in separation from the fish.

The EROI results show that building the system inside a greenhouse is more energy efficient than building in an industry building with traditional artificial lighting. These results though would only be relevant to summer time as the test was carried out in summer where no artificial lighting was used in the Akur system. Artificial lighting with LED lamps might help with more energy efficient system, LEDs have a longer lifespan and do not produce large amounts of radiant heat as traditional HPS and MH lamps do. Also LED is very customizable as the spectrum of light can be easily tampered with by increasing or decreasing the ratio of red vs blue LEDs. The energy efficiency of LED lamps is dependent on lamp design as blue LEDs use more energy than red LEDs do (Currey & Lopez, 2013). LED lamps also allow for better spatial utilization by stacking growbeds vertically with low profile lighting units suspended beneath the beds. Heat from LED lamps can in that way be used for heating the water in the system.

The FCR of the fish is lowest in Systems 2 and 3 and highest in Trial 2 in System 5. This can be contributed to two factors; the initial size of the fish and temperature. In Systems 2 and 3 the temperature was at all times higher than 21°C and the fish were at a small size of less than 100 g per individual. In Trial 1 in System 5 temperature was stable at 21°C but the fish were a lot larger 250g< but still growing considerably fast. Troubles with temperature regulation in Trial 2 likely contribute the most to the slow growth of the fish in the system as tilapia feeding and metabolism slows at temperatures below 20°C (Rakocy, 1999). The FCR of 1.0-1.5 is within the range often experienced with tilapia. The fish were fed with feed that had a very high protein and fat content.

For better TAN removal for high protein feed at high stocking densities setting up a larger biofilter would be necessary, perhaps a fixed bed filter or a moving bed filter with a larger surface area. Moving bed filters do not react as well to elevated ammonia levels as fixed bed filters. This could be contributed by the factor that biofilm is constantly being rubbed off the outer surface of the biomedia (Suhr & Pedersen, 2010). This was evident, both in the Industry building system in Reykjavik and in the Pilot commercial unit as no NO₂ was present in the system but TAN levels remained high. A low rate of nitrification could also be due to the low pH, even though it has been shown that a high rate of nitrification can be achieved at pH as low as 4.3 (Tarre & Green, 2004).
Systems 5 and 6 both would have needed a larger hydroponic unit and might have benefitted from being designed in a decoupled manner. That way nitrogen levels in the fish tank could have been kept at more desirable levels. Due to the low pH of System 5 the high TAN concentration was most likely in the form of NH$_4^+$ which is less harmful for fish (Randall & Tsui, 2002). Also a long exposure to high levels of nitrate can have a negative effect on hemoglobin in the fish (Jensen, 1996). CO$_2$ addition increases photosynthesis in the plant, increasing nitrogen uptake, whereas the fish rearing system design aims to minimize CO$_2$ levels within the system as increased CO$_2$ impairs the growth of the fish (Stiller et al., 2015).

The visitors to the systems have been from diverse groups, e.g. young children, high school and university students, entrepreneurs, researchers, aquaculture and horticulture people, policy advisors and people from government and municipalities, such as the US ambassadeur and the president of Iceland. The results of the survey show that people have a positive opinion on aquaponics. More people in Iceland are becoming environmentally conscious and want to know where their food comes from and how it was produced.

The results have been presented at Aquaculture Europe 2014 in Spain, at the Science Day at the University of Iceland in September 2015, at a seminar in Reykjavik in June 2015, at the COST training programme held at Solheimar Iceland in September 2015 and at the Icelandic Biology conference in October 2015, see Appendix B.
6 Conclusions and recommendations.

Both feed types used in this research were too high in fat and protein leading to fat deposits around the visceral organs of the fish and very high TAN concentrations in the water and would not be considered suitable for tilapia production. Pak-choi gave a good yield:feed ratio of 3:1 which is suspected to be even higher in a larger hydroponic unit. No significant effects of water flow on plant growth and nutrient uptake were measured leading to the conclusion that the hydroponic production part of system 5 could have been larger than it was.

The failure of fruiting plants in this research is more related to system flaws than suitability issues as tomatoes and okra are known to show good yields in aquaponic production.

