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Aquaponics and its potential aquaculture wastewater treatment and human urine treatment

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Abstract

The main objective of this thesis is to study the developing fields of aquaponics and its potential for aquaculture wastewater treatment and human urine treatment.

Aquaponics is a food production system which combines fish farming (aquaculture) with soilless crop farming (hydroponics). In this thesis the concept of aquaponics and the underlying processes are explained. Research on aquaculture wastewater and human urine wastewater is reviewed and its potential application with aquaponic systems is studied. An overview of the different types of aquaponic systems and current research on the field is also presented.

A case study was conducted in a farm in Askeröd, Sweden, which involved building two aquaponic systems (System 1 and System 2) and a human urine-based aquaponic system (System 3), with different degrees of component complexity and sizes. The design, building and monitoring of System 1, System 2 and System 3 was documented and described in detail. Four day experiments were conducted which tested the evolution in concentration of Total Ammonia Nitrogen (NH_4^+/NH_3), Nitrite (NO_2^-), Nitrate (NO_3^-), Phosphate (PO_4^{3-}), and Dissolved Oxygen (O_2) after an initial nutrient input. The goal was to assess the concentrations of these parameters after four days and compare them with relevant literature examples in the aquaculture industry and in source-separated urine research.

Neither of the two aquaponic systems (System 1 and System 2) displayed all of the parameter concentrations in the last day of testing below reference values found in literature. The best performing of the aquaponic systems was the more complex system (System 2) combining the hydroponic Nutrient Film Technique with a Deep Water Culture component, with a Total Ammonia Nitrogen concentration of 0,20 mg/L, a Nitrite concentration of 0,05 mg/L, a Nitrate concentration of 1,00-5,00 mg/L, a Phosphate concentration of <0,02 mg/L and a Dissolved Oxygen concentration of 8,00 mg/L. The human urine-based aquaponic system (System 3) underperformed in achieving the reference concentration values in literature for most parameters. The removal percentage between the higher recorded values after the input addition and the final day of testing was calculated for two literature examples of separated urine treatment and System 3. The system had a removal percentage of 75% for Total Ammonia Nitrogen, 98% for Nitrite, 25% for Nitrate and 50% for Phosphate. These percentages still underperformed literature examples in most of the tested parameters.

The results gathered allowed to conclude that while aquaculture wastewater treatment and human urine treatment is possible with aquaponics systems, overall these did not perform as well as some examples found in recirculating aquaculture systems and source-separated urine treatment literature. However, better measuring techniques, longer testing periods and more research is recommended in this field in order to draw an improved representative conclusion.

Keywords: Aquaculture, aquaponics, human urine, hydroponics, nutrient recovery, wastewater treatment.

Resumo

O objectivo principal da presente dissertação é a avaliação do potencial da aquaponia no tratamento da água residual proveniente de aquacultura e no tratamento da urina humana.

A aquaponia é um sistema de produção de alimentos que combina a cultura de peixe (aquacultura) com a agricultura sem solo (hidroponia). Na presente dissertação, o conceito de aquaponia e os processos subjacentes são explicados. Uma pesquisa sobre a água residual proveniente de aquacultura e a urina humana é avaliada, sendo a sua potencial aplicação em sistemas aquapónicos estudada. Uma visão geral dos diferentes tipos de sistemas aquapónicos e a pesquisa actual neste campo é também apresentada.

Um caso específico foi realizado numa quinta em Askeröd, na Suécia, que incluíu a construcção de dois sistemas aquapónicos (Sistema 1 e Sistema 2) e um sistema aquapónico suportado na urina humana (Sistema 3), com graus de complexidade dos componentes e dimensões diferentes. O dimensionamento, a construcção e a monitorização de todos os sistemas foi documentada e descrita em detalhe. Diversos testes de qualidade da água foram realizados durante um período de quatro dias em todos os sistemas, na qual a evolução da concentração de Azoto Amoniacal Total (NH_4^+/NH_3), Nitritos (NO_2^-), Nitratos (NO_3^-), Fosfatos (PO_4^{3-}), e Oxigénio Dissolvido (O_2) foi testada depois da adição de uma quantidade específica de nutrientes. O objectivo foi avaliar as concentrações desses parâmetros após quatro dias e comparar essas concentrações com exemplos relevantes encontrados na literatura inerente à indústria da aquacultura e aos processos de separação de urina na fonte.

As concentrações dos vários parâmetros em análise para os sistemas aquapónicos 1 e 2 foram inferiores aos parâmetros de referência encontrados na literatura. O sistema aquapónico com melhor desempenho foi o sistema mais complexo, combinando uma componente de "Nutrient Film Technique" com uma componente de "DeepWater Culture" (Sistema 2), com uma concentração total de Azoto Amoniacal Total de 0,20 mg/L, uma concentração de Nitritos de 0,05 mg/L, uma concentração de Nitratos de 1,00-5,00 mg L, uma concentração de Fosfatos de <0,02 mg/L e uma concentração de Oxigénio de 8,00 mg/L. O sistema aquapónico suportado na urina humana (Sistema 3) obteve um desempenho inferior quando comparado com os valores de concentração de referência na literatura na maior parte dos parâmetros. A percentagem de remoção entre os valores mais elevados registados após a adição de entrada e no último dia de teste foi calculado para dois exemplos de literatura e para o Sistema 3 . O Sistema 3 registou uma remoção de 75% de Azoto Amoniacal Total, 98% de Nitritos, 25% de Nitratos e 50% de Fosfatos. As percentagens descritas descrevem um desempenho inferior ao dos dois exemplos da literatura, na maioria dos parâmetros testados.

Os resultados recolhidos permitiram concluir que, apesar do tratamento de águas residuais provenientes de aquacultura e o tratamento da urina humana ser possível com sistemas aquapónicos, de uma forma geral estes sistemas não apresentaram resultados tão positivos como os resultados de exemplos encontrados na literatura sobre sistemas de recirculação de aquacultura e no tratamento de urina separada na fonte. Contudo, melhores técnicas de medição, um maior período de testes e mais pesquisas são recomendadas neste campo, a fim de que seja possível extrair uma conclusão mais representativa.

Palavras-Chave: Aquacultura, aquaponia, hidroponia, recuperação de nutrientes, tratamento de água residual, urina humana.

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Abbreviation List

BOD – Biological Oxygen Demand

CHOP – Constant Height One Pump

CHIFT-PIST – Constant Height in Fish Tank - Pump in Sump Tank

COD – Chemical Oxygen Demand

DWC – Deep Water Culture

IBC – Intermediate Bulk Container

LECA – Light Expanded Clay Aggregate

NFT – Nutrient Film Technique

PVC – Polyvinyl Chloride

TAN – Total Ammonia Nitrogen

UIA – Unionized Ammonia

1. Introduction

1.1. Conceptual framework of thesis

Fresh water is one of the most precious resources for the survival of the human species. It is used every day for personal needs such as drinking, hygiene, cooking and sanitation, for agriculture in the form of irrigation, for energy production and for industrial purposes. The total percent of fresh water accessible for direct human use is less than 1% of all the worldwide water sources (University of Michigan, 2006), yet its use continues to increase as population and demand increases, with projections of 9,6 billion people by the year 2050, compared to the 7,2 billion people of mid-2013 (United Nations, 2013). Considering the agricultural use of water alone, there will be an increase in global consumption demand of 19% by 2050 (UNESCOPRESS, 2012).

Not only does water benefit humans directly, but it also supports other species in oceans and seas across the Earth necessary for human food production. To the extent that the current increase in population growth and pollution has occurred, the pressure on the nearby water resources has declined the available fish stocks (Vince, 2012). Since agriculture is the human activity with the biggest consumption of fresh water annually, contributing to 92% of water use (Hoekstra & Mekonnen, 2012), the stress factors mentioned above will also greatly restrict future food production. Sustaining future human activities, at an increasing human population growth and consumption, might be incompatible with fresh water availability.

Facing these facts will lead to the conclusion that human water use and pollution must be greatly reduced, since it can jeopardize human survival in the near future. In this regard, water and wastewater treatment technology, new efficient uses of water in agriculture, and other technologies will play key roles in preventing these issues.

Currently, the treatment of wastewater from humans and from fish farming activities such as aquaculture require a high amount of energy and resources in transporting, separating and treating the waste. These treatments often require channeling vast amounts of water to centralized treatment plants and discarding useful nutrients in the process, despite opportunities for nutrient recycling (Keller, 2012). At the same time, in agriculture most farming methods are inefficient in their irrigation methods, for example though conventional flood irrigation which loses 40% to the water table and through evaporation (Prins & Brouwer, 1989). Many of the nutrients currently used in agriculture are produced unsustainably by relying heavily in fossil fuels and scarce resources (Sims, 2011), and often ignoring the potential of nutrient recycling (Refsgaard *et al*, 2005).

In this framework, a system that tackles many of these issues simultaneously appears promising. It is deserving of a careful study to identify its strengths and weaknesses, and the possible applications for the future of wastewater treatment and water conservation in food production systems.

1.2. Thesis goals

This thesis will deal with describing what aquaponics is, its potential applications and the underlying biological processes. It will also describe how to dimension a variety of aquaponic systems and how they compare with current aquaculture wastewater treatments, as well as source-separated human urine treatment in wastewater treatment plants. Understanding how an aquaponic system works, its requirements and limitations will play a key role in assessing how such systems will help solve some of the problems outlined in the first sub-chapter. Detailing the building process of these systems, the calculations and assumptions will enable a full technical understanding on how to build these systems in similar conditions to ensure reproducibility of the results.

Finally, comparing the treatment potential of aquaponics systems in regards to conventional recirculating aquaculture filtration systems and separate human urine treatment in wastewater treatment plants will enable an understanding of the advantages and disadvantages of aquaponic systems as a new method for water treatment. The added benefit of simultaneous food production in these systems will also be considered.

1.3. Thesis structure

The thesis will be structured in three main parts. The first one will focus on defining aquaponics by describing how the biological process works, taking a look into aquaculture and its wastewater, and illustrating the different types of existing aquaponic systems. Each type of aquaponic system will also have its benefits and issues weighed in. The second part will describe the calculations and assumptions used for dimensioning each of the aquaponic systems. This includes the choices for the materials, overall system design, plumbing connections, fish and plant species, and the biological system start-up. Finally, the third part will detail parameters testing on each system and the sample collection method. A comparison with the research gathered from relevant literature concerning aquaculture wastewater treatment as well as source-separated human urine treatment will also be included.

2. General considerations

2.1. Definition of Aquaponics, Aquaculture and Hydroponics

Aquaponics can be defined as "The cultivation of fish and plants together in a constructed, recirculating ecosystem utilizing natural bacterial cycles to convert fish waste to plant nutrients. This is an environmentally friendly, natural food-growing method that harnesses the best attributes of aquaculture and hydroponics without the need to discard any water or filtrate or add chemical fertilizers" (Bernstein, 2013).

In this context, Aquaculture refers to the farming of aquatic organisms with human intervention to improve production (FAO[1], 2014). On the other hand, Hydroponics refers to growing plants without soil, where the nutrient source is either a nutrient solution or nutrient enriched water (Jones, 2005). Aquaponics is therefore an attempt at converting the waste of one farming method into the nutrient input of another.

2.2. Aquaponics and aquaculture wastewater

Farming organisms such as fish in an aquaculture environment requires that the waste is removed from the environment periodically. Given that an aquaculture environment is not integrated in an ecosystem, the waste has nowhere to go, resulting in build-up which will kill the organisms if it is not actively removed.

2.2.1. Waste water from Aquaculture

The practice of aquaculture with fish as an example, leads to a diverse waste water composition. This waste can be in both solid form (fish carcasses, viscera, skin and heads) and liquid form (washing and cleaning water discharge, blood-water from drained fish storage tanks and brine) (FAO[2], 2014). Some of the parameters used in assessing the composition of aquaculture waste water include: solids content, pH, temperature, odor, organic matter, biochemical oxygen demand (BOD), chemical oxygen demand (COD), oil and grease content, nitrogen and phosphorous content (FAO[2], 2014).

Of these parameters, nitrogen in the form of ammonia is considered to be the second most important after oxygen, as it is the natural byproduct of fish metabolism (Francis-Floyd *et al*, 1996). A simple chemical explanation of ammonia is proposed by Francis-Floyd *et al* in their 1996 *Ammonia in Aquatic Systems*: "In water, ammonia occurs in two forms, which together are called total ammonia nitrogen, or TAN. Chemically, these two forms are represented as NH_4^+ and NH_3. NH_4^+ is called ionized ammonia because it has a positive electrical charge, and NH_3 is called un-ionized ammonia (UIA) because it has no charge. This difference is important to know because NH_3, un-ionized ammonia, is the form more toxic to fish".

Ammonia in itself presents no problem in simple flow-through systems; however in common recirculating systems a biofilter and regular parameter observations are required (Molleda, 2007). Even with a microbe-based biofilter, effluents from recirculating aquaculture systems have high nutrient concentration, reaching >200mg/L nitrate nitrogen and 20-30 mg/L in mean total phosphorus (Yeo *et al*, 2004). These nutrients are high enough to support typical hydroponic plant production (Resh, 1989).

2.2.2. Aquaponic biological processes - The nitrogen cycle

There are several nutrient cycles occurring in an aquaponic system, however the most studied and generally understood one is the nitrogen cycle, occurring at the biofilter level. In this cycle, nitrogen takes three main forms: ammonia (NH_4^+ or NH_3), nitrite (NO_2) and nitrate (NO_3). An explanation of the nitrogen cycle is proposed by Tyson *et al* in their 2004 *Reconciling water quality parameters impacting nitrification in aquaponics: The pH levels*. This scientific paper states that: "Ammonia is the main excretion product from fish. Both un-ionized ammonia and nitrite can be toxic to fish at very low levels. In the process of nitrification, certain autotrophic bacteria (primarily *Nitrosomona*) oxidize ammonia to nitrite and others (primarily *Nitrobacter*)

oxidize nitrite to nitrate. The overall reaction of nitrification and cell biomass formation can be written as:

Nitrosomonas

$$55\ NH_4^+ + 5\ CO_2 + 76\ O_2 \rightarrow C_5H_7NO_2 + 54\ NO_2^- + 52\ H_2O + 109\ H^+$$

Nitrobacter

$$400\ NO_2^- + 5\ CO_2 + NH_4^+ + 195\ O_2 + 2H_2O \rightarrow C_5H_7NO_2 + 400\ NO_3^- + H^+$$

The nitrogen transformation eliminates ammonia from the water. Nitrate is not toxic to fish except at very high levels and is the primary source of nitrogen for plants in hydroponic systems".

There are several strains of bacteria that take part of the nitrification process, but the ones believed to be more prominent are *Nitrosomona* and *Nitrobacter*. Ammonia removal from the water is a crucial step in such a recirculating system, as it allows the water quality to decrease in toxicity for the fish, removing the need for constant water changes. A simple overview of the nitrogen cycle can be viewed in Figure 2.1:

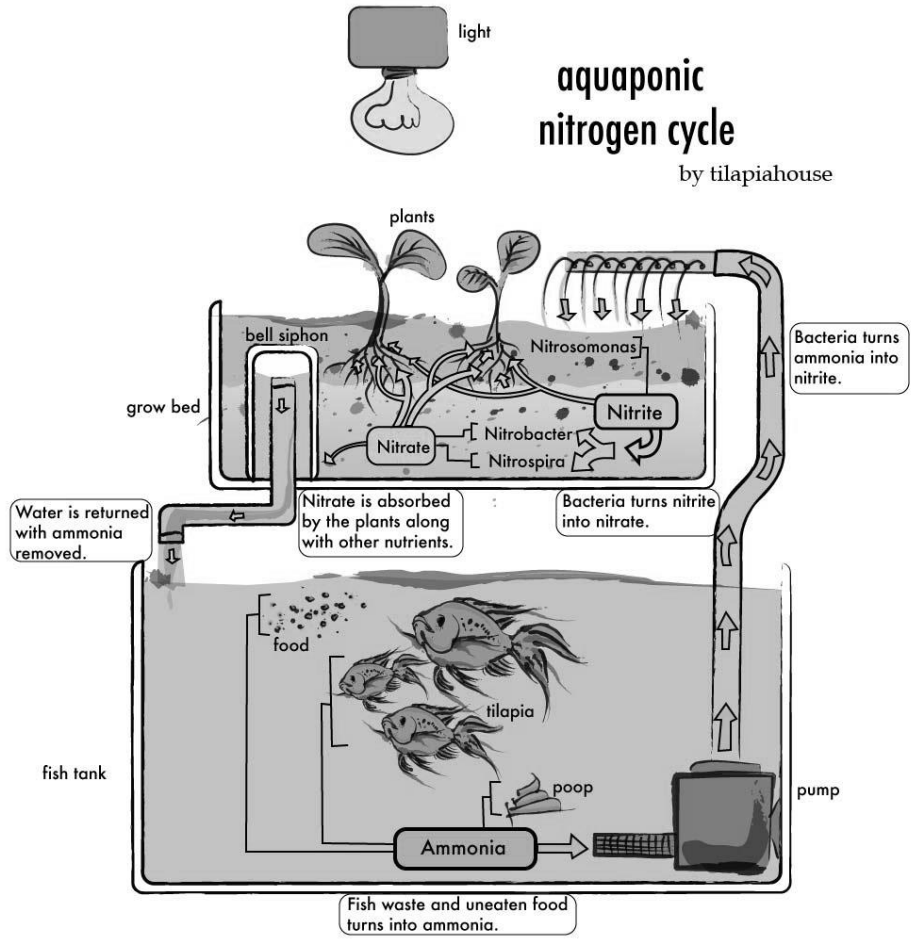

Figure 2.1. The Nitrogen cycle in an aquaponic system. Adapted from TilapiaHouse.com, by Tilapia House, 2012, Retrieved from http://tilapiahouse.com/Aquaponics_Water.html. Copyright 2012 by Tilapia House

Apart from biological filtration, solids filtration in an aquaponic system is also essential in achieving proper water quality for fish and plants (Tyson *et al*, 2004). Solids filtration generally consists of both the mineralization of the solids into plant available nutrient forms, as well as the mechanical filtration of solids (Lennard[1], 2012). Mineralization can either be aerobic or anaerobic, but it is regarded that aerobic solids mineralization should be encouraged in aquaponic systems (Lennard[1], 2012).

2.3. Types of Aquaponic systems

2.3.1. Media Bed

A media bed aquaponic system is one of the most common setup of aquaponic systems due to its simplicity of assembly. At its most basic form, it consists of a water reservoir or fish tank, a grow bed, a water pump and a return pipe or hole. The water reservoir or fish tank is where fish are kept, fed and harvested from; the grow bed is where plants are grown and harvested in a soilless media, serving also as a mechanical filter and a biofilter; the water pump will transport water from the water reservoir to the grow bed; and lastly the return pipe or hole will return clean water to the water reservoir.

Benefits of this system design include: removal of solids from the water reservoir, breakdown of solids, biofiltration, and better plant root support. It also has familiarity with traditional soil gardening as there is a media where plants are grown. A simple schematic diagram representing this system can be seen in Figure 2.2:

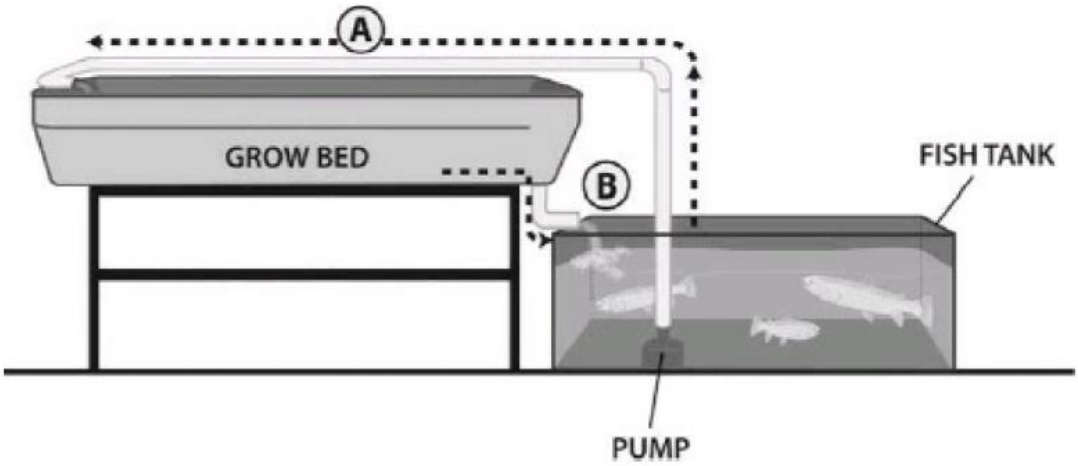

Figure 2.2. Media Bed design. Adapted from Aquaponic Gardening: A step-by-step guide to raising vegetables and fish together, by Sylvia Bernstein, 2013. Copyright 2013 by Sylvia Bernstein

Media can consist of materials such as expanded clay aggregate, lava gravel, expanded shale, or rocks. The media should be inert, not decompose, and not alter the chemical composition of the water. The media should also be free from potential release of toxins harmful to the plants, fish, and nitrifying bacteria.

A media bed aquaponic system commonly operates under a flood and drain cycle (also known as ebb and flow). Under this principle, the grow bed is flooded with water and then allowed to drain, either through the use of a pump timer or a siphon. A siphon, autosiphon, or bell siphon is a simple technology which allows water to be drained faster than the incoming flow from the pump, by covering the standpipe with a sealed tube or "bell". This bell has holes that only allow water and not air to enter after a certain level, and as the level of water rises it pushes the remaining air trapped inside through the standpipe. Eventually the whole system is filled of water which creates a flush-like mechanism and will drain the water quickly until it reaches the holes, letting air in and breaking the siphon effect (Fox *et al*, 2010).

Looking at the basic aquaponics system design (Figure 2.2), water level in the water reservoir will change as flood and drain cycles occur. With the addition of more grow beds, the water level difference in the reservoir may be stressful to the fish (Bernstein, 2013). This has led to some design suggestions on the addition of a third component: a sump tank.

A sump tank, now the lowest level of the system, is essentially a second water reservoir where the pump is located, allowing for a constant water level in the fish tank. Having the pump away from direct contact with fish waste and solids may also prevent clogging of the pump. However other variations also include fish in the sump tank, allowing for greater stocking capacity. This design is commonly referred to as CHOP (Constant Height One Pump) or CHIFT-PIST (Constant Height In Fish Tank – Pump in Sump Tank) by aquaponic enthusiasts. A downside to this design is the need for the fish tank to be higher than the grow beds, so water can be transported by gravity without the need for a second pump. A simple schematic representing this new system is presented in Figure 2.3.

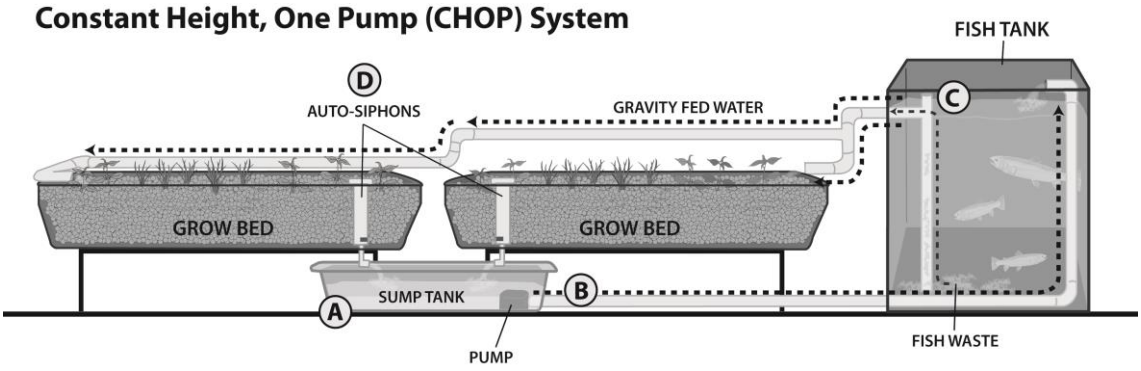

Figure 2.3. Constant Height One Pump System. Adapted from Aquaponic Gardening: A step-by-step guide to raising vegetables and fish together, by Sylvia Bernstein, 2013. Copyright 2013 by Sylvia Bernstein

A media bed aquaponic system can also operate under a continuous flood/flow design. Without the use of a pump timer or siphon, the grow bed as well as the fish tank will have a constant level of water. It is believed that one advantage of flood and drain cycle versus continuous flood/flow is the delivery of oxygen rich air to the roots of the plants (Bernstein, 2013). On the other hand, continuous flood/flow in a media bed design may cause plant roots to become saturated with water, without access to enough oxygen, and areas of the grow bed to become stagnant and anaerobic.

2.3.2. NFT - Nutrient Film Technique

A Nutrient Film Technique (NFT) aquaponic system is originally a hydroponic irrigation technique, where a very shallow constant stream of nutrient enriched water is recirculated through the bare roots of plants. The plants are usually located in channels or tubes, hanging from the top and with their roots exposed, allowing for an abundant supply of oxygen to the roots. The depth of the stream is ideally a thin film of water, allowing for dense root development at the bottom of the channels. A simple schematic representing this system is presented in Figure 2.4.

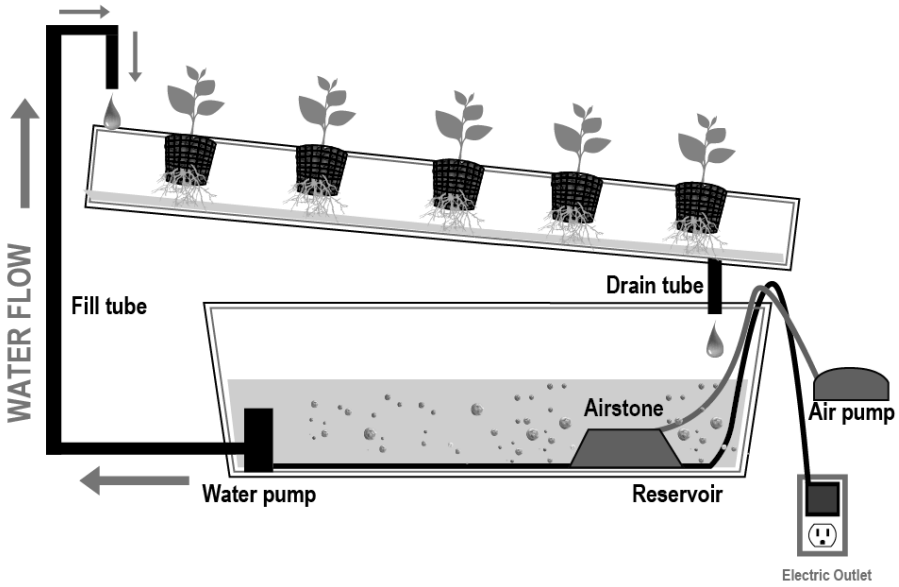

Figure 2.4. Typical Hydroponic NFT design. Adapted from Sdhydroponics.com, by Sunny Datko 2012, Retrieved from http://sdhydroponics.com/resources/articles/gardening/how-to-grow-hydroponically-%E2%80%93-overview-of-grow-systems. Copyright 2014 by San Diego Hydroponics & Organics

In hydroponics the water in the system already contains all necessary dissolved nutrients. This is in contrast to aquaponics, where an additional filter is required to perform the mechanical filtration and mineralization of fish solid waste, as well as the bio-filtration. The aquaponic filter thus allows a large surface area for nitrifying bacteria cells to colonize (DeLong & Losordo, 2012). The product of the bacteria metabolism results in nutrient-rich water that then flows through the channels, returning in the end to the fish tank.

While it is easy to plant, harvest and maintain an NFT system, some drawbacks have been discussed. These include little buffering against interruptions in the flow of water, e.g. a power outage, high water temperature fluctuations and blockages in water flow due to dead detached roots. NFT may also be limiting in the types of plants suitable, as some will have big invasive root systems which may be too heavy for the lightweight channels.

In a study comparing different hydroponic sub-systems in an aquaponic test system, overall results suggested that a NFT system was less efficient in removing nutrients from the water as well as less efficient in producing plant biomass (Lennard & Leonard, 2006), when compared to a Media Bed System or a Deep Water Culture system.

2.3.3. DWC - Deep Water Culture

A Deep Water Culture (DWC) or Raft System aquaponic design is also originally a hydroponic irrigation technique. In this technique, the plants are placed in floating trays or rafts on top of a water reservoir with heavily oxygenated nutrient rich water. An abundance of oxygen is provided mainly to prevent root rot from occurring. A simple schematic representing this system is presented in Figure 2.5.

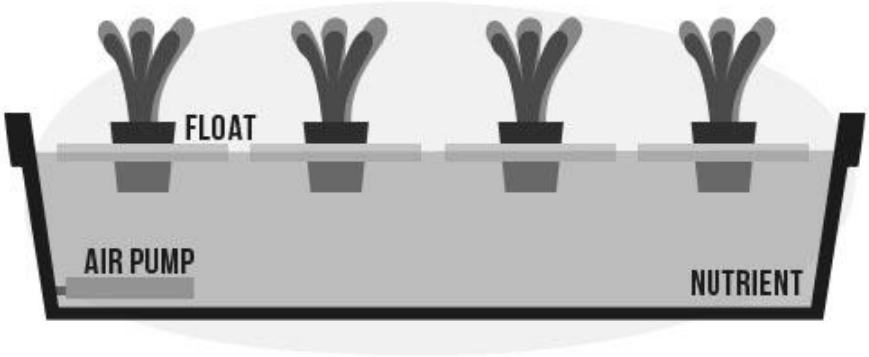

Figure 2.5. Typical Hydroponic DWC design. Adapted from Contemporary Food Lab.com, by Vanessa Gürtler 2014, Retrieved from . Copyright 2014 by Contemporary Food Lab

As with an NFT aquaponics system, an additional filter is required to perform the mechanical filtration and mineralization of fish solid waste, as well as the bio-filtration.

A DWC system is a common design found in commercial aquaponics. It is generally considered to benefit from a raft-covered water reservoir, as it makes the system less prone to water temperature and pH fluctuations. It also allows for excellent root development due to the easy access to oxygen in the water. Compared to an NFT system, it also provides buffering against interruptions in the flow of water. Visual access to the roots by lifting the raft systems allows for easy plant health monitoring. However, due to the lightweight nature of the rafts or trays, large plants may be very difficult to support. Therefore, the most common DWC plants include salad greens and herbs.

2.3.4. Other Systems

Aquaponics allows for a diverse amount of systems and designs based on the Media Bed, Nutrient Film Technique and Deep Water Culture designs.

Concerning Media Bed Systems, some designs have been proposed with special focus on keeping the fish tank water level constant or preventing the need for a fish tank at a higher level than the grow bed, while others focus on materials cost or space availability. One of these designs includes adding float switches and a second pump to disable the need for a fish tank at a higher level than the grow bed (Figure 2.6).

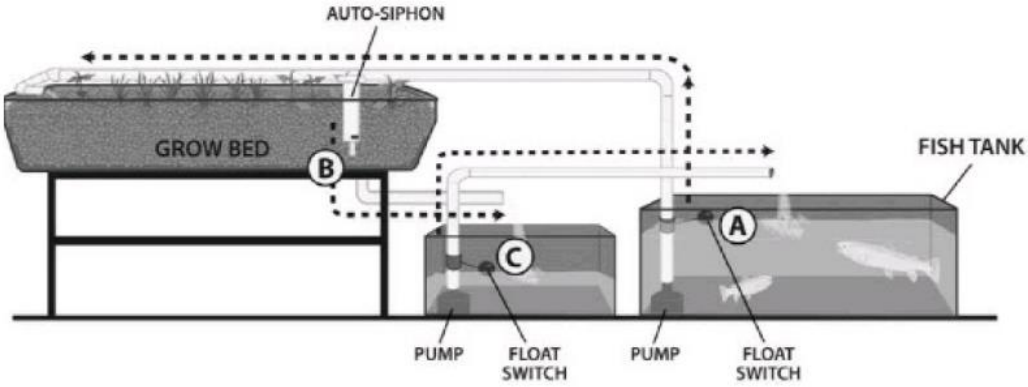

Figure 2.6. Two Pump system. Adapted from Aquaponic Gardening: A step-by-step guide to raising vegetables and fish together, by Sylvia Bernstein, 2013. Copyright 2013 by Sylvia Bernstein

Another design improvement uses an indexing valve (Figure 2.7) to sequentially irrigate several grow beds. With this valve, the number of grow beds can be increased without needing to buy a bigger fish tank.

Figure 2.7. Indexing/Sequencing Valve. Adapted from AquaponicLynx.com, by Aquaponic Lynx LLC 2014, Retrieved from http://www.aquaponiclynx.com/products/aquaponic-systems-and-components/plumbing-and-valves/aquaponics-indexing-valves. Copyright 2014 by Aquaponic Lynx LLC

Design of aquaponic Media Bed Systems can also be made with a variety of materials. One of the designs is Barrelponics®, a design that uses inexpensive or recycled materials with focus on developing countries and with freely available instructions (Figure 2.8).

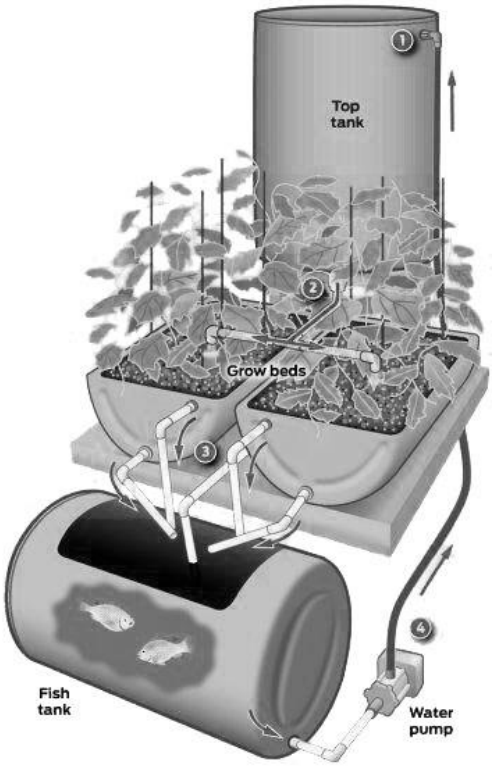

Figure 2.8. Travis Hughley's Barrelponic system. Adapted from npecom.com, by Jeff 2013, Retrieved from http://npecom.com/rootz/save-money-on-gardening-supplies/. Copyright 2014 by Travis Hughley

Aquaponic systems can also be integrated with each other to complement their weaknesses. For example, the NFT or DWC need for an additional filter may be supplemented by integrating a Media Bed System between the pumped water and the system of choice. This set-up will remove most of the solids in the system (Bernstein, 2013).

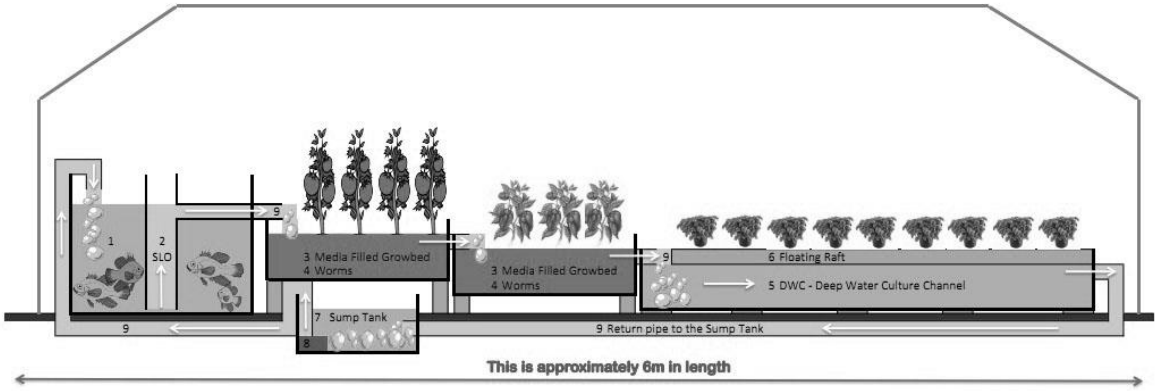

Figure 2.9. Example of a hybrid aquaponic system, combining DWC and Media Beds. Adapted from Aquaponic Source.com, by Japan Aquaponics 2012, Retrieved from http://community.theaquaponicsource.com/forum/topics/aquaponics-in-japan-feedback-on-design-for-community-group. Copyright 2014 by Sylvia Bernstein

Aquaponic systems may also take advantage of vertical farming as it requires less horizontal growing area, ideal for urban farming. Most vertical aquaponic designs are a variation of a Media Bed System, which uses a soilless media to grow the plants. In a vertical design, priority is given to lightweight media such as expanded clay aggregate to prevent the structure from collapsing under its own weight (Figure 2.10).

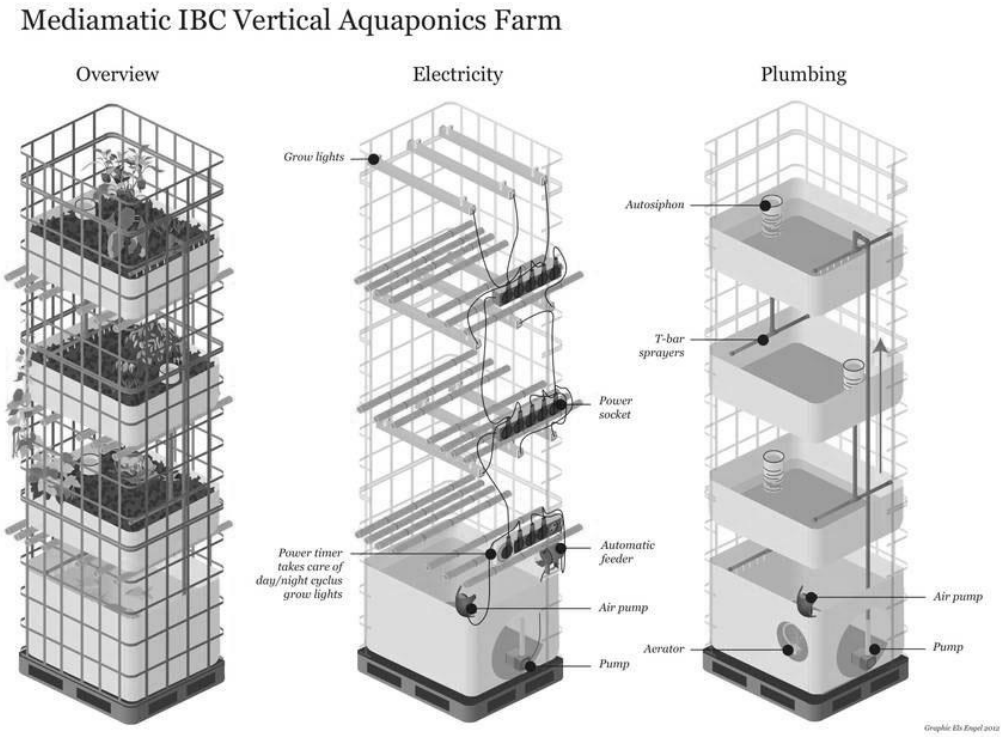

Figure 2.10. Example of a vertical aquaponics set-up, using a Media Bed system design. Adapted from MediaMatic.com, by Els Engel 2012, Retrieved from http://www.mediamatic.net/321620/en/mediamatic-ibc-strongvertical-strong-lt-strong-gt. Creative Commons 2012 by Els Engel

2.4. Aquaponics and human urine treatment

2.4.1. Human urine composition

Human urine is an aqueous solution secreted by the kidneys which consists primarily of water. Remaining main components include urea and dissolved ions such as chloride, sodium, potassium, and creatinine (Putnam, 1971). Urine can provide a plant-available source of nitrogen by a process known as ammonia volatilization from urea. In this process, urease catalyzes the hydrolysis of urea to unstable carbamic acid, followed by a rapid decomposition of carbamic acid to form un-ionized ammonia (NH_3) and carbon dioxide (Tisdale *et al*, 1985). The above description can be expressed as the following chemical reaction, stated by (Brady & Weil, 2001):

$$(NH_2)_2CO + H_2O \xrightarrow{\text{urease}} NH_3 + H_2NCOOH \rightarrow 2NH_3\,(gas) + CO_2\,(gas)$$

The formed ammonia might escape to the atmosphere unless it reacts with water to produce ionized ammonia (NH_4^+), according to the following reaction:

$$NH_3(gas) + H_2O \rightarrow NH_4^+ + OH^-$$

This reaction is important to note since ionized ammonia is a plant available source of nitrogen while un-ionized ammonia is not (Brady & Weil, 2001).

It is worth referring that urine is generally considered as fertilizer and for aquaponic use only when it is acquired from a healthy individual without any current illness or infection, and under no type of medication. This requirement can create some limitations for the collecting of source-separated urine and its further treatment.

2.4.2. Contemporary aquaponic uses of human urine

Discussion of the use of urine in aquaponic systems can be traced back to online aquaponic discussion communities, one of the more popular communities being Backyard Aquaponics. By some aquaponics enthusiasts, urine has been considered as having several benefits since it can allow for an ammonia source to function as the base of bacterial population for the aquaponic system, a process commonly referred to as "cycling". A human source of ammonia can also be used in separate tanks to grow duckweed (*Araceae lemnoideae*), as an alternative source of fish food (Leng *et al*, 1995).

More interesting however, is the possibility of creating an aquaponics system without any fish, using human urine as the only source of ammonia. There is no standard name for this sort of practice, although common terms found online include "urineponics" and "peeponics". A human urine aquaponic system grants some liberties in the water reservoir tank size, as there is no fish and no overstocking limit to restrict the ammonia source. Therefore, water reservoir tanks can be much smaller, and the amount of ammonia added is slightly more controllable when compared with ammonia from fish waste. On the other hand, only fresh produce is grown as opposed to the additional growing of fish in traditional aquaponics systems. Thus this urine-based aquaponic system serves a different purpose: a waste water treatment and nutrient recovery system rather than a constructed ecosystem.

In some of the testimonies and experiments of aquaponic online communities, the methodology seems to be based on the research conducted by Pradhan *et al* on the use of urine as a plant-fertilizer. According to their methods, urine is first aged to kill any possible hazardous pathogens that may contaminate the produce. Sterilizing the urine helps minimize the risk of any possible health problem, since it leads to very few detected microorganisms such as fæcal coliforms, clostridia, enterococci and coliphages (Pradhan *et al*, 2007).

There is mixed research suggesting that urine is sterile until it reaches the urethra (Madigan & Brock, 2009), while other suggests that urine is not sterile even in the bladder (Hilt *et al*, 2013). A source-separation of urine, should contemplate that the risk for transmission of disease when

using urine mostly depends on cross-contamination by fæces (Höglund, 2001). Considering urine may not be sterile, bacterial population can be reduced by allowing the urea to be degraded by the urease enzyme to ammonium and water. It has been observed that allowing the urine to degrade until it reached a pH level exceeding 9 will result in bacterial reduction (Pradhan *et al*, 2007). Recommended storage time is 6 months for the use of urine as fertilizer in soil in colder climates (Jönsson *et al*, 1997), however it should be sufficient to wait until the target pH level has been reached since a recommended storage time of 6 months assumes the stored urine to be subject to colder climate outdoor temperatures (Pradhan *et al*, 2007).