For establishing Aquaponic systems for industrial production I give these following recommendations on system design based on the findings of this research.

1. Good particulate filtration is necessary. This could be done with a combination of a settling tank, to remove larger particles and a microscreen drum filter, as in System 6, to remove the finer matter. All of the systems built showed some accumulation of solids in the hydroponic beds, the least solids were encountered in System 6 which had the most effective filter.

2. NFT systems are more vulnerable to mishaps than DWC and F&D systems. In the case of pump failure the NFT have very little water present at the roots of the plants whereas DWC has the roots submerged in water and the substrate in the F&D beds has very good moisture retention. For the longevity of the F&D system the bed has to be cleaned regularly as solids will build up in the media, regardless of filtration methods, and are hard to flush out without manually removing and rinsing the media.

3. For lower TAN concentration feed with a lower protein content than used in this experiment would be more feasible, This could also be done by improving biofilter design e.g. by using media that has a larger surface area. Another way of dealing with this would be removing more of the solids from the system mineralizing them in a separate container before releasing nutrients back into the system.

4. For less compromise between optimal conditions for fish rearing and hydroponic plant production a decoupled design would be preferred as the plants prefer higher nutrient and CO₂ concentrations, both of which have negative effect on the fish.

5. Leafy green vegetables with similar requirements as lettuce and pak-choi might be a good choice for production in a larger scale system. Further research into plant choices looking into current hydroponic production is necessary.
References


Appendix A feed and additive ingredients

Ingredients of char feed
Ingredients of cod feed
Hafkorn CaCO$_3$ supplement ingredients

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>CaCO$_3$</td>
<td>85%</td>
</tr>
<tr>
<td>Magnesium</td>
<td>MgO</td>
<td>11.5%</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>P</td>
<td>0.8%</td>
</tr>
<tr>
<td>Potassium</td>
<td>K</td>
<td>0.1%</td>
</tr>
<tr>
<td>Sulfur</td>
<td>S</td>
<td>0.045%</td>
</tr>
</tbody>
</table>

and other minerals
Appendix B Posters and other material
An informational Poster for public presentation at the University of Iceland

Samrækt
(Aquaponics)

Regnar Íngi Davur og
Regnbúðar Ínga Hornsundar
Oktober 2014

Hvort er Samrækt?
Somrækt er (A. Aquaponics) er rekkinsemitt hefur þannig semvinnið fiskið (Aqua-culture) og vatnsemitt á gømmari (A. Hydroponics). Athafstvöruð er hefur því til þess að fiska í vatnnum varða ekki þeim semvinni ásamt þess að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við að skera að því að þau séu ekki því við a
Optimizing aquaponics

Ragnar Ingi Dannevig og
Ragnhildur Inga Pálsdóttir

October 2015

A poster for the Icelandic Biology conference 2015

What is Aquaponics?

Aquaponics is a food production method combining aquaculture with hydroponics. Aquacultural wastewater has nutrients that can cause eutrophication in nature. Aquaponics uses these nutrients for growing vegetables or other useful plants. By recycling nutrients, water and energy, aquaponics implements a more sustainable food production.

A deep water culture system where the plants are cultured in rafts that float over a waterbed. The roots are suspended in water and draw nutrients from there. Salad and other plants that don’t need support are commonly grown this way.

Aim of the research:

The aim is to optimize the growth rate of Pak Choi (Bassia rapa var. Chinensis) in a deep water culture aquaponic system, mainly focusing on flow rate through the grow beds. A schematic illustration of the system can be seen in figure 1.

Methods

Tilapia (Oreochromis niloticus) are grown in a tank where they are fed daily. The water is filtered mechanically, in the sedimentation tank, and biologically, in the biofilters (blue circles in figure 1). The water then flows to the growbeds which are set up as pairs. Each pair has the same flow rate but different pairs have different flow rates. Pair A has the highest flow rate (420-450 l/hr), Pair B has medium flow rate (140-160 l/hr) and pair C has the lowest flow rate (40-60 l/hr) from the beds the water goes to the nump where it is pumped back into the fish tank, closing the cycle.

Results

Preliminary results show that the beds with the fastest flow rate are the least productive. As of now nutrient values for the beds are not ready. Fish are growing at the rate of 1 kg biomass added per 1.5 kg feed and the plants, as a whole, are growing at the rate of 4 kg biomass per 1 kg feed.

Figure 1: A schematic overview of the system

Figure 2: A photograph taken from the last growbed (C2), the fish tank can be seen in the background (Oliver Holmy, 2015)

What is left to do?

Proper measurement of water parameters and nutrients which are still being processed from water samples gathered from the system, statistical analysis of the results is also not finished. The results displayed here are therefore not final.

Figure 3: Tilapia

Acknowledgements:

Special thanks go to Marvin Ingi Einarsson for assistance with measurements and the building of the system. Ulla Mankinsh for assistance and guidance in water quality measurements. Ísak Mar Jóhannesson, Olafur Pétur Þulsson, Bjarar Þórðarson and Soffía Karen Magnúsdóttir for assisting with feeding and monitoring. Ragnhildur Inga Bœurísdóttir my instructor and Kesara Anamathurahidi my supervisor.

References:

Certificate of attendance in COST training school FA1305

Certificate of Attendance
Presented to
Ragnar Ingi Danner
For attending the
Training School on Commercial Aquaponics
Organized by the University of Iceland
On September 8th-12th 2015
at Solheimar Esoyvillage

This participant was awarded with a grant funded by the FA COST Action FA1305 The EU Aquaponics Hub – Realising Sustainable Integrated Fish and Vegetable Production for the EU.

Dr. Beng Holmen
University of Greenwich
Chair of the Action FA1305
Confirmation of abstract acceptance for Aquaculture Europe 2014.

-------- Original Message --------
Subject: Abstract Acceptance
Date: Sunday, May 4, 2014 23:53 GMT
From: John Cooksey <admin@was.org>
To: <rth@hi.is>

To: Dr Ragnheidur Thorarinsdottir  Abstract ID# 352
     (This message is for your information only. Please do not reply to this email.)

Re: Abstract submission for AQUACULTURE EUROPE 14
     (to be held in San Sebastián, Spain - October 14-17, 2014)

This is your OFFICIAL NOTICE that the Program Committee of AQUACULTURE EUROPE 14 has ACCEPTED your abstract for presentation. The exact presentation assignment will be sent in August 2014. You will be sent a notice of the session, day and time for your presentation after assignment has been made.

PLEASE PROOFREAD THE INFORMATION LISTED BELOW CAREFULLY.
   *If you find an error in the abstract title or author names, you must inform us if a correction is to be made. Conference Management will not be held responsible for errors or omissions made in the transmittal form or the abstract as submitted. Italics and special characters will appear in the final publication, as they do not always translate via email. Professional titles will not be used with author names.

   *Abstract Title: IMPLEMENTING COMMERCIAL AQUAPONICS IN EUROPE - FIRST RESULTS FROM THE ECOINNOVATION PROJECT ECOPONICS

   *Presenting Author: Ragnar Ingi Danner

   *Co-Authors: Ragnheidur Thorarinsdottir

Presentation Method selected: Oral Preferred

Abstract Topic selected: Aquaponics

LANGUAGE:
   All abstracts must be presented in English - the official language of this conference.

CANCELLATION:
   If you are not going to attend AQUACULTURE EUROPE 14, please contact this office to withdraw your abstract.
Lecture schedule for a short course on aquaponics in June 2015

Námskeið í Aquaponics - samest þann 10. júní 2015.