2.5. State-of-the-art in Aquaponics

2.5.1. Existing applications

Aquaponic systems can currently be found in a variety of applications. These include commercial systems, urban farming in backyards and apartments, and some educational systems and events. Commercial aquaponic systems typically strive to profit from both the hydroponic as well as the aquaponic components, as grown fish and plants can be sold for a premium price with marketing efforts (Goodman, 2011). Out of the two products, plants tend to be more profitable than fish (Bernstein, 2013). However, there is few existing literature on the financial sustainability of these commercial systems (Goodman, 2011).

While aquaponics businesses may strive to produce fish and vegetables commercially, some aquaponics businesses instead focus on selling systems and solutions. Even though some solutions are targeted for commercial systems, other designs include pre-fabricated backyard and home-scale systems for individuals and families. As a result of pre-fabricated systems for purchase and readily available information, aquaponic practice is spreading through urban environments (Brown-Paul, 2013).

Additionally, other pre-fabricated aquaponic systems are targeted directly as educational tools for classrooms (Figure 2.11). Many aquaponics courses and workshops are also offered, ranging from a basic understanding of aquaponics to a full preparation for starting a commercial system (Goodman, 2013).

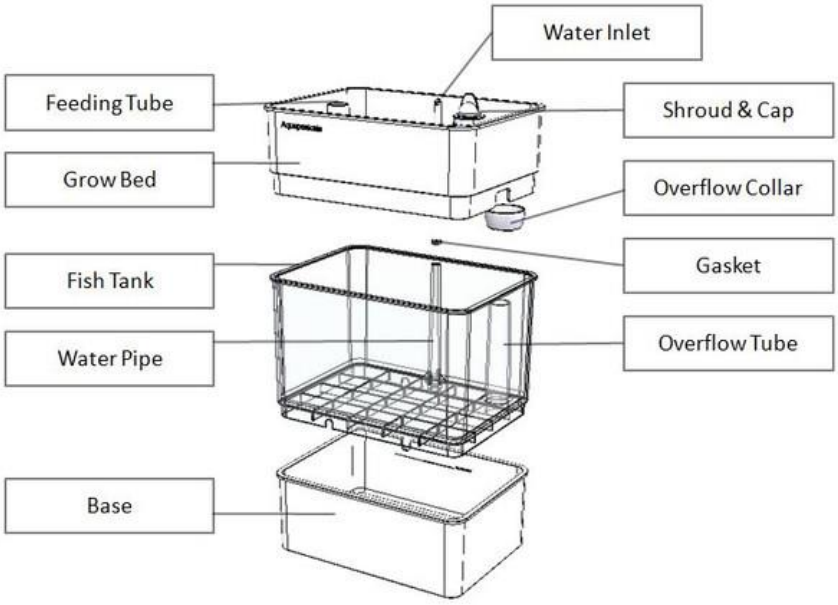

Figure 2.11. Aquaponicals Education Set, a desktop sized aquaponics system. Adapted from TheAquaponicStore.com, by TheAquaponicStore 2014, Retrieved from http://www.theaquaponicstore.com/Aquaponicals-Education-Set-p/tpdas003.htm. Copyright 2014 by The Aquaponic Source, Inc

2.5.2. Research & Development in the field

Most of the research and development in aquaponics has been done on the topic of how to design and operate aquaponics systems from a scientific and technical perspective. Research may cover fish to plant ratios (Lennard[2], 2012), Media Bed sizing (Lennard[3], 2012), fish tank shape and design (Lennard[4], 2012) as well as comparison of three different types of aquaponic sub-systems. Out of these sub-systems, the Media Bed system performed the best while the NFT performed the worst in both biomass gain and removing nutrients from fish culture (Lennard & Leonard, 2006).

Other research has studied the use of ornamental fish as a complementary species, concluding that while not suitable for commercial plant production alone, they would be a good addition to systems in temperate regions (Bathia, 2012). Additionally, a study on the impact on pH levels of aquaponic nitrification concluded that the optimal pH range should be between 6,5 and 7 for optimal plant and fish growth (Tyson *et al*, 2004). Using geothermal energy to heat water in aquaponic systems has also been studied, providing a successful case study of the use of waste heat for growing warm temperature aquaponic fish in Iceland (Sigurgísladóttir, 2011) and may provide new possibilities for temperate and cold regions. Factors affecting the economic sustainability of aquaponic systems were investigated, showing how system design affects chemo-physical parameters, system stability and fish and plant production (Palm *et al*, 2014).

Comparing aquaponic production versus other types of production has also been performed. A study comparing the effectiveness of aquaponic gardening to traditional gardening concluded that there was no significant difference in plant growth between aquaponic, hydroponic and traditional methods, while confirming a correlation between increased levels of nitrates with plant growth (Yamamoto & Brock, 2013). Biomass production and nutrient dynamics compared aquaponic production with hydroponic production, concluding that aquaponic production with nutrient supplementation can yield equal biomass accumulation and chlorophyll concentration indexes as hydroponic production (Licamele, 2009). A microbial profile of aquaponic grown versus in-soil grown lettuce has also been developed, indicating that aquaponically grown

lettuce had significantly lower concentration of fæcal microorganisms and spoilage (Sirsat & Neal, 2013).

Some research has also looked into alternative fish food such as Black Soldier Fly larvae (*Hermetia illucens*), concluding that it can be used for aquaponic feeding, though processing it into dehydrated ground meal will increase the quality of the feed (Stankus, 2013). A study comparing duckweed, soybean meal, rice bran and sorghum as alternative fish food sources found that sorghum and rice bran produced lower plant yields, while soybean meal yielded better fish growth (Aguilera-Titus *et al*, 2014).

Concerning human urine based aquaponics, currently no research is found except for accounts in backyard experiments by aquaponic enthusiasts. These experiments include: water chemistry and *Escherichia coli* tests in a backyard human urine-based aquaponics system, growing duckweed (*Araceae lemnoideae*) as fish food using human urine, and comparing plant growth in aquaponic systems versus plant growth in human urine based aquaponic systems.

3. Case Study

3.1. Location and Entity

A case study was performed with the company Grönare Stad AB. The enterprise was created in 2011 by Louise Lundberg, with the goal of sustainable city development. This includes urban farming, aquaponic systems, roof gardens, urban drainage and storm water management, as well as education in these topics.

The aquaponic systems developed for the case study were located at a small farm in Askeröd, part of the Hörby County, in the Skåne region of Sweden. The farm was acquired by the current owners in 2007, and has 12 000 m^2 of land. In the farm one of the systems was built in a boiler room, which provides hot water all year round for the buildings, as well as heating for the main house during the winter. Two other systems were built in a greenhouse with 10 m^2, which had been previously used for growing tomatoes in soil.

3.2. Climate characteristics of the region

Sweden has a cold climate, with the Skåne region having a temperate climate (CIESIN, 2007). According to data from the Swedish Meteorological and Hydrological Institute SMHI, Skåne has the mildest temperature in Sweden, even with local differences (SMHI[1], 2007). The Swedish Meteorological and Hydrological Institute (SMHI) is a government agency that operates under the Ministry of the Environment, offering forecasts, statistics and climate studies. The SMHI presents average temperature data in degrees Celsius for specific measured periods of thirty years. This average temperature is taken throughout both day and night and results for a thirty year period are shown in Table 3.1.

Table 3.1. Average temperature in degrees Celsius in Hörby A station (station number 5353) between 1961 and 1990, adapted (SMHI[1], 2007)

Month	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp. (ºC)	61-90	-1,6	-1,5	1,0	5,4	10,4	14,4	15,5	15,3	11,9	8	3,6	0,1	6,9

Despite having a milder temperature, the region of Skåne is still too cold for many plant species. The most common grown crops include potatoes, wheat, sugar beets, grains, winter wheat, and plants suitable for oil production (Kyllmar *et al*, 2005) such as rapeseed. Various vegetables are generally grown in greenhouses to survive the cooler temperatures. This is an important factor to consider when planning which plant species to cultivate in the aquaponic systems.

Concerning wind, southern Sweden experiences slightly stronger winds than the northern part of Sweden. The typical annual mean wind speeds in Sweden ranges between 2 and 5 m/s (Achberger *et al*, 2005). Southern Sweden to the south of ≈58°- 60°N, which is the case of Hörby, usually has higher annual means since the region is more directly exposed to winds from the west and the southwest (Achberger *et al*, 2005). Absolute humidity (g water/m^3) is highest in the south of Sweden (SMHI[2], 2013), with humidity values ranging between 4 g water/m^3 to 11 g water/m^3 depending on whether it is winter or summer, respectively (SMHI[2], 2013).

Overall, the region of Skåne appears to have the best climate conditions for outdoor and greenhouse cultivation. However, outdoor temperatures are too cold for outdoor cultivation in soil and thus outdoor aquaponic cultivation of many vegetables. For this reason, the aquaponic systems were built in a greenhouse and in an indoor environment.

3.3. Economic and Demographic aspects of the case study

Most of the resources used to build the aquaponic systems were re-used materials found on the farm. This includes old farm equipment, leftovers from construction operations, and a re-purposed Intermediate Bulk Container (IBC). Other materials were purchased in Swedish retail

stores and at internet stores. The available budget of Grönare Stad AB for building the aquaponic systems was set for 8 000 Swedish kronor (approximately 870 € on June 30th 2014) for a one year period. The most expensive individual items included an IBC, several pumps and expanded clay aggregate bags for the grow beds.

During the period stated above, two positive income sources resulted from the aquaponic systems, in the form of guided tours of the systems and workshops concerning aquaponics. This enabled the Grönare Stad AB company to break even in the expected costs and to have some food production with almost no cost. The aquaponic systems will produce food for the owners and residents of the farm. These consist of a family of four, two adults and two children, with occasional volunteer farming assistants.

3.4. Existing limitations/restrictions

Limitations on the construction of the aquaponic systems were mostly of economic nature. Several contacts were made in hopes of negotiating a partnership. Meetings took place with some institutions, companies, and universities, however without success. As such, the financial resources for the materials came exclusively from the company Grönare Stad AB. The 8 000 Swedish kronor budget limit had an important impact in design decisions, as it encouraged the re-use of available materials. This also restricted the ability to purchase test kits for parameters other than the ones used to monitor the cycling process and limited the fish species considered. The chosen fish species were less expensive ornamental fish rather than edible varieties or species requiring additional water temperature heating. The budget limit also made it unfeasible to purchase existing commercial aquaponic and hydroponic materials as they are either too expensive to import to Sweden from abroad, or too expensive to buy in existing Swedish retail stores. Additionally, some of the building materials that had to be bought took some time to find, delaying the construction and assembly time.

Another important restriction was space as the greenhouse was only 10 m^2. To maximize growing space, small vertical farming towers were combined with the more common designs. The greenhouse height restricted the size of these towers to 0,8 m, which is less than ideal for being able to take advantage of vertical farming. After the aquaponics systems were built and operating, some of the vegetable growth made maintenance practices difficult, particularly in IBC based Media Bed systems. As aquaponics and especially human urine based aquaponic systems are a relatively new field of practice, theoretical and practical dimensioning guidelines from academic sources were hard to find. Most information available was found in communities of aquaponic enthusiasts or instruction books.

3.5. Dimensioning

3.5.1. General systems overview

Three systems were built in total. The systems range in complexity, from a simple Media Bed system to systems incorporating NFT, DWC and even vertical designs. The difference in complexity was chosen to test different designs in their ability to filter the fish waste or human urine, and in their capacity to grow plants.

The first system built is located in the farm's boiler room, and is a simple Media Bed design (System 1). It runs on a flood and drain cycle with a bell siphon combined with a timer, and was made from an Intermediate Bulk Container (IBC). The bell siphon is coupled with a timer as it would occasionally remain stuck in the siphoning effect, preventing incoming water to flood the system. The grow bed was filled with expanded clay aggregate (LECA), as well as lava gravel. Since the system is in an indoor environment with no windows nearby or access to sunlight, an indoor grow light source was provided (Figure 3.1).

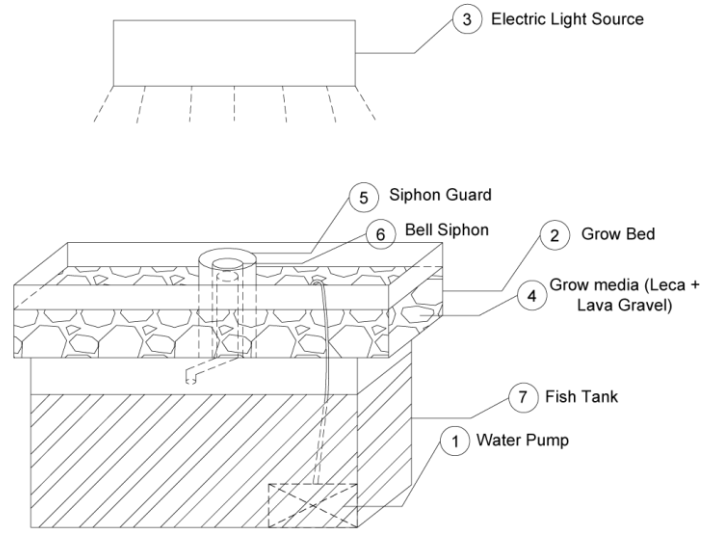

Figure 3.1. System 1 Overview

The second system built is located in the greenhouse, and is a combination of a NFT system with a DWC system, coupled with two filters in a continuous flow cycle (System 2). The system has a fish tank where the water is pumped from and diverted into two parallel filters. These return the filtered water to a descending NFT pipe, which channels the water into a small DWC reservoir with a standpipe that delivers the water back to the fish tank. The filters are filled with charcoal, which has a high surface area (Campbell *et al*, 2012) suitable for the colonization by the bacteria in the biofilter, in addition to LECA. Incoming water to the filters can be regulated by a valve which controls the flow of water, allowing for the water level in both filters to be controlled. An additional air pump was placed to supply enough oxygen to the DWC component (Figure 3.2).

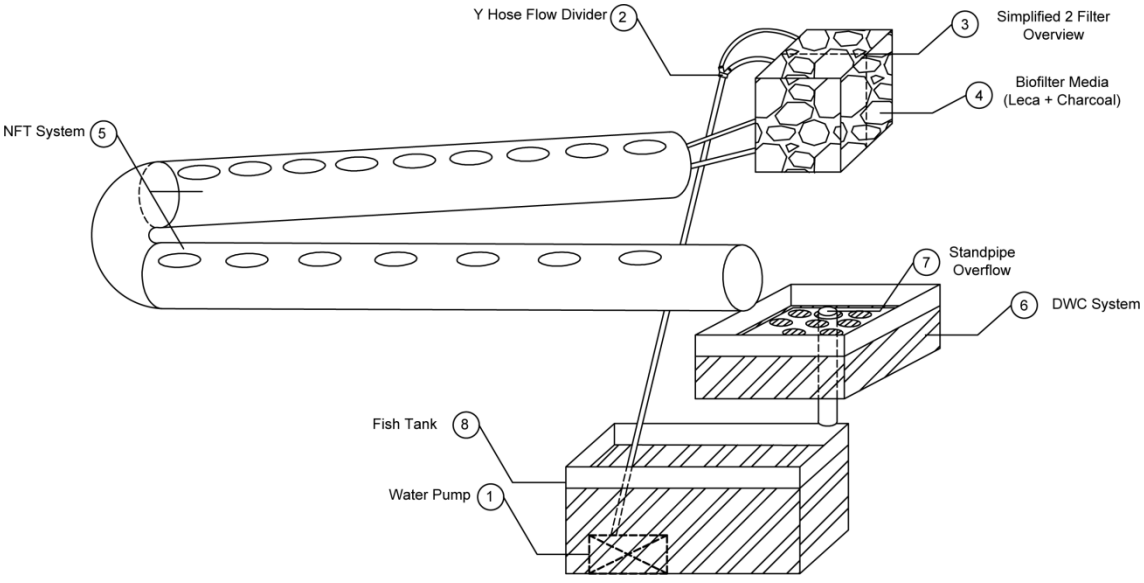

Figure 3.2. System 2 Overview

The third system built is also located in the greenhouse, and is a combination of a Media Bed system with a DWC system and vertical farming (System 3), using aged human urine as the ammonia source rather than fish waste. The Media Bed component, made from an IBC, is running on a flood and drain cycle with a bell siphon while the DWC component and the towers

of the vertical farming component are running on a continuous flow cycle. Since the system runs on aged human urine, there are no fish in any part of the system. The overall system has a sump tank from which the water is pumped to twelve towers filled with LECA, and to the Media Bed component. The water drips into the towers through valves that allow for flow regulation, with eight of the towers being located on top of the DWC component and the remaining four being located on top of the Media Bed. The DWC component has a standpipe which allows for a constant water level and returns the overflow to the sump tank. The water from the four towers on top Media Bed component, as well as the water pumped from the sump tank, supplies water to the grow bed. Since the flow rate from these two sources was not enough to start the bell siphon automatically, an extra water pump was added in the water reservoir below the grow bed to recirculate the water. An overflow pipe on the water reservoir below the grow bed returns the water to the sump tank. As an additional oxygen source, an air pump provides air to two air stones, one on the DWC component and the other to the water reservoir below the grow bed (Figure 3.3).

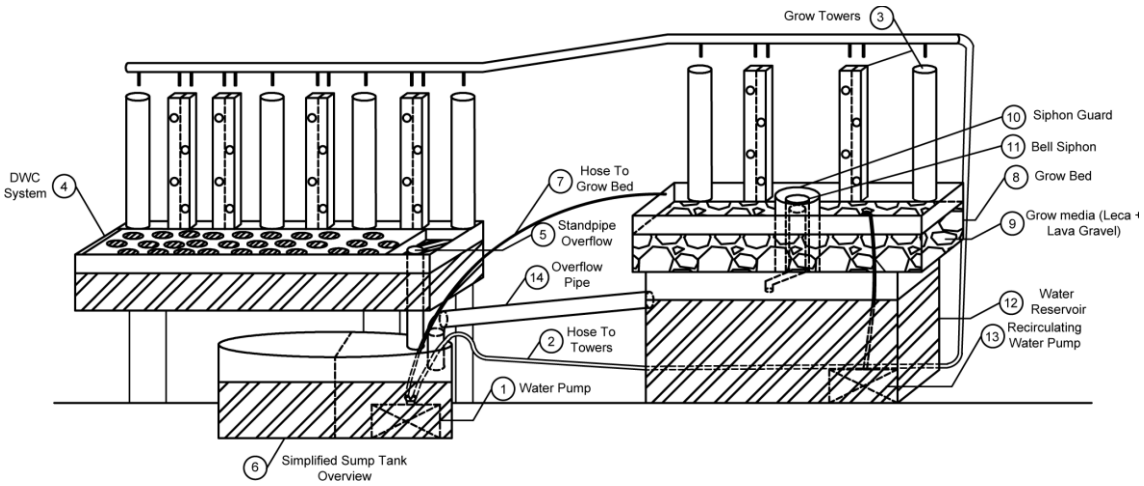

Figure 3.3. System 3 Overview

3.5.2. Assumptions, Building and Calculations

Assumptions

For the building of Media Bed systems it is often suggested to follow a 1:1 ratio or 2:1 of volume occupied by the grow media in the grow bed to the water volume in the fish tank (Bernstein, 2013). However, other designs using an IBC ignore this suggestion, achieving ratios of 1:2 or 1:3 (Malcolm & Faye, 2011). As such, the main assumption followed when building Media Bed systems from IBC is the suggestion that all of the water volume should circulate through the grow bed within one hour (Bernstein, 2013), which requires a certain minimum pump flow rate. The Media Bed system used indoors (System 1) as well as the Media Bed component of the human-urine based aquaponics system in the greenhouse (System 3) were both built out of an IBC, and the instructions were adapted from Malcom & Faye's 2011 *IBC of Aquaponics Edition 1.0*. In that document together with Bernstein's 2013 *Aquaponic Gardening*, it is recommended that the grow bed has at least 30 cm of depth as a standard, although there is no scientific research behind this recommendation (Bernstein, 2013).

The type of media chosen was LECA and lava gravel, mostly out of convenience as they were already available in the farm, but also since they possessed an appropriate diameter between 12 mm and 18 mm (Bernstein, 2013). During the system designing stage, attention was focused on the water returning to the lowest point of the system to ensure that some splashing of the water occurred. This is done to accomplish an increase in the dissolved oxygen of the water, by

increasing the surface area of the water body and thus the amount of gas exchange from the water body to the atmosphere (Lennard[5], 2012).

Siphon size and piping is dependent on the size of the bulkhead fitting, a device used to connect a pipe through a grow bed whole without leaking water. The recommended ratio of bell siphon diameter to the standpipe drain is 2:1 (Fox *et al*, 2010), and was the minimum ratio followed. The available materials found in stores resulted in a ratio of bell siphon diameter to the standpipe drain of 3:1.

The main design assumptions for the two more complex systems (System 2 and System 3) were to place more nutrient demanding plants in the biofilter (such as the grow bed and towers of System 3) or immediately after it (such as the NFT component of System 2). Less nutrient demanding plants would be placed immediately before the fish tank or the sump tank, in a DWC system. This was based from Lennard & Leonard's 2006 *A comparison of three different hydroponic sub-systems (gravel bed, floating and nutrient film technique) in an Aquaponic test system*, where it was concluded that NFT and DWC systems were less able to support more nutrient demanding plants with bigger root systems.

Building

The first aquaponics system built was the indoor Media Bed system (System 1) located in the boiler room of the farm. It was built out of an IBC and was adapted from the instructions of Malcom & Faye's 2011 *IBC of Aquaponics Edition 1.0*. Construction began on February 12th 2014 and it was completed on March 3rd 2014, without any plants or fish added. The construction included cutting the IBC and its metal frame from the bottom to a height of 70 cm. The end result is a fish tank with a volume of 1464,75 L (135 cm x 155 cm x 70 cm), and a grow bed with a volume of 627,75 L (155 cm x 135 cm x 30 cm) (Figure 3.4).