13:00-13:30 Heildur þáttarafall: Stjórnungur Athabaska
13:30-14:00 Val í þáttrum av Ragnhildur Þorarinsdottir
14:00-14:30 Vatnsleiðingur: Ingibjörg Ólafsdóttir
14:30-15:00 Kortlið: Ólafur Ingriðarson
15:00-15:30 Breiðavöld: Sólrún Þorodóttir
15:30-16:00 Reykjavík: Kjartan Þorvaldsson
16:00-16:30 Flokkur: Örvar Björnsson
16:30-17:00 Samankomst: Konan Hjartarson
17:00-18:00 Fólkakápi

Allt velkomn

Þúttakugildi 5.900. Kaffi innflétt.
Energy return on investment of Icelandic and Spanish aquaponics systems

R.S. Atlason, R.I. Danner, R. Unthorsson, G.V. Oddson, F. Sultaeta, R. Thorarinsson

*University of Southern Denmark, Institute of technology and innovation, Campusvej 55, 5000 Odense, Denmark

1 University of Iceland, Faculty of life and environmental sciences
2 University of Iceland, Faculty of industrial engineering, mechanical engineering and computer science
3 Danish, Decided on Green Ltd.
4 University of Iceland, Faculty of civil and environmental engineering

Abstract

Energy use in food production is closely linked to environmental impact as many agricultural practices are heavily reliant on fossil fuels. It is therefore of importance to locate food production methods that are less energy intensive than current methods and are less polluting. Energy return on investment (EROI) is the ratio between the energy used to construct and maintain a given system, against the energy that is provided by the system. For this study, three aquaponics systems were constructed to analyse their operational performance. Two systems are located in Iceland, while one is located in northern Spain. The EROI for the aquaponics systems is explained and calculated. The EROI results show that the Ilondarriba system delivered an EROI of 0.055 after 10 years of partially simulated operation. The Icelandic system in Súðavögu had an EROI of 0.019 after 10 years of partially simulated operation, while the Icelandic system in Akkr returned an EROI of 0.103. This indicates that aquaponics operations benefit from operating within a greenhouse and that direct electricity consumption is the largest contributor to energy consumption in the aquaponics systems.

1. Introduction

Production of fish is expected to increase by 19% from the period 2013-2014 to 2024 [1]. Most of this increase is expected to be the result of increased aquaculture production. In 2024, the FAO expects that aquaculture will contribute 66 Mt of the global 101 Mt fish production. In fact, according to the FAO, aquaculture production surpassed conventional fisheries in raw output for the first time between 2012 and 2014. Per capita consumption of fish per year globally is also expected to increase from 12.7 kg in 2012 to 21.5 kg in 2024. FAO states that future consumption of fish will inevitably be highly dependent on aquaculture [1]. This is of little surprise as the rate of global consumption has increased, especially since late 1990s. In Figure 1 it can be seen that fish consumption has grown proportionally with global population. However, around 1005 the previously mentioned increase in fish production can be seen as production rate increase greatly.

*Principal corresponding author, Tel.: +45-21051122
Email addresses: raudditi.sdu.dk (R.S. Atlason), ragger_danner@gmail.com (R.I. Danner), ronunthorsson@hi.is (R. Unthorsson), grothi@is (G.V. Oddson), frestastafa@is.is (F. Sultaeta), svinsvatina.is (R. Thorarinsson)

Preprint submitted to Elsevier

November 30, 2015
Appendix C Test kit user manuals.

Free & Total Ammonia

Free Ammonia Test
1. Fill sample pipette to base of bulb and dispense to test cavity of the test plate.
2. Unscrew the cap from the sensor container and remove a sensor using the supplied forceps, rinse with clean water, and place in the test cavity containing the sample. To avoid damaging sensors, do not handle with bare fingers. Use the supplied forceps to manipulate sensors. Avoid excessive pressure.
3. Read after 10-15 minutes from bottom scale (less sensitive) or after 30 minutes from top scale (more sensitive) in mg/L.
4. On completion of tests, rinse sensors, and return to their container where they will regenerate within a few hours.

Total Ammonia Test
1. Fill sample pipette to base of bulb and dispense to test cavity of the test plate.
2. Unscrew the cap from the sensor container and remove a sensor using the supplied forceps, rinse with clean water, and place in the test cavity containing the sample. To avoid damaging sensors, do not handle with bare fingers. Use the supplied forceps to manipulate sensors. Avoid excessive pressure.
3. Add one drop of Total Ammonia Reagent.
4. Read after 10-15 minutes from bottom scale (less sensitive) or after 30 minutes from top scale (more sensitive) in mg/L.
5. On completion of tests, rinse sensors, and return to their container where they will regenerate within a few hours.