Figure 3.4. Cutting the IBC metal frame where the grow bed will rest. February 13th 2014

The lid of the IBC is located in the grow bed component, which was drilled to create a ⌀=3 cm hole. A bulkhead fitting was placed in the hole to allow for the standpipe to be placed above as well as to ensure a watertight seal of the grow bed. A white plastic pipe (⌀=3 cm) was cut to a length of 35 cm and inserted through the bulkhead fitting, rising 20 cm from the bottom of the grow bed with the remaining 15 cm below the grow bed. This pipe serves as the standpipe and will regulate the maximum height of water the grow bed will have before the siphon begins. An additional rubber connection (⌀=2,5 cm) was added at the bottom of the standpipe near the bulkhead fitting, to ensure further watertight seal. The bottom of the standpipe had a 90° connector attached followed by a 60 cm long pipe of the same type as the standpipe, but with aeration holes drilled into it.

The bell siphon was built from a ⌀=9 cm PVC pipe, cut to a height of 30 cm and with an airtight lid placed on its top. The bell siphon had ⌀=0,5 cm holes drilled in the bottom 5 cm of the PVC pipe to allow water inflow. The siphon guard, which serves as a physical protection of the bell siphon from clogging with media, was cut from an orange plastic pipe (⌀=20 cm) to a length of 30 cm. The siphon guard also had slits cut to ensure water inflow, but small enough to prevent media from flowing through.

The media, consisting of LECA and lava gravel, was rinsed with tap water and mixed in the grow bed to a height of 20 cm. The lack of layering between these two types of media resulted in the LECA to float as the water level increased, resulting in some occasional siphon clogging as well as plant submersion. Until the LECA became soaked enough to stop rising with the water level, an overflow exit was built consisting of a ⌀=3 cm hole with a bulkhead fitting, a protective net, and a 90° pipe with another 40 cm length pipe.

Regular tap water was added to a height of 55 cm in the fish tank, corresponding to 1150 L of water. An available pond pump with a flow rate of 7 600 L/h was inserted in the bottom of the fish tank, and a ⌀=4 cm hose connected the pump to the top of the grow bed. The final step was adding 400 W High Pressure Sodium lamps at a height of 60 cm to the media level in the grow bed (Figure 3.5).

Figure 3.5. Evolution of the Indoor aquaponics system (System 1). March 3rd 2014 - July 7th 2014

The second aquaponics system built (System 2) was the NFT and DWC combined system located in the farm's greenhouse. It was built using materials available at the farm such as an aquarium, a container, pipes, and barrels. Construction began on April 1st 2014 and it was completed on April 4th 2014, without any plants or fish added. The fish tank used had a volume of 220 L (110 cm x 40 cm x 50 cm), the two filters have a combined volume of 60,2 L (35,2 L + 25 L), and the DWC reservoir had a volume of 147 L (70 cm x 70 cm x 30 cm). The total water volume in the fish tank with 40 cm of water height and DWC reservoir with 20 cm of water height corresponds to 274 L (176 L + 98 L).

Construction began by digging an approximately 15 cm deep pit in the greenhouse soil to place the fish tank in. A steel framed table was placed on top of the fish tank, with the supports resting on concrete bricks that were placed on both sides of the pit near the fish tank. In the middle of the steel framed table there is enough space and support to place the DWC reservoir, which had a ⌀=3 cm hole drilled where a bulkhead fitting was inserted. A ⌀=3 cm white plastic pipe 30 cm long serving as the standpipe was then placed through the bulkhead fitting, with 20 cm of it inside the DWC and the remaining 10 cm right above the fish tank (Figure 3.6).

Figure 3.6. NFT pipes and DWC reservoir placement. April 1st 2014 – April 3rd 2014

Initially only the 35,2 L filter was placed on the top part of the steel framed table and above the DWC, but later on a second filter with an additional 25 L of total volume was placed at an elevated height next to the first filter. A ⌀=12 cm PVC pipe with a length of 200 cm attached to the greenhouse wall with a slope of 4%. An additional ⌀=10 cm plastic pipe with a length of 240 cm was placed slightly further away from the greenhouse wall with a slope of 6,25%. The tip of the 240 cm plastic pipe rests on the edge of the DWC reservoir. The NFT pipes used had a total of sixteen ⌀=8 cm holes drilled into them, separated from one another by 25 cm – 30 cm of distance to place net pots (Figure 3.7).

Figure 3.7. NFT pipe holes with a diameter of 8 cm and spaced 25 cm from one another. April 4th 2014

The filters were filled with rinsed LECA and charcoal, and later covered in a black plastic to prevent excessive algae growth. The individual system components were connected by first placing a 1 750L/h pump in the fish tank, with a ⌀=1,5 cm garden hose connecting the pump to the first filter and continuing to the second filter through a garden hose Y connector, to a height of 150 cm. The hose enters the filter container through an open lid at the top and exits through an exit valve at the bottom, which has a ⌀=1,5 cm garden hose connecting it to the NFT 200 cm pipe.

Both NFT pipes were connected to one another through a rubber inner tube tire, which was washed prior to use to remove any existing contaminants. The ends of the rubber inner tube tire are secured to each pipe with metal pipe holders. In the DWC reservoir, a 24,5 L Styrofoam board (70 cm x 70 cm x 4 cm) was placed with thirteen ⌀=8 cm holes drilled into them, twelve of them used for net pots and one to prevent blocking of the standpipe. The fish tank was then

covered with pond liner on the sides, and a lid was placed over the fish tank to prevent an increase in algae growth due to excess sunlight (Figure 3.8).

Figure 3.8. Evolution of the Greenhouse aquaponics system (System 2). March 4th 2014 – June 9th 2014

The third system built was the human urine-based aquaponic system (System 3) located in the farm´s greenhouse, combining a Media Bed, towers and a DWC component. It was built using a repurposed aquaponic grow bed as the DWC reservoir, two plastic barrels, an IBC and several PVC pipes and recycled plastic towers available at the farm. Construction began on April 31st 2014 and it was completed on May 9th 2014, without any plants or fish added. The main components include a sump tank made of two connected barrels, a DWC water reservoir, a Media Bed water reservoir and a grow bed.

The sump tank used had a combined volume of 368 L (214 L + 154 L), the DWC water reservoir had a volume of 370,5 L (190 cm x 65 cm x 30 cm), the grow bed had a volume of 627,75 L (155 cm x 135 cm x 30 cm), and the Media Bed water reservoir had a volume of 1 464,75 L available (135 cm x 155 cm x 70 cm). The total water volume in the system is 1 746,6 L (136,1 L + 10, L + 247 L + 1 255,5 L), where the water height of the connected sump tanks is 35 cm and 28 cm, 20 cm in the DWC water reservoir, and 60 cm in the Media Bed water reservoir.

Construction began by repurposing an old aquaponic grow bed built from recyclable plastic towers into the DWC water reservoir. The previous media was rinsed and removed, the existing pond liner was washed and a new ⌀=3 cm standpipe with 20 cm of height from the bottom of the DWC water reservoir was added. This standpipe had a total length of 200 cm and was placed directly above the sump tank where the pump would be located. Three recycled plastic towers were cut to a height of 20 cm and placed in the DWC water reservoir and underneath a plastic fit for the support of the growing towers (Figure 3.9). The plastic fit was 190 cm in length and had been drilled with ⌀=0,5 cm holes every 10 cm for drainage of the water coming from the towers above.

Figure 3.9. Tower support structure in the DWC water reservoir. April 16th 2014

The total number of towers used above the water reservoir was eight, four made from ⌀=8 cm PVC pipe and four made from recyclable plastic. All towers have a height of 70 cm, and the four towers made from recyclable plastic had four ⌀=5 cm holes drilled for future plant placement. The towers were all filled with LECA as it was the lightest type of media available. The construction of the Media Bed component followed the same steps and used the same materials as the construction of the indoor aquaponic system in the boiler room of the farm (Figure 3.10).

Figure 3.10. From left to right: Cutting the IBC, drilling the grow bed support and final assembly. March 31st 2014 – April 16th 2014

The media added on the grow bed was added in layers of LECA and lava gravel to ensure enough weight on the LECA to prevent it from rising with the water level (Figure 3.11). On top of the final layer of LECA, a plastic fit with a length of 155 cm was placed and four growing towers were positioned, comprising of two ⌀=8 cm PVC towers and two recyclable plastic towers. These last towers had the same number and diameter of the holes as the recyclable towers in the DWC water reservoir, and the plastic fit also had the same drainage holes mentioned previously.

Figure 3.11. Media layering technique. March 16th 2014

The Media Bed water reservoir had a ⌀=3 cm hole drilled at a height of 60 cm to regulate the maximum water level. A bulkhead fitting was inserted in that hole, with an outside ⌀=3 cm pipe with a length of 75 cm, connected to a same diameter pipe with 150,0 cm of length through a 90° connector. The end of the 150 cm length pipe reaches the sump tank where the pump would be located.

The individual System 3 components were connected by first placing a 1 750 L/h pump in the sump tank below the DWC water reservoir tank, with a Y connector with flow regulation. Two ⌀=1,5 cm garden hoses connect the pump to the IBC grow bed and to the top of the first tower on top of the grow bed, at a total height of 170 cm from the pump to the top of the tower. Here the hose connects to a ⌀=2,2 cm dripper hose which had ⌀=0,3 cm holes drilled above each tower. The end of the dripper hose was bent in order to create positive water pressure so the water would flow from all the drilled holes. Later on regulating flow valves were added to each hole in the dripper hose. An additional pump was added to the Media Bed water reservoir, with a flow rate of 380 L/h and pumping the water to a height of 110 cm to help start the bell siphon. An air pump with a double connector and two air stones supplied oxygen to the DWC water reservoir as well as the Media Bed water reservoir (figures 3.12 and 3.13).

Figure 3.12. Greenhouse human urine-based aquaponic system overview. May 27th 2014

Figure 3.13. Greenhouse human urine-based aquaponic system overview. July 7th 2014

Calculations

The indoor Media Bed system (System 1) built out of an IBC had a total of 1 150 L of available water with a height required to pump the water of 115 cm. The siphon used has problems in breaking the siphon action correctly, requiring the use of a timer to stop the incoming flow of water to the grow bed. As the timer works only during 15 minutes every hour, the pump used must have a minimum flow rate of 4 600 L/h (1 150 x 4). There was fortunately a pump available in the farm with enough flow rate, offering 7 600 L/h, thus not requiring any extra costs in purchasing a pump.

The Media Bed water reservoir built out of an IBC in the greenhouse human-urine based aquaponic system (System 3) had a total of 1 255,5 L of available water. The grow bed received water from the sump tank (360 L/h) and distributed from the towers (875 L/h) which was not enough to start the siphon. Therefore, a recirculating pump was needed, and it would have to overcome a height of 110 cm. The addition of a recirculating pump with a flow rate of 380 L/h not only provided enough flow to start the siphon, but it also allowed for all of volume of water in the Media Bed water reservoir to be circulated through the grow bed within 1 hour.

The greenhouse aquaponic system (System 2) did not require flow calculations as it operates in a continuous flow without any siphons, and the pump flow rate (1 750 L/h) was enough to pump the water to the necessary 150 cm of height to the filters.

3.5.3. Cycling process

Cycling is the process by which a beneficial nitrifying bacteria colony is established in an aquaponics system (Bernstein, 2013). Certain autotrophic bacteria (mainly *Nitrosomonas*) convert ammonia, the main excretion product from fish, to nitrite (NO_2^-) and others (mainly *Nitrobacter*) convert nitrite to nitrate (NO_3^-) (Tyson *et al*, 2004).

The cycling process starts by adding an ammonia source in an appropriate quantity. According to Bernstein's 2013 *Aquaponic Gardening* this can be done with fish, with commercial ammonia and even with human urine. Commercial ammonia was chosen as it was already available at the farm and it would hasten the cycling process without risking any harm to the fish, which are added after the cycling process. On the other hand, some plant species and seedlings were placed in cycling systems to uptake the available nitrates from the nitrifying bacteria. Cycling using commercial ammonia was only used for the indoor aquaponics system (System 1) and the greenhouse aquaponics system (System 2), whereas the cycling for the greenhouse human urine-based aquaponics system (System 3) was done with aged human urine.

The ammonia source used had 24,5% of ammonia by weight (Figure 3.14). The recommended dosage to add is 24,65 mL for every 378,54 L of fish tank water volume with 10% ammonia (Bernstein, 2013).

Figure 3.14. Commercial ammonia used (24,5%). April 24th 2014

The first step was to calculate how many milliliters of 10% ammonia would be required for the volume of water in liters of the cycling systems' fish tanks. The indoor system (System 1) has a fish tank water volume of 1 150 L and would require:

$$\frac{1\,150\ L\ x\ 24{,}64\ mL}{378{,}54\ L} = 74{,}87\ mL \text{ of } 10\% \text{ ammonia}$$

However, since the available ammonia had a higher percentage of ammonia per weight (24,5%), the required amount of mL is:

$$\frac{74{,}87\ mL\ x\ 0{,}10}{0{,}25} = 30{,}56\ mL \text{ of } 24{,}5\% \text{ ammonia}$$

The same calculations were done for the greenhouse aquaponics system (System 2), which has a fish tank water volume of 176 L and requires:

$$\frac{176\ L\ x\ 24{,}64\ mL}{378{,}54\ L} = \ 11{,}48\ mL \text{ of } 10\% \text{ ammonia}$$

Resulting in:

$$\frac{11{,}48\ mL\ x\ 0{,}10}{0{,}25} = 4{,}69\ mL \text{ of } 24{,}5\% \text{ ammonia}$$

The greenhouse human urine-based aquaponics (System 3) system was cycled with aged human urine rather than commercial ammonia. Given that there was no reliable method to estimate the percentage of ammonia per total weight, a more experimental approach was followed. The average volume of urine per occasion was 0,4 L, thus this was the amount of urine added to the system, after aging. The urine was aged on average for a period of 2-4 weeks (Figure 3.15), and litmus paper was used to gauge the pH levels. The final concentration of urine to the water volume of System 3 (1 746,6 L) was 0,02%.

Figure 3.15. Example of the aged urine used for cycling and maintaining the greenhouse human urine-based aquaponics system (System 3). June 25th 2014

After adding the ammonia or urine, monitoring of Total Ammonia Nitrogen or TAN, nitrite and nitrate levels was conducted through the use of commercial test kits (Figure 3.16). Temperature and pH levels were also monitored through a thermometer and a commercial test kit, respectively.

Figure 3.16. From left to right: JBL test kits for ammonium/ammonia, nitrite and nitrate. March 30th 2014.

All tests rely on titration methods with a colorimetric analysis; however the companies were unable to give out information regarding reagents used in their test kits.

The cycling of the indoor aquaponics system (System 1) began on February 23rd 2014 and ended on March 16th 2014. A system is considered cycled once ammonium levels and nitrite levels have tested positive, peaked in value, and then dropped to zero (Bernstein, 2013). There is of course flexibility in ranges of these parameters, and the indoor aquaponics system (System 1) was considered cycled once TAN (Total Ammonia Nitrogen) levels and nitrite levels were tested as less than 0,10 mg/L. Below are the results (Figure 3.17).

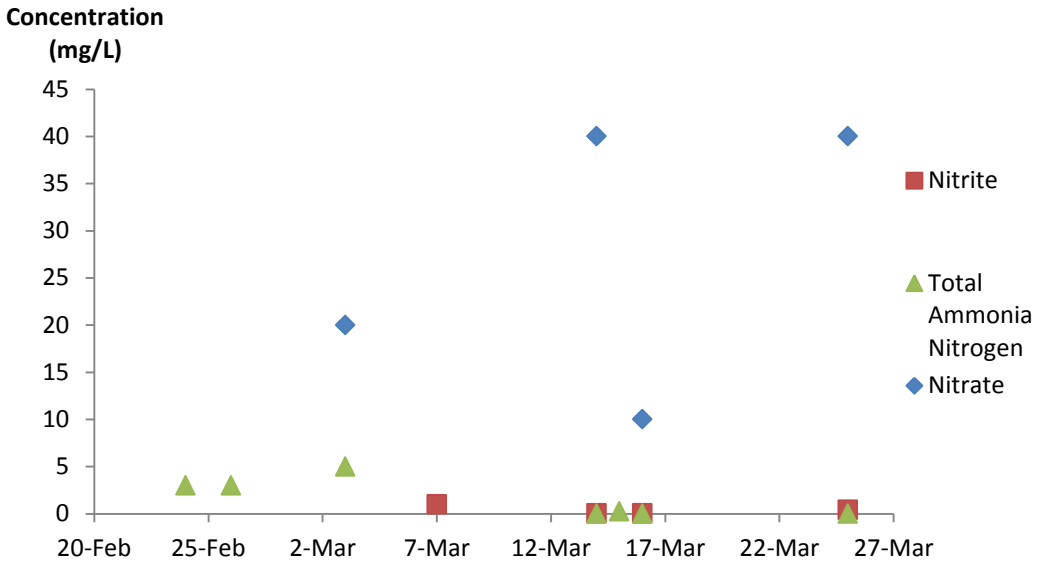

Figure 3.17. Cycling parameters of total ammonia nitrogen, nitrite and nitrate in the indoor aquaponics system (System 1) through a period of one month

In Figure 3.17, it is noticeable how the nitrifying bacterium converts the amount of TAN and nitrites into nitrates, despite an outlier for nitrate concentration. Although the relationship is observable, the values of each parameter largely depend on which step of the nitrifying process the system is in. A much better correlation could have been observed if the chemical tests had been done three times a day or even daily. Unfortunately, there were time and material restrictions which prevented such possibilities.

The cycling of the greenhouse aquaponics system (System 2) began on April 3rd 2014 and ended on April 24th 2014. The results are presented in Figure 3.18.

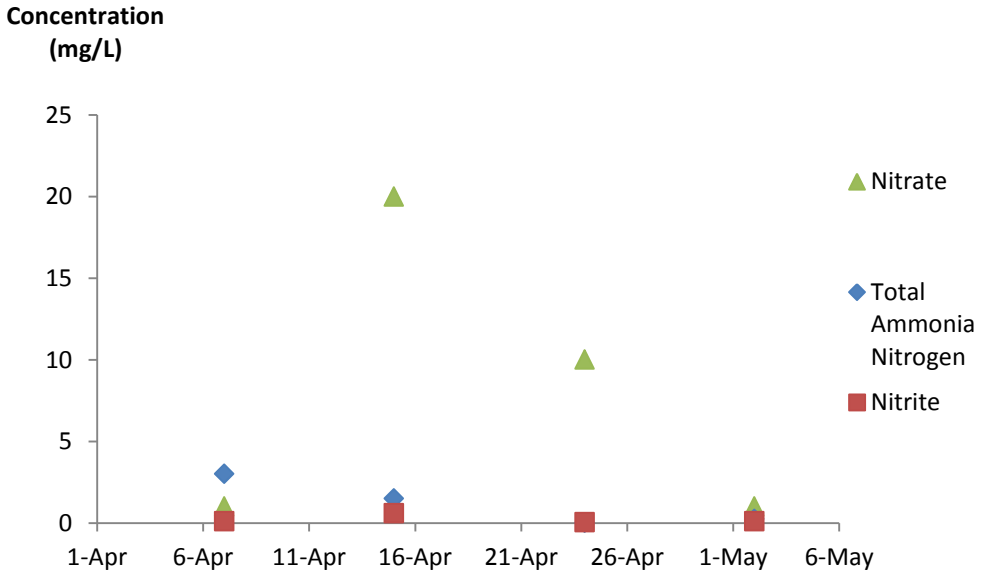

Figure 3.18. Cycling parameters of total ammonia nitrogen, nitrite and nitrate in the greenhouse aquaponics system (System 2) through a period of one month

Once again, it is observable how the nitrifying bacterium converts the amount of TAN and nitrites into nitrates. Once more, testing three times a day or just daily would have been preferable.

The cycling of the greenhouse human urine-based aquaponics system (System 3) began on May 9th 2014 and ended on May 21st 2014. Below are the results:

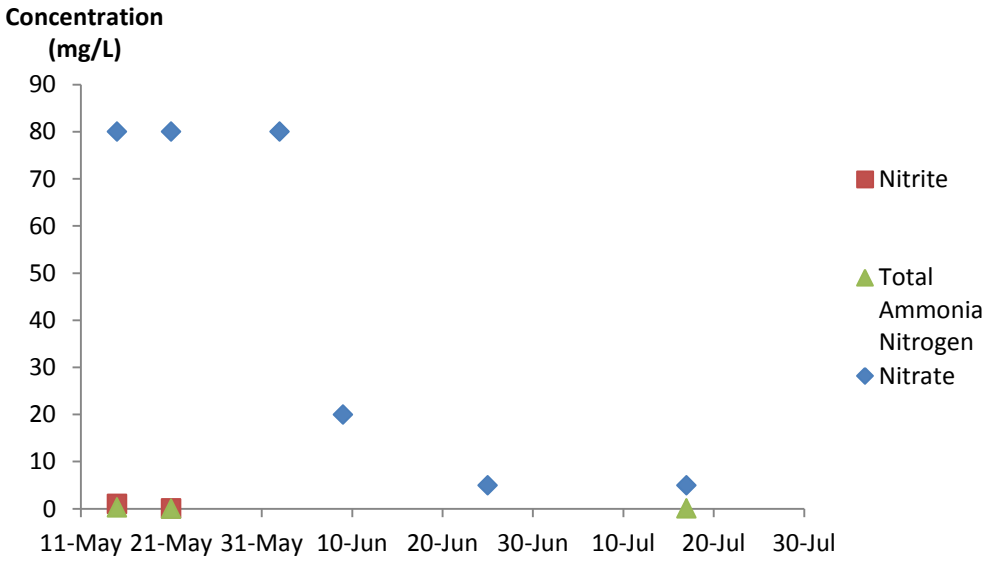

Figure 3.19. Cycling parameters of total ammonia nitrogen, nitrite and nitrate in the greenhouse human urine-based aquaponics system (System 3) through a period of about one month

In this particular system, very few tests were made due to time constrains and required system maintenance. Like in the other systems, a decrease of the concentration of TAN and nitrite was observed, however relatively small. The continued decrease of nitrates signaled nutrient uptake by the plants, which was also observed by the amount of produce collected during the same time period.

3.5.4. Monitoring parameters and maintenance

After the cycling process, regular chemical tests were conducted until August 2014. Weekly chemical testing of pH and ammonia is recommended (Bernstein, 2013); however tests for all parameters were conducted semi-regularly due to time constraints. All tested parameters (temperature, pH, TAN, nitrite and nitrate) were plotted for each system and are presented in Annex I.

Testing of all parameters also allowed for remediating action as they are indicators of biological activity. On two occasions the death of fish in the greenhouse aquaponic system (System 2) signaled a malfunctioning filter and required a partial water change as well as a lower fish feed input until TAN and nitrite levels lowered. High nitrate levels also signal that the system can support more vegetative growth. High pH levels were tested, and driftwood was added on occasion as a way to lower pH levels to a range that enables the nitrification process to occur optimally, between 6,5 and 7 (Tyson *et al*, 2004).

Common maintenance practices for all systems include adding Liquid Iron Chelate (0,03% Fe-DTPA and 0,03% Fe-EDDHA) and SM6 Seaweed Extract for iron supplementation and for other trace nutrients as well as for an increased nutrient uptake (Chase Organics, 2010) (Figure 3.20). Nutrient deficiencies are somewhat common in aquaponic systems as the fish waste does

not supply all of the nutrients necessary for plant growth in the needed quantities (Lennard[2], 2012). A number of resources exist to identify nutrient deficiencies based on the vegetative growth of the plant leaves (Bright Agrotech, 2014).

Figure 3.20. From left to right: Liquid Iron Chelated and SM6 Seaweed Extract. May 29th 2014 and April 24th 2014 respectively

Different aquaponic systems require differing maintenance practices. For example, the indoor aquaponics system (System 1) requires the light height to be adjusted to the vegetative growth. On the other hand, the greenhouse aquaponics system (System 2) requires regular flow control of the water arriving to the filters and pump cleaning, as solid fish waste can clog the pump and the filters' outflow. The greenhouse human urine-based aquaponics system (System 3) also requires regular pump cleaning in addition to cleaning the irrigation holes that feed the towers due to biofilm build-up. The bell siphon of the greenhouse human urine-based aquaponics system (System 3) also has to be adjusted occasionally as the flow can be irregular. Additionally, slugs entering the greenhouse from the garden have to be removed to protect the plants.

3.6. Integration with food production and living organisms

Several approaches exist to calculate the amount of fish that an aquaponics system can support. One of them establishes a relation between the amount of fish feed with the plant growing area (Lennard[2], 2012), although it is restricted to a specific fish (*Tilapia spp.*) studied. Another approach suggests ≈ 0,45 kg of fish for every ≈30 - 38 L of water (Downing, 2013). One other approach suggests using 500 g of fish for every 100 to 200 liters of fish tank water (Bernstein, 2013). Ultimately, the approach followed was the one which yielded the least fish stocking density, as fish production was not a study objective.

The fish species selected were ornamental rather than edible fish found in common aquarium shops, with the highest possible tolerance to wide temperature and pH ranges. Since indoor Swedish winter temperatures in the region of Skåne may be too cold for fish, there were few affordable and adequate fish species choices available. The fish chosen were Koi (*Cyprinus carpio haematopterus*) and Goldfish (*Carassius auratus auratus*) as they are resistant, relatively affordable, and used with success in aquaponic systems as reported by aquaponic enthusiasts.

The fish stocking was calculated for all systems by assuming full-grown Koi weight of 1 000grams (Albert, 2005), and a full-grown goldfish weight of 300grams (L.G. *et al*, 2013). Since the fish tank water volume of the indoor aquaponics system (System 1) has 1 150 L, five Koi were added and twenty Goldfish were added. For the greenhouse aquaponics system (System 2) with a fish tank water volume of 176 L, seven Goldfish were added. Koi were not

added since the water volume of the fish tank was considerable lower to support both Goldfish and Koi.

The feeding of the fish in both systems was done daily and followed the rule of thumb that fish should be fed as much as they will eat in a period of five minutes (Bernstein, 2013). This resulted in approximately 0,05 L of commercial fish food per system every day. Red wigglers (*Eisenia foetida*), a type of worm, were added to all grow beds and the filters to help breakdown uneaten fish food as well as fish waste (Bernstein, 2013). However, this addition does not prevent the existing limitations of grow beds as a mechanical filter of aquaponic systems (Lennard[1], 2012).

The plants chosen were species that were reported successful by aquaponic enthusiasts. These include Rosemary (*Rosmarinus officinalis*), Lettuce (*Lactuca sativa*), Rucola (*Eruca sativa*), Tatsoi (*Brassica narinosa*), Dill (*Anethum graveolens*), Basil (*Ocimum basilicum*) and Parsley (*Petroselinum crispum*). More nutrient demanding plants that bear fruit such as Cucumber (*Cucumis sativus*), Tomato (*Solanum lycopersicum*), and Strawberry (*Fragaria* × *ananassa*) were placed in grow beds and NFT component. Less nutrient demanding plants such as salad greens, lettuce and herbs were placed in the DWC components of the greenhouse systems.

In the indoor system (System 1) as well as in the Media Bed component and the towers of the human urine-based aquaponics system (System 3), all plants were placed directly in the grow media. In the NFT and DWC components of both aquaponics system (System 1 and 2) the plants were placed in net pots filled with LECA, or they were held in the holes with pieces of aquarium filter, as a lighter weight solution.

Iron nutrient deficiency was observed in many plants of the systems and was diagnosed using Bright Agrotech's 2014 *A simple key for diagnosing common nutrient deficiencies in aquaponic systems* (Figure 3.21).

Figure 3.21. Comparison of a strawberry plant with Iron deficiency (left) from the greenhouse aquaponics system, and a strawberry plant without Iron deficiency (right) from the greenhouse human urine-based aquaponic system. May 27th 2014 and June 16th 2014

Liquid Iron Chelate was dosed in all systems to supplement the deficiency, considering a moderate deficiency of 1 ml of Liquid Iron Chelate per liter of water volume, according to the bottle dosing instructions. As Liquid Iron Chelate is an expensive product sold in 1 L bottles and the total requirement mounted to 3 L, only one bottle was bought as an experiment. The amount of Liquid Iron Chelate that should have been added was 1,15 L for the indoor aquaponics system (System 1), 0,27 L for the greenhouse aquaponics system (System 2) and

1,75 L for the greenhouse human urine-based aquaponics system (System 3). Instead, the dosing was divided as 0,2 L for the indoor aquaponics system and the greenhouse aquaponics system and 0,5 L for the greenhouse human urine-based aquaponics system, as it presented the most noticeable Iron deficiency signs. The remaining 0,1 L of the 1 L bottle was added 45 days later to the greenhouse human urine-based aquaponics system as iron deficiency signs re-emerged in new plant growth.

4. Chemical Analysis and Discussion of the Results

4.1. Description of the Chemical Analyses

The chemical analyses were performed during a period of four days, from August 5th to August 8th 2014 in all aquaponic systems. The goal was to observe the evolution of several nutrient parameters concentration after a certain volume of nutrient input added to each system.

Relevant parameters that are commonly used in aquaculture effluent quality control and waste water effluent quality control include:

- Biological Oxygen Demand (BOD)
  A measure of the biological activity of aerobic bacteria; high values could indicate that there is an excess in nutrients in the water.
- Total Ammonia Nitrogen (TAN)
  A measure of fish waste, which includes ammonia (NH_3)and ammonium (NH_4^+) , where high values are dangerous to fish.
- Total Nitrogen (TN)
  A measure of the main forms of nitrogen: ammonia, nitrite, nitrate and organic nitrogen. It is a common measurement for human and aquaculture waste water, where high values indicate a lack of nitrifying bacteria essential in removing the pollution from the water.
- Total Phosphorus (TP)
  A measure of all forms of phosphorus: orthophosphate, condensed phosphate, and organic phosphate present in human and aquaculture waste water. High values can lead to death of aquatic animals since it triggers algae blooms and lower levels of dissolved oxygen.
- Dissolved Oxygen (DO)
  A measure of the oxygen in an aquatic environment. Low values are harmful for aquatic animals and inhibit the nitrification process by the nitrifying bacteria.
- Total Organic Carbon (TOC)
  A measure of the amount of carbon in an organic compound. High values indicate decaying organic matter which is harmful for aquatic life forms.
- Total Coliforms
  A measure of all coliform bacteria which indicates the presence of environmental stress or pollution. High values indicate the possibility of waterborne disease outbreaks to occur.
- Fecal Coliforms
  A measure of facultative anaerobic coliform bacteria which indicates the presence of fecal matter. High values indicate the possibility of waterborne disease outbreaks to occur.
- *Escherichia coli*
  A type of fecal coliform which indicates true fecal contamination. High values indicate the possibility of waterborne disease outbreaks to occur.

No nearby University or credited laboratory was able to assist in any of these tests. A commercial test kit solution for these parameters as well as paying for private laboratories or companies for the tests was a too expensive solution for the project budget. Available test kit solutions that were available and affordable for the project budget included TAN or Total Ammonia Nitrogen (NH_4^+/ NH_3), Nitrite (NO_2^-), Nitrate (NO_3^-), Phosphate (PO_4^{3-}) and Dissolved Oxygen (O_2). While less representative, and susceptible to induce biased results, these tests still allow an overview of the evolution of the parameters to assess how the aquaponics systems filter and remove nutrients from water.

All inputs to the systems, such as commercial fish food for the aquaponic systems (Systems 1 and 2) and aged urine for the human urine-based aquaponic system (System 3), ceased on

August 4th 2014. On August 5th, the chemical tests described earlier were conducted. After performing the tests, 15 mL of commercial fish food was added in each aquaponic system (System 1 and 2), and 0,38 L of aged urine was added in the human urine-based aquaponic system (System 3) (Figure 4.1).

Figure 4.1. Commercial fish feed added to System 1 and 2 (left) and aged urine added to System 3 (right). August 5th 2014

For the next four days, the chemical tests were performed on each system every 24h after the initial nutrient input. All the samples were taken in the system component where the inputs were added. In the case of the indoor aquaponic system (System 1) and the greenhouse aquaponic system (System 2), the samples were taken from the fish tank. In the greenhouse human urine-based aquaponic system (System 3), the sample was taken from the sump tank.

A control consisting of the farm well water, used to originally fill all systems, was also collected and tested for the same parameters. The colorimetric analyses results were recorded, and graphed for a better understanding of the development of the various concentrations through the time period (Figure 4.2).

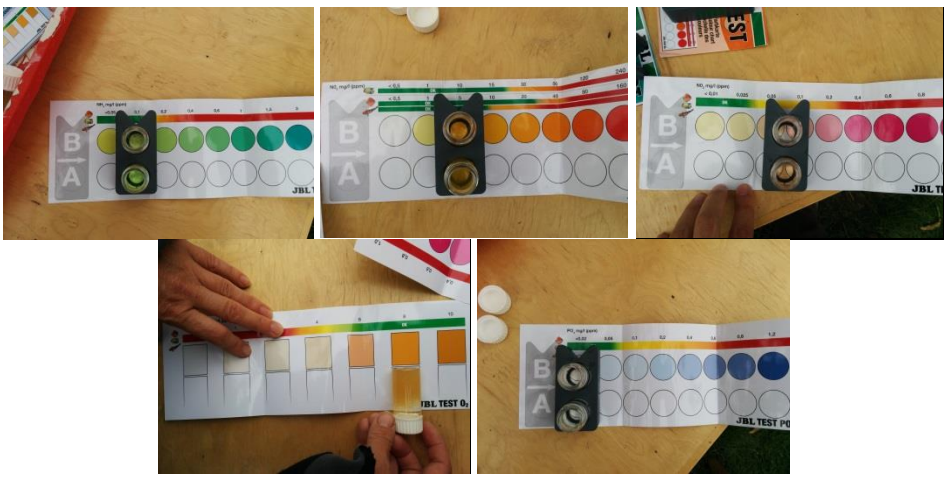

Figure 4.2. Example of colorimetric results from all the parameters tested. August 5th 2014

4.2. Expected results

The expected results are based on the knowledge of how the nitrifying bacteria decompose fish waste or urine, as described in sections 2.2.2 and 2.4.1. The basic process involves ammonium in the fish waste being broken down by nitrifying bacteria into ammonia, nitrites and nitrates. Thus the expected results should be an initial peak in total ammonia nitrogen, followed by a simultaneous decrease in total ammonia nitrogen and increase in nitrites. The resulting nitrites decrease as they are converted into nitrates which continue rising until plants are added for the nitrate absorption. Overall, it is expected TAN, NO_2^- and NO_3^- levels to simulate a starting biofilter (Figure 4.3) but in a shorter time span as all the case study systems already have a working bacterial colony.

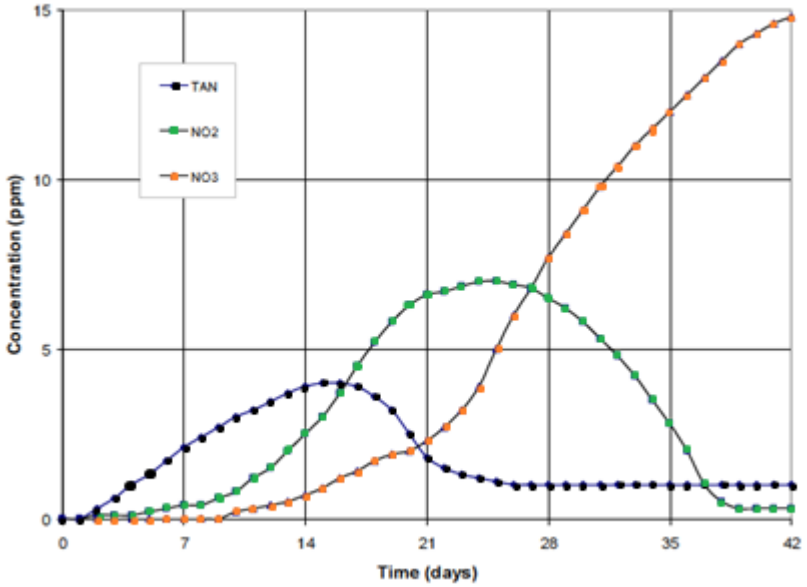

Figure 4.3. Adapted figure on the evolution of TAN, NO_2^-, and NO_3^- on a starting biofilter of a Recirculating Aquaculture System (Molleda, 2007).

Phosphate levels should increase after the fish food and aged urine is added, as it is a traceable component of the two inputs. Over time they should decrease as they are absorbed by the plants and algae present in the systems. Dissolved oxygen levels should remain constant due to constant water aeration, however slightly lower values can be expected after the input is added since the nitrifying bacteria are aerobic and consume oxygen while metabolizing the nutrients.

4.3. Results and discussion

The results are presented in the form of graphs which plot the concentration of each parameter in mg/L over the test period (August 5th 2014 to August 8th 2014). On many occasions the colorimetric results were between two values on the color scale. While this is normal since colorimetric results may be subjective, an average of the values was calculated when creating the graphs in order to plot a single value. If colorimetric results was the lowest detectable value for the testing kit scale (e.g. = <0,05 mg/L) the absolute value was used (e.g. = 0,05 mg/L).

An additional green cross was placed in the graphs to indicate when the nutrient input was added in the systems. To simplify the graph titles and to facilitate the discussion of the results, the indoor aquaponic system was termed “System 1”, the greenhouse aquaponic system was termed “System 2” and the greenhouse human urine-based aquaponic system was termed “System 3”.

It is important to note that the results may have been subject to human error while conducting the chemical tests or while judging the colorimetric results which, in addition with the reduced liability of the used methods, can introduce biased results. The aquaponic systems are also a complex biological system and could not be tested in an ideal controlled laboratory environment.

4.3.1. Control results

The results for the control tests performed on the farm's well water presented good results for water quality for watering and drinking purposes (Table 4.1), according to the WHO drinking water quality guidelines (WHO, 2011). All parameters tested were on the lowest range value of the testing scale, with the exception of nitrate and oxygen. These two parameters were closer to the lower-middle range of the scale, but still with acceptable values that are not harmful.

Table 4.1. Concentration of the tested parameters in the farm's water well

Parameter	Concentration (mg/L)
NH_4^+/ NH_3	<0,05
NO_2^-	<0,01-0,025
NO_3^-	5-10
PO_4^{3-}	<0,02
O_2	4

4.3.2. System 1 results

The first test conducted in System 1 was the TAN (NH_4^+/NH_3) test (Figure 4.4). After the addition of the fish feed the TAN levels did not increase during the duration of the tests as expected, which would suggest that they were quickly converted to nitrites. However, nitrite levels only increased on the third day of testing. The evolution of the concentration of TAN decreased over time as expected, but later increases in the last day of testing. A possible explanation for the unexpected rise of concentration in the last day of testing may be due to human error during testing or when judging the colorimetric results. Another possible explanation may be differences in fish metabolism, or decomposing matter such as uneaten fish food or vegetation in the fish tank.

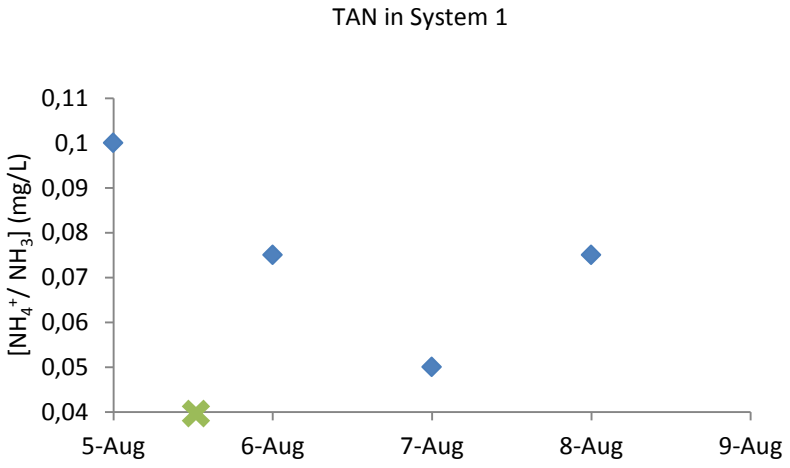

Figure 4.4. Evolution of Total Ammonia Nitrogen concentration in System 1

Nitrite levels in System 1 recorded an increase with some time delay as expected when bacteria convert ammonia to nitrite, and then decreased as nitrites are converted to nitrates (Figure 4.5).

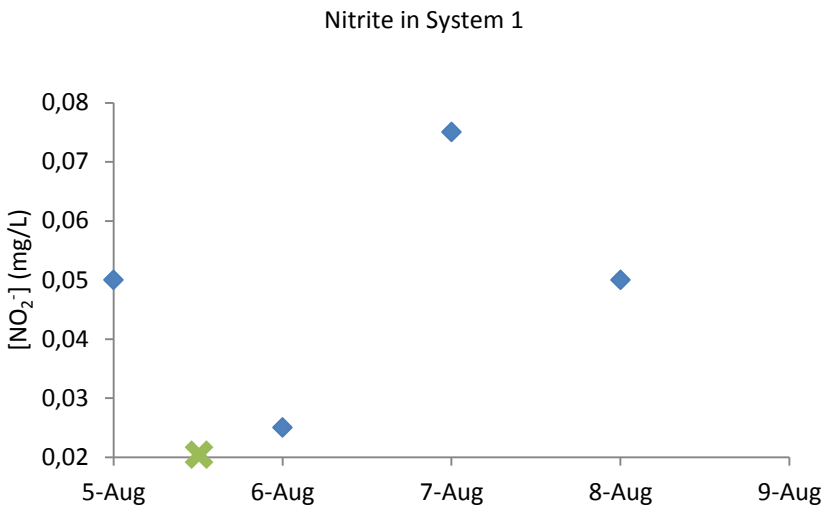

Figure 4.5. Evolution of nitrite concentration in System 1

Nitrate levels in System 1 recorded a small increase which remained unchanged through the testing period (Figure 4.6). It was expected for the nitrate levels to initially be fairly low and later rise after nitrite levels rose, however this was not the case. The nitrate levels observed in this system are close to the testing range limit which indicates they can be harmful for fish. A possible explanation could be that the current number of plants is unable to absorb the nitrates either because there are not enough of them planted or developed, or some chemical is inhibiting the absorption of nitrate. Another explanation could be human error while testing or judging the colorimetric results.