Reference test
The proper performance of this kit may be validated by running a total ammonia test in the normal manner except that the reference sample is used in place of a aquarium sample. It is not necessary to run a reference test to use this kit. The only time you might choose to run a reference test is if you have cause to believe the test is giving incorrect results. If you run a test using the reference sample and obtain the correct result (based on the known reference value provided), then you know the test is giving correct results. To run a reference test use the Total Ammonia Reagent on the sample in a total ammonia test. Reference value is 1.0 mg/L.

Hints
Readings before 15 minutes or low ammonia concentrations may show an uneven color or a darker color on one side of the sensor. The correct color is the darker shade. If color response is off scale, run test on sample diluted with distilled water. Dilution may be prepared directly in test cavity: for example, use 5 drops of sample with 5 drops of distilled water, multiply result by 2; use 2 drops of sample with 6 drops of distilled water, multiply result by 3, etc. The sensors are small, yellow discs and may occasionally stick to the container lid. In rare cases, the blotter paper in the sensor container may get wedged to the underside of the lid and will hide the sensors; simply remove the blotter paper with the forceps to reveal the sensors.

Interpretation
This kit may be used with freshwater or marine water. Unlike other kits on the market, the chemical basis for this test assures that interference from other substances is highly unlikely. The values reported by this kit are expressed as ammonia, not nitrogen. To convert to nitrogen multiply by 0.52. Ammonia is toxic and should be undetectable in any well-established aquarium. During cycling (i.e., initial aquarium set-up stage), it may exceed 20 mg/L. Ammonia exists in two forms, free ammonia (NH₃) and ionized ammonia (NH₄⁺). In an equilibrium dependent on pH. Of the two, free ammonia is the most toxic and increases proportionately to increasing pH.

WARNING
KEEP AWAY FROM CHILDREN! The Total Ammonia Reagent of this kit contain strong acid and the sensor storage/ regeneration gel contains a strong acid. Either may be hazardous if used carelessly. If accidental spillage or contact occurs, wash exposed area thoroughly with water. If eye injury occurs, rinse eyes immediately with water for 10 minutes and then seek medical attention.

This insert is an integral part of this kit and must not be separated from it.

953-042 © 2006, Seachem Laboratories, Inc. • Mableton, GA 30126 • 800-SEACHEM • www.seachem.com • Made in the USA
Nitrite & Nitrate

Nitrite test
1. Fill sample pipette to base of bulb and dispense to a test cavity of the test plate. Repeat, adding to same cavity.
2. Add one drop of Nitrite Reagent 1.
3. Compare to color chart (top scale) after 3-5 minutes.
4. Promptly dispose of completed test solutions by rinsing test cavity under running water.

Nitrate test
1. If you have just run a nitrite test, you can jump to Step 3, otherwise, fill sample pipette to base of bulb and dispense to a test cavity of the test plate. Repeat, adding to same cavity.
2. Add one drop of Nitrite Reagent 1.
3. Add one level scoop of Nitrate Reagent 2. Stir to mix. It is normal for not all powder to dissolve.
4. Compare to color chart (bottom scale) after 5-8 minutes.
5. Promptly dispose of completed test solutions by rinsing test cavity under running water.

Reference test
The proper performance of this kit may be validated by running a nitrate test in the normal manner except that the reference sample is used in place of aquarium sample. It is not necessary to run a reference test to use this kit. The only time you might choose to run a reference test is if you have cause to believe the test is giving incorrect results. If you run a test using the reference sample and obtain the correct result (based on the known reference value provided), then you know the test is giving correct results. To run a reference test use the Nitrate Reference as the sample in a nitrate test. Reference value is 10 mg/L.