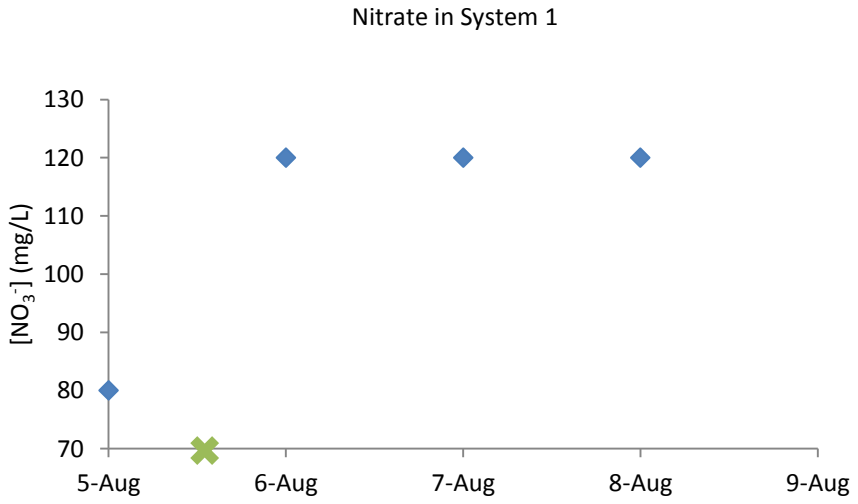

Figure 4.6. Evolution of nitrate concentration in System 1

Phosphate levels in System 1 remained relatively constant (Figure 4.7). There was a rise in concentration after the fish feed was added, followed by a decrease. In the last day of testing, the concentration rose again, which was not an expected result.

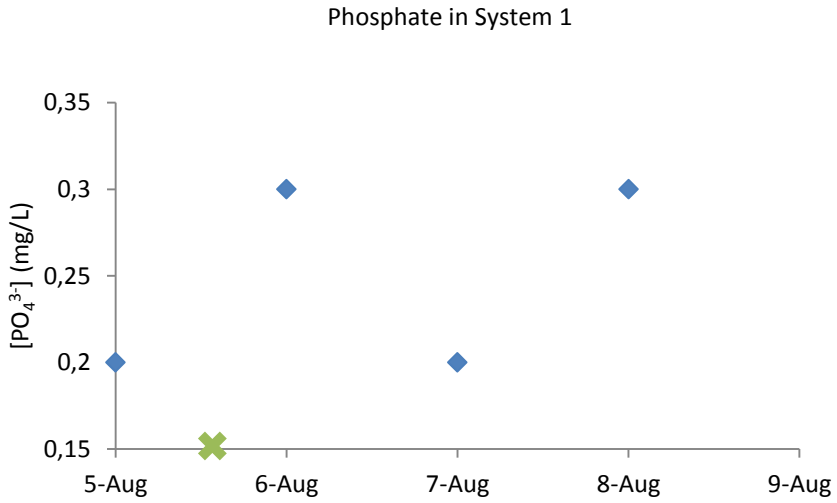

Figure 4.7. Evolution of phosphate concentration in System 1

Dissolved oxygen levels in System 1 remained mostly constant and close to the maximum value of the testing range (10 mg/L), which indicates the existing siphon drain with aeration holes in the returning pipe provides excellent aeration (Figure 4.8).

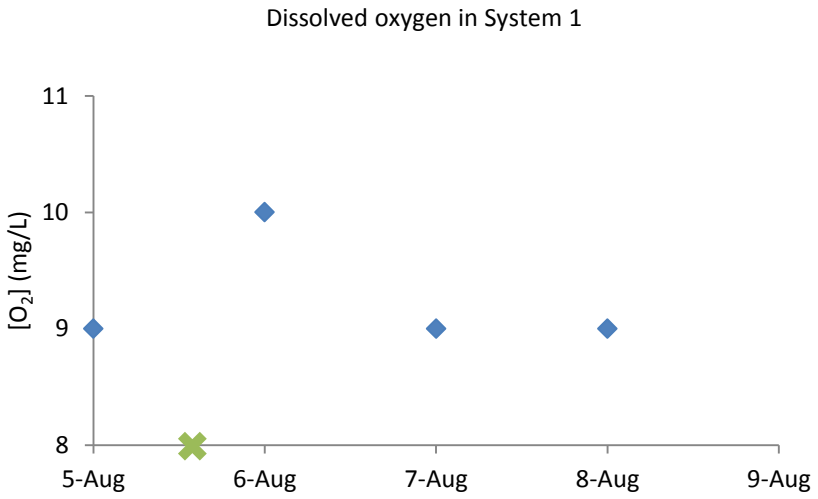

Figure 4.8. Evolution of dissolved oxygen concentration in System 1

4.3.3. System 2 results

TAN levels in System 2 followed an expected increase in concentration followed by a decrease, then increased again in the last day of testing as also seen in System 1 (Figure 4.9). Similarly to System 1, the increase in TAN concentration on the last day may be due to fish metabolism fluctuation. However, given that System 2 is located in the greenhouse which is open to the rest of the farm through the day for ventilation, the increase in TAN concentration can also be the result of contamination from other animals, insects, and plant debris. The possibility of human error can also not be discarded.

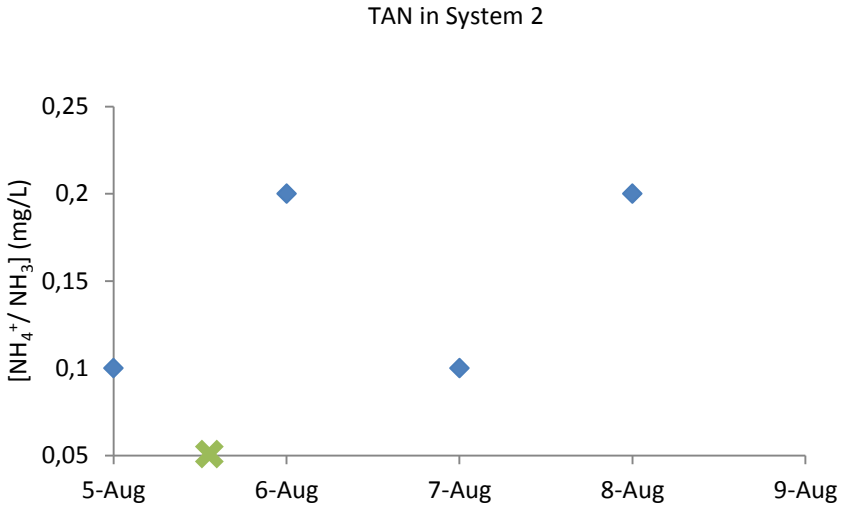

Figure 4.9. Evolution of Total Ammonia Nitrogen concentration in System 2

Nitrite levels in System 2 followed the expected results, with a rise in concentration after the fish feed was added and then decrease in concentration over the following days (Figure 4.10).

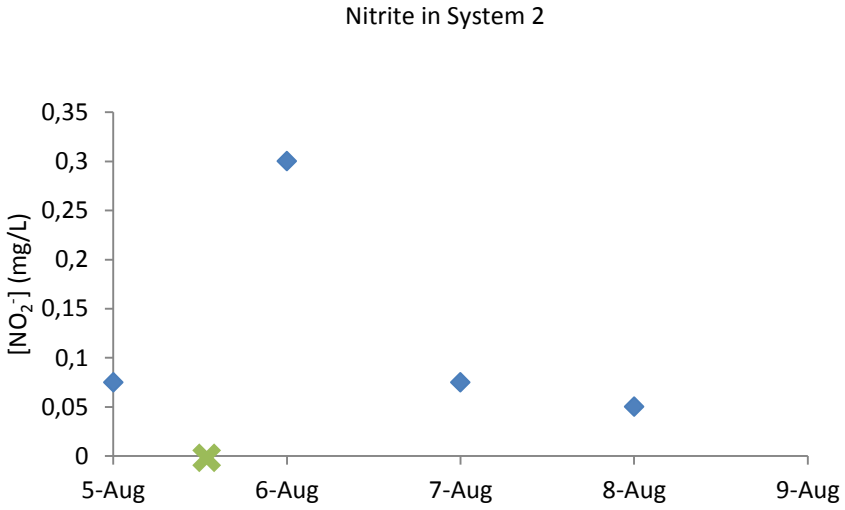

Figure 4.10. Evolution of nitrite concentration in System 2

Nitrate levels in System 2 remained with a low concentration through all tests (when comparing with values present at chapter 4.3.2.). It is not possible to conclude if there was a lack in concentration increase, or if it occurred but was absorbed quickly by the plants. An overall decrease in concentration was observed, and expected as no further fish feed was added through the remaining test period (Figure 4.11).

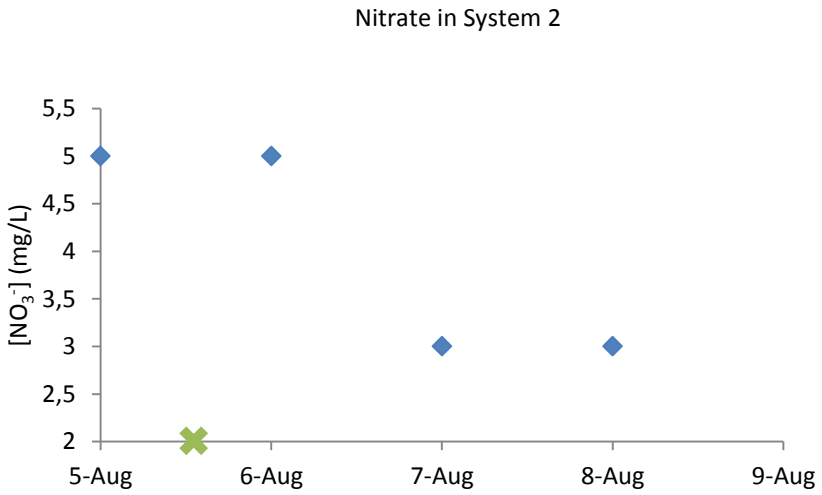

Figure 4.11. Evolution of nitrate concentration in System 2

Phosphate levels in System 2 showed an increase in concentration which followed the decrease in concentration of other parameters. The phosphate concentration levels decreased after the rise, as expected due to plant and algae phosphorus uptake (Figure 4.12).

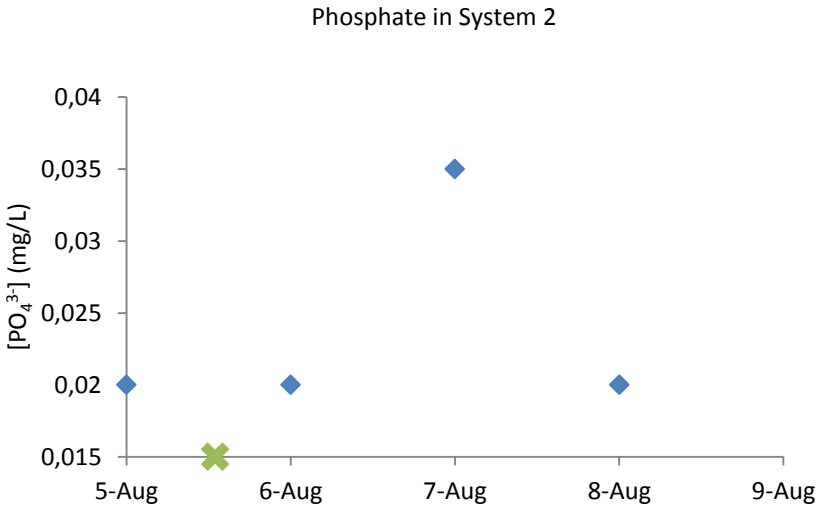

Figure 4.12. Evolution of phosphate concentration in System 2

Dissolved oxygen levels in System 2 varied through the experiment (Figure 4.13). It is important to note that unlike the other two systems, System 2 has less aeration provided by the splashing of the water. The decrease in the oxygen concentration after the fish feed was added

may be explained by the increased activity of the nitrifying bacteria, as they are aerobic. The last two data values show high oxygen levels which would indicate less aerobic activity after the nitrifying bacteria used the available ammonia and converted it to nitrate.

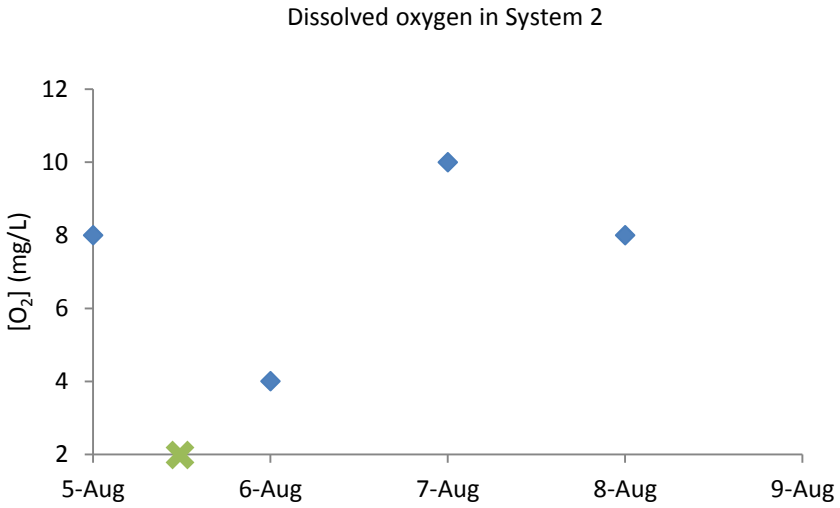

Figure 4.13. Evolution of dissolved oxygen concentration in System 2

4.3.4. System 3 results

TAN levels in System 3 did not show an increase in the concentration, which could indicate that the conversion of ammonia to nitrite occurred in less than 24h since the first sample was taken (Figure 4.14). The other tests showed a decrease in concentration over time as expected.

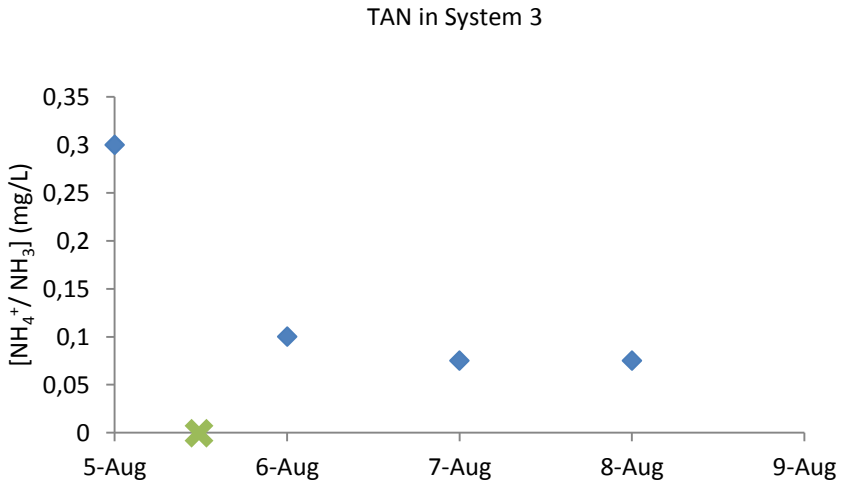

Figure 4.14. Evolution of Total Ammonia Nitrogen concentration in System 3

Nitrite levels in System 3 show an increase in concentration after the aged urine was added, followed by a decrease in concentration as expected (Figure 4.15). If the premise that TAN levels converted to nitrite levels in less than 24h is accepted, then finding higher concentrations of nitrite and lower concentrations of TAN in the second test corresponds according to the expected results.

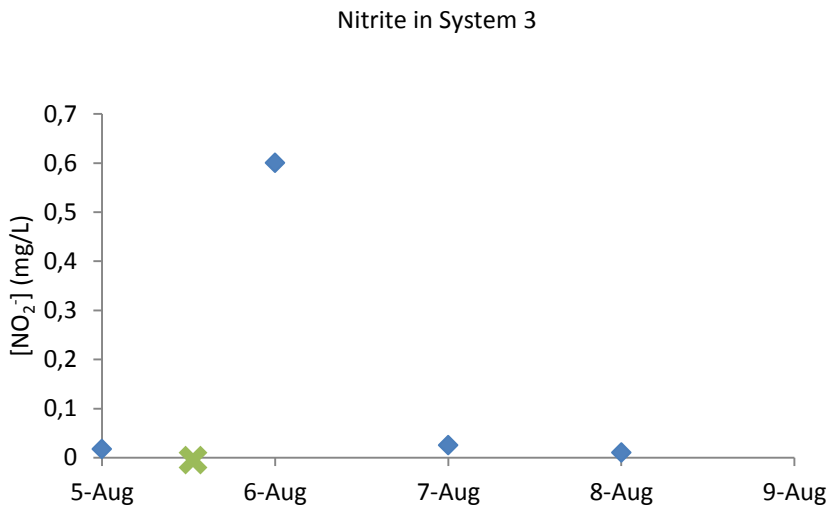

Figure 4.15. Evolution of nitrite concentration in System 3

The nitrate levels in System 3 also followed the expected results, showing an increase in concentration which peaks after the previous peak in concentration of nitrites. A decrease in nitrate concentration is registered in the last day of testing as expected (Figure 4.16).

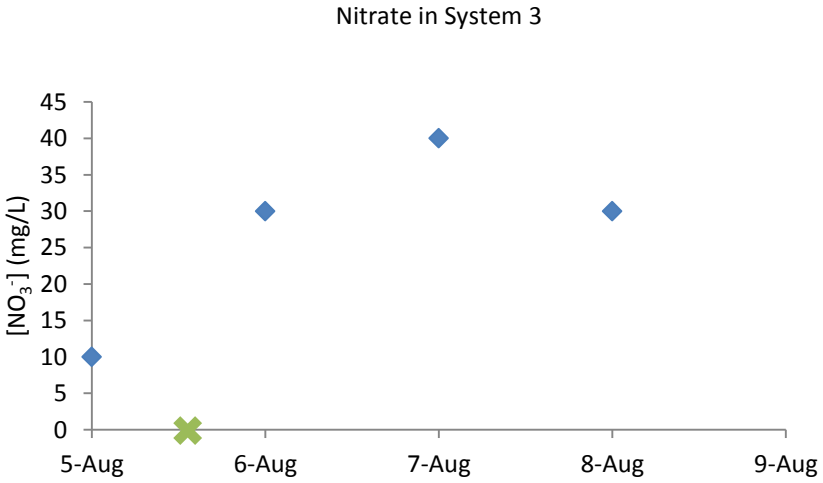

Figure 4.16. Evolution of nitrate concentration in System 3

Phosphate levels in System 3 show an increase in concentration after the aged urine was added as expected. A decrease in concentration was observed as also expected, due to plants and algae absorbing the phosphate. However, an increase in concentration in the last test was not expected (Figure 4.17). A possible explanation could be either an unexpected input from the environment with phosphate, or human error when performing the test or judging the colorimetric result.

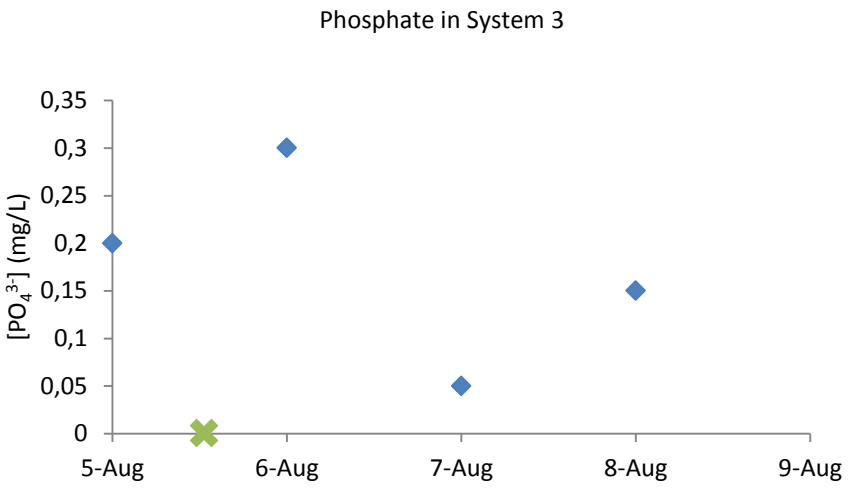

Figure 4.17. Evolution of phosphate concentration in System 3

Dissolved oxygen levels in System 3 remained relatively constant and with high concentrations (Figure 4.18). This indicates that current aeration levels are adequate and able to compensate for any metabolic use of oxygen by the aerobic nitrifying bacteria.

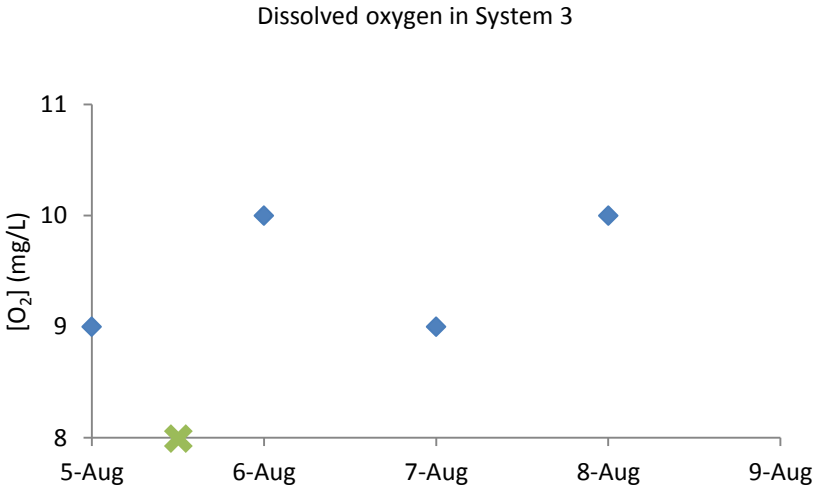

Figure 4.18. Evolution of dissolved oxygen concentration in System 3

All the original recorded data as judged directly from the colorimetric results is presented in the form of a table in Annex II for further analysis.

4.3.5. Discussion

The data gathered has shown that all aquaponic systems have the ability to remove nutrients and filter the water to some extent. The indoor and greenhouse aquaponic systems (Systems 1 and 2) nutrient test results will be compared with aquaculture and recirculating aquaculture systems literature to assess reference values. The greenhouse human urine-based aquaponic system (System 3) nutrient test results will be compared with urine composition and source-separated urine treatment literature to also assess reference values. In the latter case, it would be irrelevant to compare with common wastewater treated effluent literature as it combines fæces and urine.

Aquaponics comparison

Aquaculture and recirculating aquaculture system literature offers a wide range of reference values for acceptable concentrations of nutrients. It is important to note that most literature does not provide reference values for phosphate, indicating instead the concentration of phosphorus or total phosphorus. As such, this parameter from the case study (phosphate) cannot be objectively compared with literature references, and will only be reviewed briefly. Below is presented an overview of the literature values for the tested parameters (Table 4.2).

Table 4.2. Literature parameter values by a few authors for aquaculture and recirculating aquaculture systems. The parameter with an asterisk (*) indicates that it cannot be directly compared with the case study results

Concentration of parameters	Francis-Floyd *et al* (1996)	Losordo *et al* (1998)	Yeo *et al* (2004)	Molleda (2007)	Delong & Losordo (2012)	Lucas & Southgate (2012)
$[NH_4^+ / NH_3]$ (mg/L)	< 0,05	< 0,05	0,10 - 1,00	< 0,05	-	< 0,25
$[NO_2^-]$ (mg/L)	< 0,10	< 1,00	-	< 1,00	-	< 2,00
$[NO_3^-]$ (mg/L)	< 250,00	200,00	200,00	< 10,00	200,00	-
$[PO_4^{3-}]$* (mg/L)	-	-	< 0,01	-	-	< 0,01
$[O_2]$ (mg/L)	-	-	-	> 5,00	-	> 3,00-4,00

Given that there is a wide range for some parameters, a specific approach is necessary. It was decided to use the most demanding values from a hypothetical regulatory point of view. Below is the result of such approach (Table 4.3).

Table 4.3. Literature parameter values by a few authors for aquaculture and recirculating aquaculture systems after applying an approach for the most demanding values from a hypothetical regulatory point of view. The parameter with an asterisk (*) indicates that it cannot be directly compared with the case study results

Concentration of parameters	Reference values
$[NH_4^+/ NH_3]$ (mg/L)	< 0,05
$[NO_2^-]$ (mg/L)	< 0,10
$[NO_3^-]$ (mg/L)	< 10,00
$[PO_4^{3-}]$* (mg/L)	< 0,01
$[O_2]$ (mg/L)	> 5,00

When comparing the case study results with Table 4.3, it was decided to analyze the case study values from the last day of testing, despite unexpected fluctuations. This is because, in theory, the last day of results should provide the best water quality for the parameters being tested, while ensuring enough time for the nitrification process to have occurred. The comparison is presented in Table 4.4.

Table 4.4. Comparison between reference values found in literature with the case study values from both the indoor and the greenhouse aquaponic systems (Systems 1 and 2 respectively) . Values with an asterisk (*) indicate the case study results were inferior than the reference values. Bolded values indicate how a certain system performed better than the other in each parameter

Concentration of parameters	Reference Values	System 1	System 2
$[NH_4^+/ NH_3]$ (mg/L)	< 0,05	**<0,05-0,10***	0,20*
$[NO_2^-]$ (mg/L)	< 0,10	0,05-0,10	**0,05**
$[NO_3^-]$ (mg/L)	< 10,00	80,00-160,00*	**1,00-5,00**
$[PO_4^{3-}]$ (mg/L)	< 0,01	0,20-0,40*	**<0,02***
$[O_2]$ (mg/L)	> 5,00	8,00-10,00	**8,00**

When comparing the literature reference values with the case study results, it is apparent that different systems are better at removing certain nutrients and worse at others. The greenhouse aquaponics system (System 2) performed better than the indoor aquaponics system (System 1) in all parameters excepting Total Ammonia Nitrogen (NH_4^+/ NH_3). This result was to be expected as System 2 is more complex and has more components than System 1; despite both using essentially the same filter technique (composed of media such as expanded clay aggregate).

A subjective analysis view which integrates food production and aquaculture wastewater treatment systems indicates that the most productive system in terms of food yield was System 2, when compared with System 1. This comparison is subjective as the food harvested from the

systems was not quantified or weighted for data collection. It is noteworthy to refer that both systems had solids build-up in the fish tank which needed to be removed manually.

Human urine-based aquaponics comparison

Source-separated urine literature offers a more narrow range of reference values for common concentrations of nutrients given that results presented by most authors are shown in mass or percentages rather than concentrations.

Before analyzing the literature, a few remarks have to be mentioned regarding the compilation of literature data found. Most authors do not provide reference values for phosphate, indicating instead the concentration of phosphorus or total phosphorus. As such, this parameter for most authors cannot be objectively compared with the case study results, and will only be briefly reviewed. In Kirchmann & Pettersson (1995) values for [NH_4^+/NH_3] are presented as the sum of [NH_4^+] ranges with [NH_3] ranges. Wilsenach *et al* (2005) values show the composition of incoming urine before and after a source-separating component of a wastewater treatment plant which routes the urine to an anoxic compartment of activated sludge, which is directly downstream of primary sedimentation and is followed by a trickling filter. The effluent, unlike other values from most authors shows the concentration of phosphate in the form of struvite which is a phosphate mineral. Pradhan *et al* (2007) values use stored urine which had been previously diluted with toilet flush water. The values only display ammonium (NH_4^+) rather than TAN (NH_4^+/ NH_3), and values for nitrites (NO_2^-) and nitrates (NO_3^-) are presented jointly. Jana *et al* (2012) values show the composition of urine under storage for eleven months and the water quality after phytoplankton production for sixteen weeks. The results after sixteen weeks, while not eligible to be directly compared with those from the case study after three days, still provide relevant data. The available data only displays ammonium (NH_4^+) rather than TAN (NH_4^+/ NH_3), although it does present phosphate (PO_4^{3-}) concentration unlike most of the other authors. The literature parameter values are presented in Table 4.5.

Table 4.5. Literature parameter values for urine composition of source-separated fresh urine (1), source-separated stored urine (2), and source-separated urine after treatment (3). The parameters with an asterisk (*) indicate a special condition relevant to the comparison between authors.

Parameter	**Kirchmann & Pettersson (1995) (2)**	**Adamsson *et al* (2003) (1)**	**Simons & Clemens (2003) (3)**	**Wilsenach *et al* (2005) (1) (3)**		**Pradhan *et al* (2007) (2)**	**Jana *et al* (2012) (2) (3)**	
				Influent	Effluent		Initial stored urine quality	Water quality after 16 weeks of use
$[NH_4^+/NH_3]$ (mg/L)	1691-2499*	2300	400	6000	2100	940*	365,34±0,01*	0,08±0,014*
$[NO_2^-]$ (mg/L)	0,001-0,002	-	-	-	2300	< 0,5*	9,8±0,11	0,048±0,009
$[NO_3^-]$ (mg/L)	0,0045	-	-	-	-		13,50±0,21	0,303±0,005
$[PO_4^{3-}]$* (mg/L)	200-210	130	500	500	480* (struvite)	63	0,442±0,02*	0,439±0,083*
$[O_2]$ (mg/L)	-	-	-	-	-	-	-	8,87±0,44

Given that there is a wide range for some parameters and a specific approach is necessary. It was decided to use the most demanding values from a municipal regulation point of view. When comparing the case study results with the literature values, it was decided to analyze the case study values from the last day of testing, despite unexpected fluctuations. This is because, in theory, the last day of results should provide the best water quality for the parameters being tested, while ensuring enough time for the nitrification process to have occurred in its entirety. In Table 4.6 the comparison is presented.

Table 4.6. Comparison between reference values found in literature for urine composition of fresh urine, source-separated urine, stored urine, and after treatment applying an approach for the most demanding values from a hypothetical regulatory point of view with the case study values from the greenhouse human urine-based aquaponic (System 3). The System 3 values with an asterisk (*) indicate the case study results were inferior to the reference values

Concentration of parameters	Reference values	System 3
$[NH_4^+/ NH_3]$ (mg/L)	< 0,07	<0,05-0,10*
$[NO_2^-]$ (mg/L)	< 0,001	<0,01*
$[NO_3^-]$ (mg/L)	< 0,0045	20,00-40,00*
$[PO_4^{3-}]$ (mg/L)	< 0,36	0,10-0,20
$[O_2]$ (mg/L)	> 9,31	10,00

When comparing the literature reference values with the case study results, it is apparent that the case study system failed to reach the reference values after three days of testing. The only parameter in which the case study system proved to be superior was in phosphate concentration. The fact that the testing only took three days could be an important reason as to why the case study system failed to reach the reference values in most of the tested parameters.

While useful to compare the concentrations of reference values with the case study values, another important comparison that can be made is the nutrient percent removal, a common calculation used in wastewater industries. Percent removal is calculated by the following formula:

$$\frac{Influent\ Concentration - Effluent\ Concentration}{Influent\ Concentration} x\ 100$$

Using such formula, it is possible to compare the nutrient percent removal from two authors presented in Table 4.5 with the nutrient percent removal from System 3. In System 3, the influent concentrations used for each parameter corresponded to the peak in concentration tested, while the effluent concentrations used corresponded to the last day of testing.. The final comparison is presented in Table 4.7.

Table **4.7**. Comparison between nutrient percent removal found in literature with the nutrient percent removal of the greenhouse human urine-based aquaponic system

Parameter	**Wilsenach *et al* (2005)**	**Jana *et al* (2012)**	**System 3**
NH_4^+/ NH_3	65%	99,98%	75%
NO_2^-	-	99,51%	98,33%
NO_3^-	-	97,76%	25%
PO_4^{3-}	4%	0,68%	50%

Calculating nutrient percent removal gives a new perspective when comparing the case study system (System 3) with literature examples. System 3 removed a higher percentage of all tested nutrients when comparing with Wilsenach *et al* (2005). When compared to Jana *et al* (2012), System 3 was less effective in removing TAN, nitrites and nitrates, while being more effective in removing phosphate. This effectiveness in removing phosphate might be due to the fact that System 3 had many different hydroponic components (Media Bed component, towers and a DWC component) where plants could uptake phosphate, as well as more volume of water where algae could have developed and consumed the existing phosphate.

Overall, it seems that while a human urine-based aquaponics system (System 3) may be effective in removing a considerable amount of nutrients from urine, it is not as effective as other source-separated urine treatment systems. Nevertheless, any conclusions that can be drawn are limited by the scope of the testing, the materials available, and the information collected.

It is interesting to mention that in terms of food yield, the most productive system was System 3, when compared with System 1 and System 2. This comparison is subjective as the food harvested from the systems was not quantified or weighted for data collection.

5. Conclusions

Aquaponics is often regarded as a food production system, with its wastewater treatment potential overlooked. This investigation has described the developing field of aquaponics as an integrated food production system, while exploring its potential for effluent treatment.

Aquaponics was described conceptually and biologically, with an analysis of the nitrogen cycle and how aquaculture is integrated with hydroponics. An analysis of the different types of systems, with benefits and disadvantages of each component were also researched. Similarly, aquaculture wastewater as well as source-separated urine was analyzed in its composition and treatment potential in aquaponic systems. While some literature was found on recent aquaponics research, none covered human urine use in aquaponics. It was concluded that both fish waste and urine can theoretically be removed from the water, with the recovered nutrients being used for hydroponic plant biomass growth.

A case study was conducted consisting of two aquaponic systems (System 1 and System 2) and a human urine-based aquaponic system (System 3). Their dimensioning, building and biological start-up was described in detail. The systems were built ranging in complexity as a way to test different designs and their potential to remove nutrients from the water, while simultaneously growing plants. All systems were subject to chemical tests that were used to observe the evolution of TAN (NH_4^+/NH_3), Nitrite (NO_2^-), Nitrate (NO_3^-), Phosphate (PO_4^{3-}) and Dissolved Oxygen (O_2) during a four day period. The majority of tests were done after an initial nutrient input of commercial fish feed in the aquaponic systems (System 1 and System 2) and of aged human urine in the human urine-based aquaponic system (System 3).

Neither of the two aquaponic systems displayed all of the parameter concentrations below reference values found in literature in the last day of testing. The lowest performing of the aquaponic systems was System 1 which consisted of a simple Media Bed System, with a Total Ammonia Nitrogen concentration of <0,05-0,10 mg/L, a Nitrite concentration of 0,05-0,10 mg/L, a Nitrate concentration of 80,00-160,00 mg/L, a Phosphate concentration of 0,20-0,40 mg/L and an dissolved oxygen concentration of 8,00-10,00 mg/L. The best performing of the aquaponic systems was System 2 combining NFT with DWC, with a Total Ammonia Nitrogen concentration of 0,20 mg/L, a Nitrite concentration of 0,05 mg/L, a Nitrate concentration of 1,00-5,00 mg/L, a Phosphate concentration of <0,02 mg/L and an Dissolved oxygen concentration of 8,00 mg/L. The human urine-based aquaponic system had a concentration of <0,05-0,10 mg/L of Total Ammonia Nitrogen, <0,01 mg/L of Nitrite, 20,00-40,00 mg/L of Nitrate, 0,10-0,20 mg/L of Phosphate and 10,00 mg/L of Dissolved oxygen. These concentration values failed to achieve the reference concentration values in literature for most parameters. The percent removal between the highest recorded values after the input addition and the final day of testing was calculated for two literature examples and the case study system. The system had a percent removal of 75% for Total Ammonia Nitrogen, 98% for Nitrite, 25% for Nitrate and 50% for Phosphate. These percentages still underperformed one of the two literature examples in most of the tested parameters.

The results gathered allowed to conclude that while aquaculture wastewater treatment and urine treatment is possible with aquaponics systems, overall these did not perform as well as some examples found in recirculating aquaculture systems and source-separated urine treatment literature. It is also important to keep in mind that the comparison between some authors regarding the composition of urine under storage and the case study cannot be directly performed as the storage times were different. Given that the testing was also limited in its scope, and there were budget restrictions that limited the type and amount and type of chemical tests performed, more research is recommended in this field in order to draw an improved representative conclusion.

It is clear from the results that aquaponics has potential to play a key role in managing effluent pollution from aquaculture systems and source-separated urine. While aquaponics may be more easily implemented at an industrial scale for aquaculture applications, its use for human urine

treatment is limited to more decentralized applications since source-separation of urine is not a recognized solution. It may be possible that the increase in future research on the topic of urine treatment through aquaponics may one day enable a more convenient, affordable and rational approach in nutrient recovery from wastewater treatment.

6. Suggestions for future research

The present thesis was able to confirm that aquaponic systems can remove some of the pollution from aquaculture waste and human urine. However, it was not possible to perform testing with enough significance and sample size which would allow for a rigorous understanding of how the various parameters evolve over time in several aquaponic systems.

Future research on this topic should seek to build aquaponic and human urine-based aquaponic systems ranging in complexity for a comparison on how different aquaponic components improve the overall performance of wastewater treatment. An example would be to build two of each for the most common aquaponic systems, one using fish waste as the nutrient source and the other using aged human urine. These systems include: Media Bed systems, Nutrient Film Technique (NFT) systems and Deep Water Culture (DWC) systems. Hybrid systems combining two or more of these components would also be relevant to study. The systems should be kept in controlled environments in order to prevent outside contamination when performing chemical testing. The systems should also test different types of filter and biofilter material since the present thesis only studied grow beds and filters using LECA, lava gravel and charcoal.

Future research should also attempt to test Biological Oxygen Demand (BOD), Total Ammonia Nitrogen (TAN), Total Nitrogen (TN), Total Phosphorus (TP), Total Organic Carbon (TOC), Total Coliforms, Fecal Coliforms and *Escherichia coli*; as these were the parameters identified as most relevant for water and wastewater quality observations. The testing should also be performed over a longer time period and more frequently each day if possible. There is also a necessity to use analysis methods which offer a greater reliability and accuracy, since these factors are important limitations of the developed tests.

The study of the phosphorus cycle in an aquaponics system, and the bacteria present in that cycle process is also a relevant study goal which might bring future implications in phosphorus recovery in the face of peak phosphorus.

A chemical and microbiological analysis of aged urine should be studied with the goal of researching the average time it takes aged urine to reach the desired volatilization of urea to ammonia and the elimination of possible pathogens. Storage time for urine is a critical component to be studied since different authors have different methods which makes a direct comparison difficult at present. The results should be analyzed in order to study potential ways how human urine-based aquaponic systems could be integrated with existing source-separation of urine infrastructure such as urine diversion toilets and urine diversion dry toilets.

7. References and Annexes

7.1. References

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7.2. Annexes

Annex I

Plotted monitoring parameter data

I.1 Parameter data for the Indoor Aquaponics System (System 1)

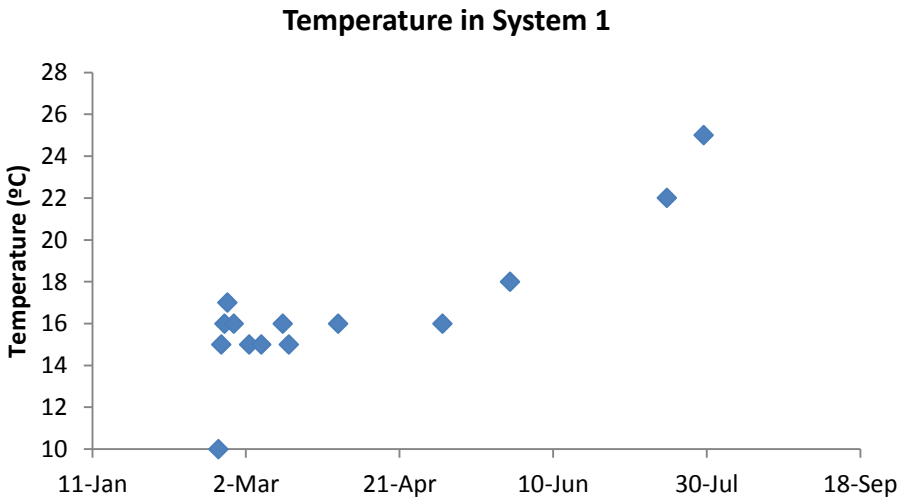

Figure 7.1. Evolution of temperature in the Indoor Aquaponics System

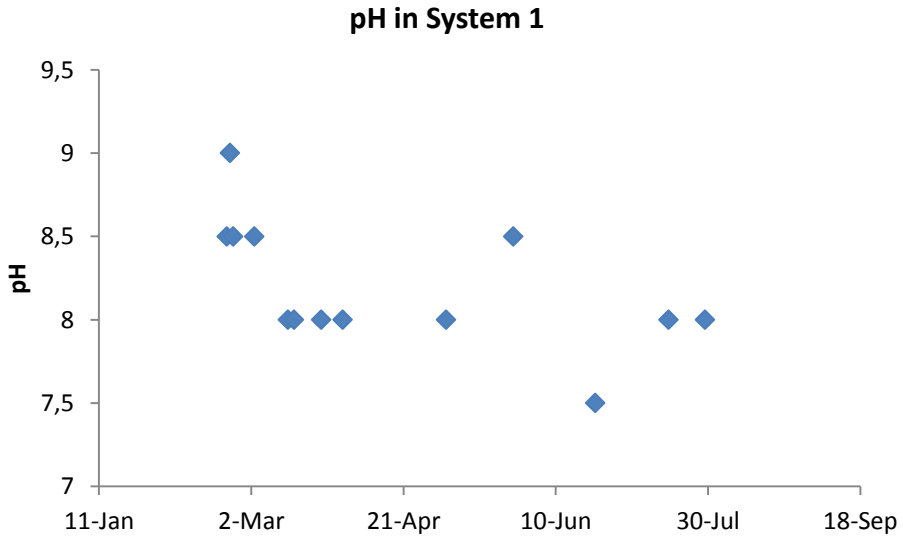

Figure 7.2. Evolution of pH in the Indoor Aquaponics System

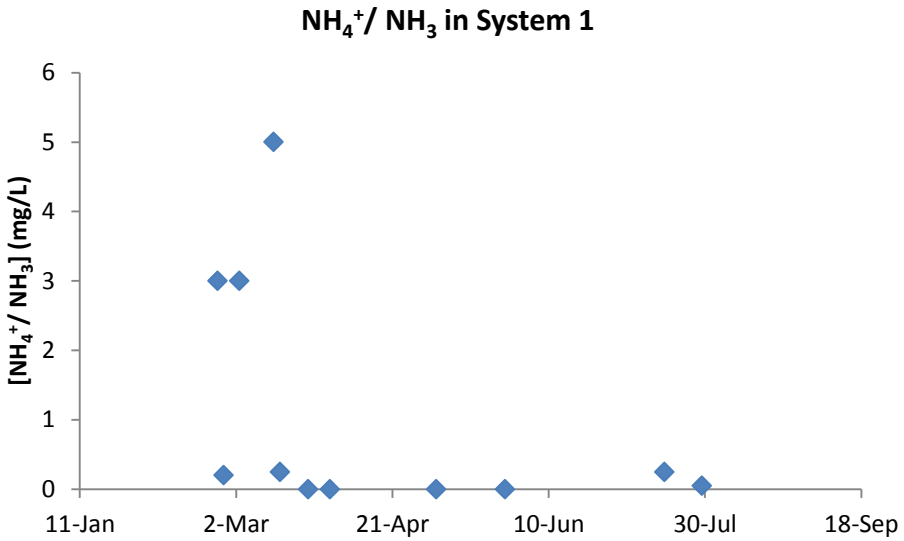

Figure 7.3. Evolution of Total Ammonia Nitrogen in the Indoor Aquaponics System

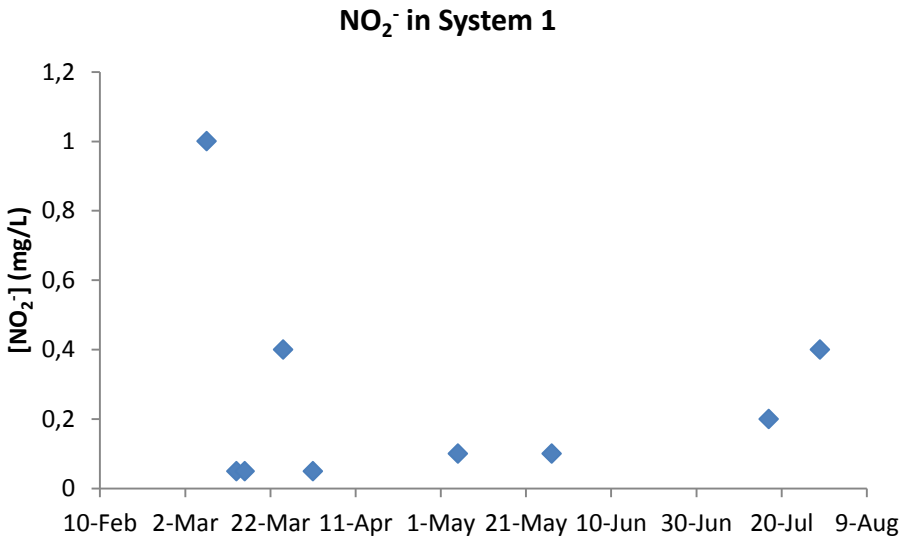

Figure 7.4. Evolution of Nitrite in the Indoor Aquaponics System

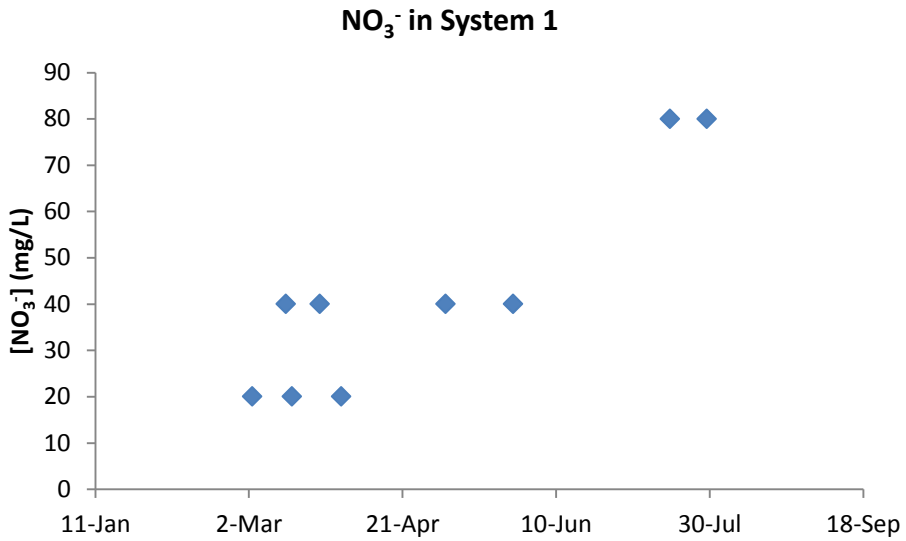

Figure 7.5. Evolution of Nitrate in the Indoor Aquaponics System

I.2 Parameter data for the Greenhouse Aquaponics System (System 2)