Hints
If the test plate becomes stained, soak or clean with a dilute bleach cleaner then rinse well. It may be difficult to thoroughly clean Nitrate Reagent 2 from the test plate. This could cause some nitrites to be measured as nitrites. For that reason, you may wish to reserve some cavities of your test plate for nitrite use only, i.e., never use Nitrate Reagent 2 in those cavities. If necessary, Nitrate Reagent 2 may be purged by soaking test plate in vinegar overnight. If color response is off scale, run test on sample diluted with distilled water. Dilution may be prepared directly in test cavity; for example, use 14 drops of sample with 14 drops of distilled water, multiply result by 2; use 4 drops of sample with 24 drops of distilled water, multiply result by 7, etc. If you have any nitrates present, note the corresponding nitrate value for that color, then subtract that from the final nitrate value you obtain.

Interpretation
This kit may be used with freshwater or marine water. The values reported by this kit are expressed as nitrite (NO₂⁻) and nitrate (NO₃⁻), not nitrogen. To convert to nitrogen divide by 3.3 and 4.4, respectively. Nitrite is toxic and should be undetectable in any well established aquarium. During cycling, it may exceed 20 mg/L. Nitrate is relatively non-toxic, but it is advantageous to control it to under 20 mg/L.

WARNING
Keep away from children!

KEEP AWAY FROM CHILDREN!

Components of this kit contain acids and organic solvents and may be hazardous if used carelessly. If accidental spillage or contact occurs, wash exposed area thoroughly with water. If eye entry occurs, rinse eyes immediately with water for 10minutes and then seek medical attention.

This insert is an integral part of this kit and must not be separated from it.

**Phosphate**

**Instructions**

1. Fill sample pipette to base of bulb and dispense to a test cavity of the test plate.
3. After about 5 seconds to 30 seconds (or time frame that produces good matching with scale), compare color to chart to determine concentration.
4. Promptly dispose of completed test solutions by rinsing test cavity under running water. If the test plate becomes stained, soak or clean with a dilute bleach cleaner, then rinse well.

**Reference test**

The proper performance of this kit may be validated by running a test in the normal manner except that the reference sample is used in place of a aquarium sample. It is not necessary to run a reference test to use this kit. The only time you might choose to run a reference test is if you have cause to believe the test is giving incorrect results. If you run a test using the reference sample and obtain the correct result (based on the known reference value provided) then you know the test is giving correct results. To run a reference test, use the Phosphate Reference as the sample in a phosphate test. Reference value is 1.0 mg/L.

**Hints**

Sample volume is critical: you must use exactly one full stem of sample. Low phosphate levels generally develop faster (5-10 seconds) while higher levels take a bit longer (30 seconds). This kit is designed to measure low phosphate concentrations (< 0.05 to 3 mg/L). Very high concentrations will cause a precipitation of the reagent and consequently could be mistaken for a low reading. The appearance of tiny black or blue specks indicates beyond range concentrations. In such cases, prepare a known dilution of your sample with distilled water and test again.

**Interpretation**

This kit measures soluble inorganic phosphate, reported as phosphate, not phosphorus. To convert to phosphorus divide result by 3. Natural seawater ranges from less than 0.01 mg/L to 0.3 mg/L. For corals in reef aquariums, such phosphates should be 0.2 mg/L or less. Phosphates are non-toxic to fish and most invertebrates, but are ideally kept below 1 mg/L to minimize algae growth. In freshwater, phosphates are not critical and the allowable concentration is dependent on variables such as nitrate, manganese, iron, and vitamin concentrations, as well as the extent of use of live plants. Usually, freshwater phosphate concentrations will be beyond the range of this kit, and dilutions of the sample with distilled water will be required. If excessive algae growth is not a problem, then the phosphate concentration may be considered as acceptable.

---

**WARNING**

This kit is a toy. Reagent 1 contains sulfuric and nitric acids and is corrosive. It may be hazardous if used carelessly or contrary to instructions. Reagents are corrosive to skin, metal, and fabrics. Avoid contact. Protect work surfaces with plastic liner or newspaper. If accidental spillage or contact occurs, wash and rinse exposed area thoroughly with water. If eyes are affected, rinse eyes immediately with water for 10 minutes and then seek medical attention. This item is an integral part of this kit and must not be separated from it.

**CAUTION**

970.041 © 2006, Seachem Laboratories, Inc. • Madison, GA 30650 • 888-SEACHEM • www.seachem.com