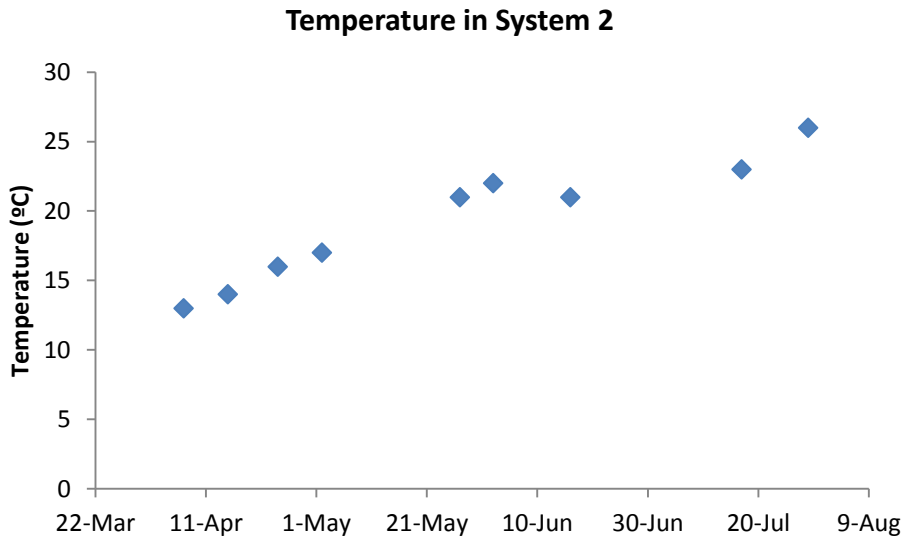

Figure 7.6. Evolution of Temperature in the Greenhouse Aquaponics System

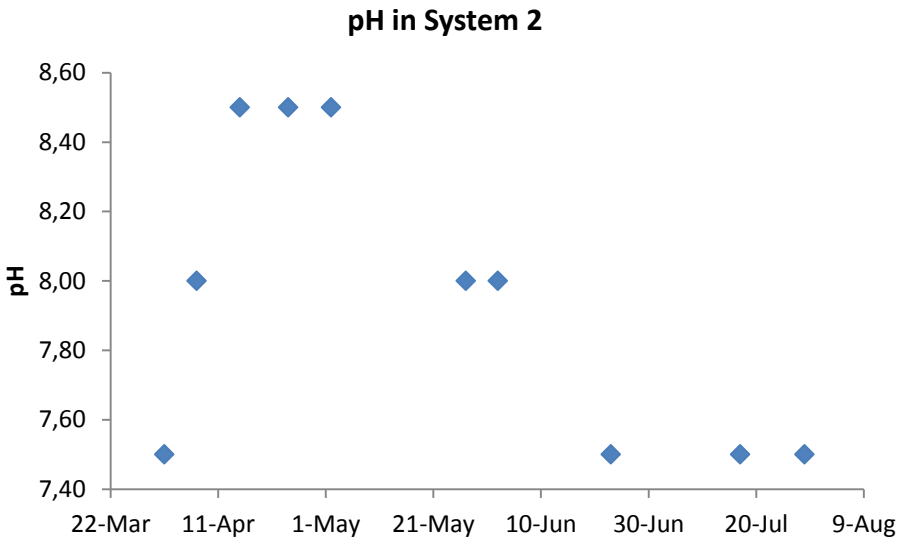

Figure 7.7. Evolution of pH in the Greenhouse Aquaponics System

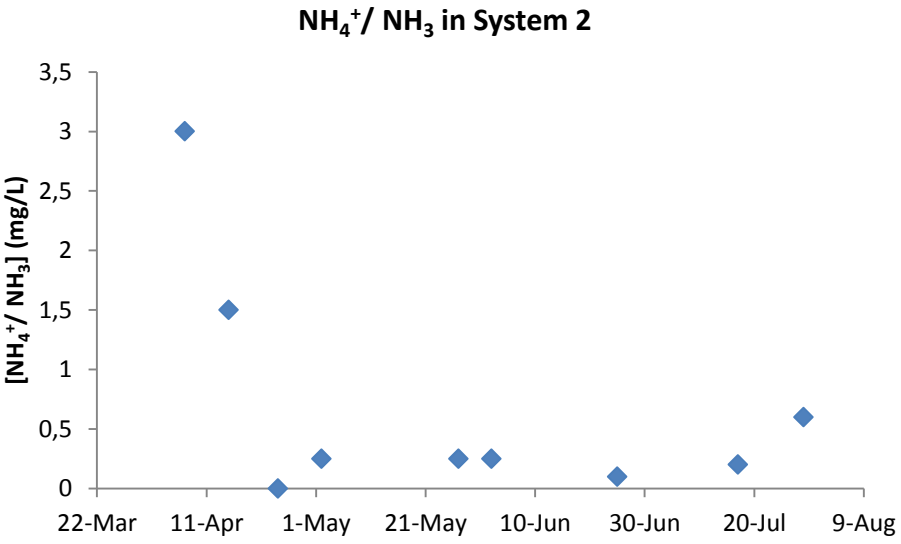

Figure 7.8. Evolution of Total Ammonia Nitrogen in the Greenhouse Aquaponics System

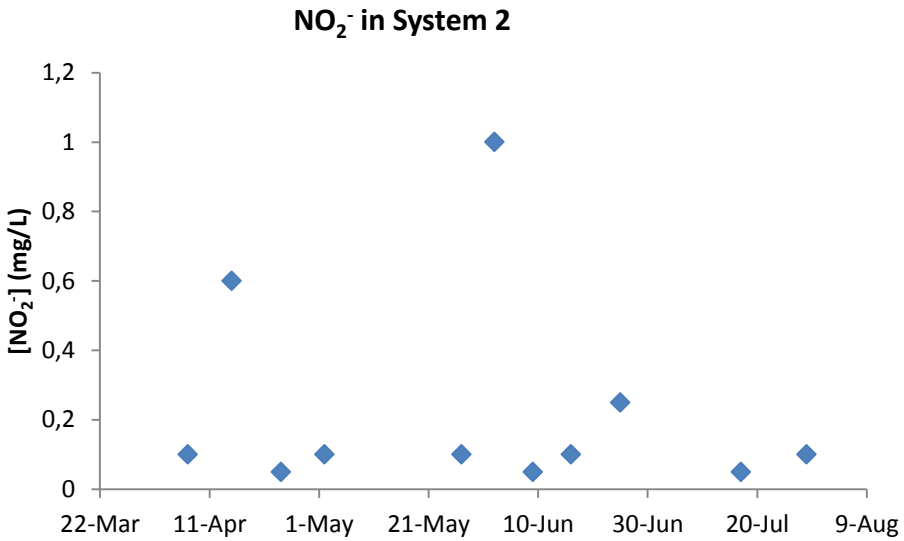

Figure 7.9. Evolution of Nitrite in the Greenhouse Aquaponics System

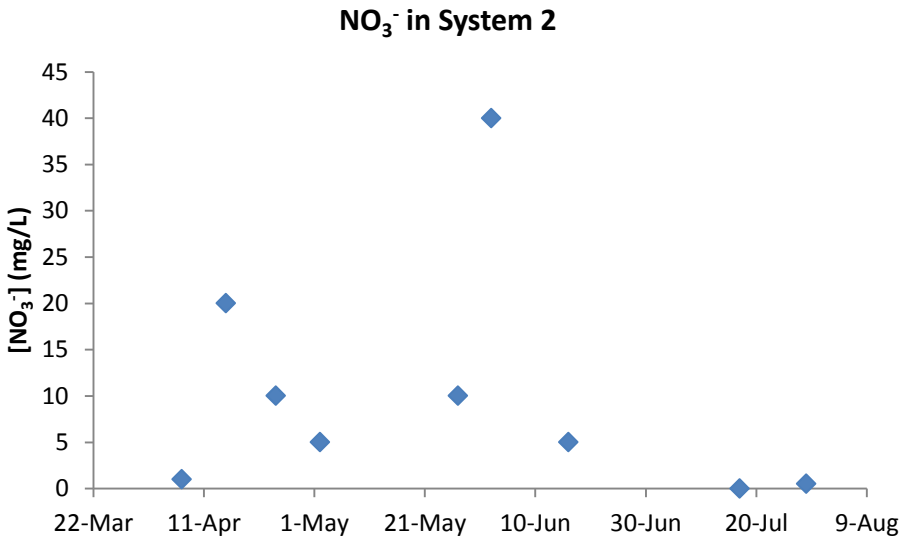

Figure 7.10. Evolution of Nitrate in the Greenhouse Aquaponics System

I.3 Parameter data for the Greenhouse Human Urine-Based Aquaponics System (System 3)

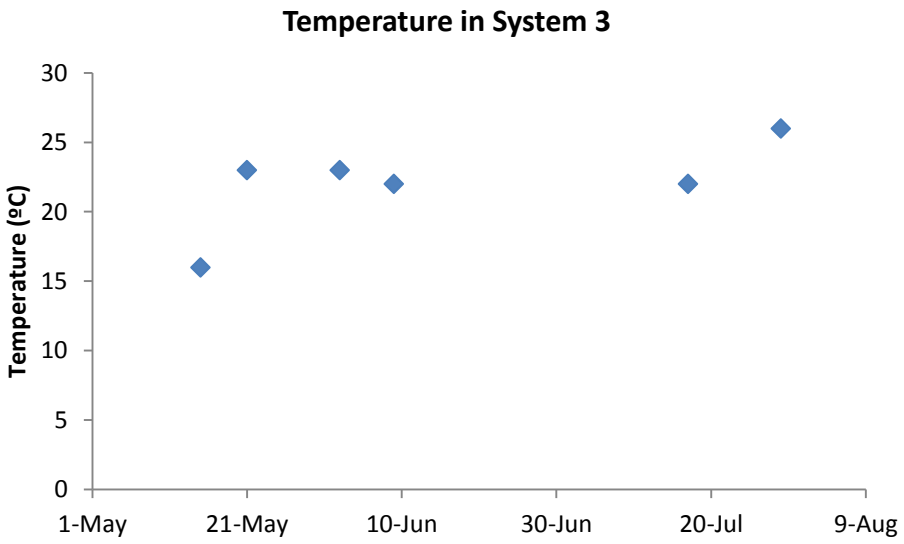

Figure 7.11. Evolution of Temperature in the Greenhouse Human Urine-Based Aquaponics System

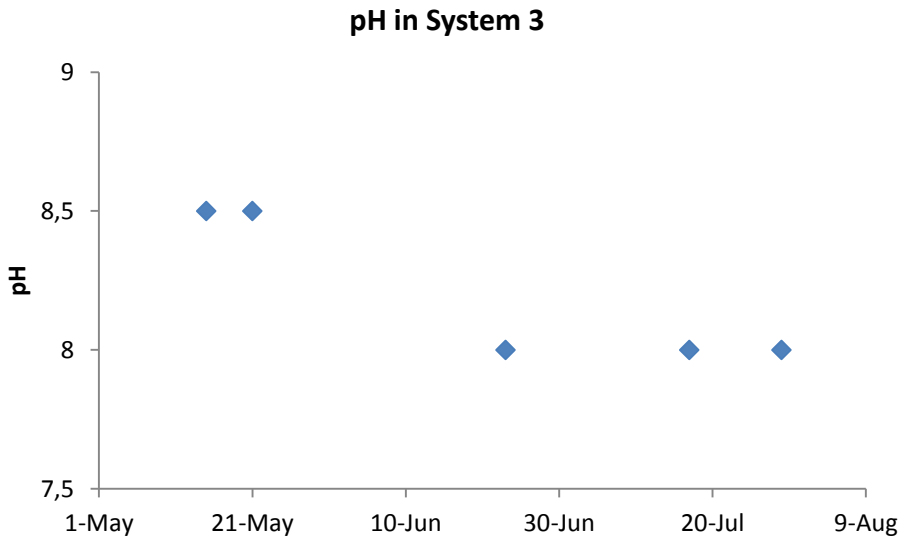

Figure 7.12. Evolution of pH in the Greenhouse Human Urine-Based Aquaponics System

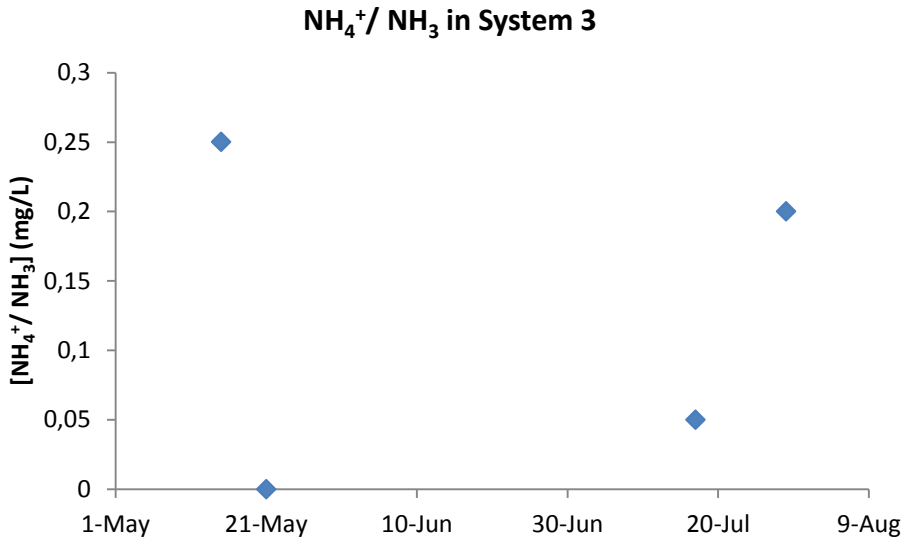

Figure 7.13. Evolution of Total Ammonia Nitrogen in the Greenhouse Human Urine-Based Aquaponics System

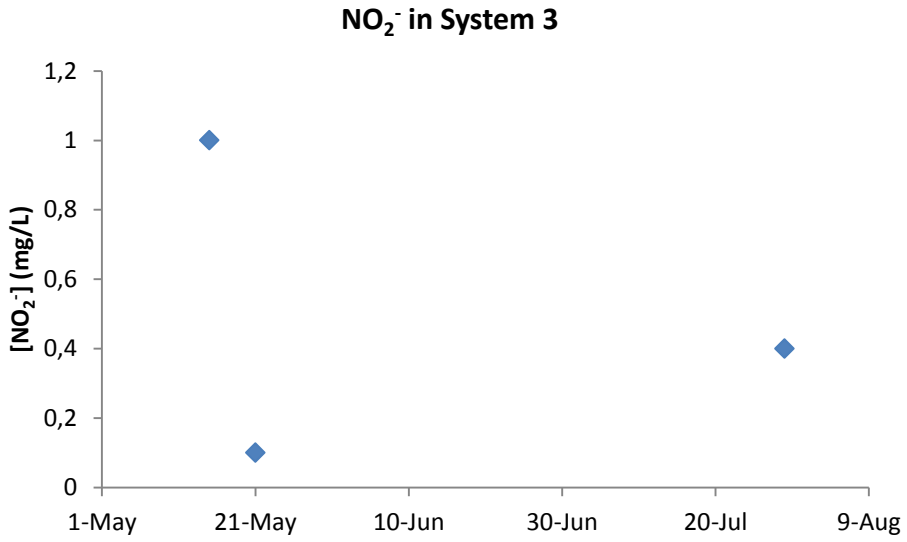

Figure 7.14. Evolution of Nitrite in the Greenhouse Human Urine-Based Aquaponics System

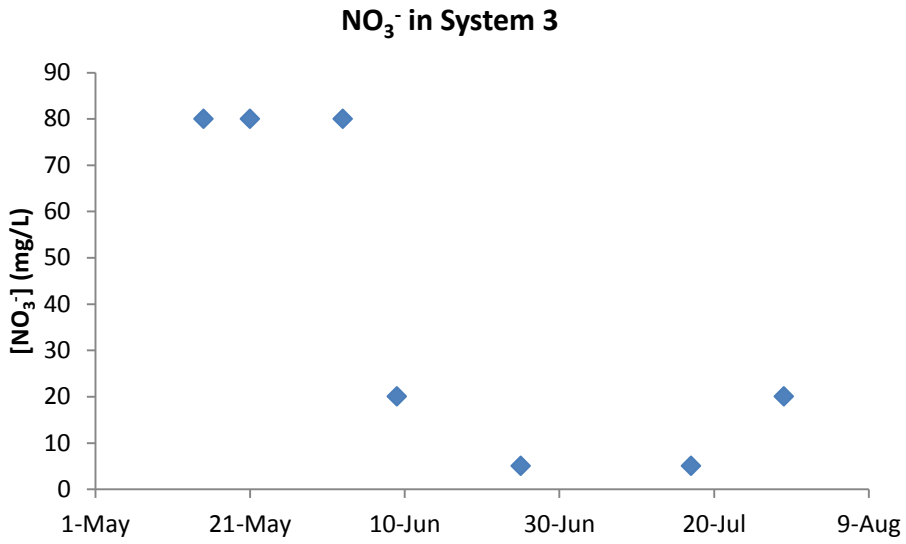

Figure 7.15. Evolution of Nitrate in the Greenhouse Human Urine-Based Aquaponics System

Annex II

Tabled testing parameter data

System 0 is defined as the control, System 1 is defined as the indoor aquaponic system, System 2 is defined as the greenhouse aquaponic system and System 3 is defined as the greenhouse human urine-based aquaponic system.

Table 7.1. Recorded data from the commercial test kits concerning Total Ammonia Nitrogen, Nitrite, Nitrate, Phosphate and Dissolved Oxygen during the four day testing period for all three systems and a control (System 0) for the first day with the well water

Date	Systems	Concentration (mg/L)				
		NH_4^+/ NH_3	NO_2^-	NO_3^-	PO_4^{3-}	O_2
August 5th	**0**	<0,05	<0,01-0,025	5-10	<0,02	4
	1	0,1	0,05	80	0,2	8-10
	2	0,1	0,05-0,1	5	<0,02	8
	3	0,2-0,4	<0,01-0,025	10	0,2	8-10
August 6th	**1**	<0,05-0,1	0,025	80-160	0,2-0,4	10
	2	0,2	0,2-0,4	5	<0,02	4
	3	0,1	0,6	20-40	0,2-0,4	10
August 7th	**1**	<0,05	0,05	80-160	0,2	8-10
	2	0,1	0,05-0,1	1-5	<0,02-0,05	10
	3	<0,05-0,1	0,025	40	0,05	8-10
August 8th	**1**	<0,05-0,1	0,05-0,1	80-160	0,2-0,4	8-10
	2	0,2	0,05	1-5	<0,02	8
	3	<0,05-0,1	<0,01	20-40	0,1-0,2	10