Master Thesis

Growth rate and health aspects of leafy vegetables produced in small-scale aquaponic systems with fish fed on conventional and insect-based fish food

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Growth rate and health aspects of leafy vegetables produced in small-scale aquaponic systems with fish fed on conventional and insect-based fish food

by Samuel Kessens

Spring 2016
Abstract

The combination of fish farming (aquaculture) together with growing fruit and vegetables in a hydroponic system is called aquaponics. It is a water efficient technique to produce a wide variety of food on a small area. To investigate the growth rates of fish and vegetables in small-scale units, two aquaponic systems and a hydroponic system, serving as a reference, were built in Bethlehem, Palestine. All systems were planted with Swiss chard (Beta vulgaris subsp. vulgaris). The aquaponic systems were stocked with approx. 100 Nile tilapia (Oreochromis niloticus) each.

To find alternatives to the unsustainable fish meal, which is commonly used as a protein source in fish food, an insect-based fish food was evaluated. Fish in one system were fed with conventional fish food based on fish meal whereas in the other system they were fed with fish food based on the meal of the larvae of the black soldier fly (Hermetia illucens).

The nitrate concentration of harvested plant tissue, which is assumed to be carcinogenic, was evaluated to assess health risks of plants grown in the different systems. Further the cost effectiveness of the aquaponic systems was compared.

Data collection period started on March 4, 2016 and ended on June 1, 2016. Monthly plant growth in the aquaponic systems (1.24 ±0.71 kg m⁻²) was decreased compared to the hydroponic system (10.42 ±3.18 kg m⁻²) due to nutrient deficiency in the beginning. Due to heat stress, no significant difference between the systems was found in the last three harvests. Fish growth was significantly (p<0.01) decreased for the fish fed with insect-based fish food. A different composition of amino acids and the chitin content, which can decrease digestibility of fish food, were assumed to be the reason for the decreased growth rate.

The nitrate concentration in the tissue of the Swiss chard from the hydroponic system exceeded the maximum levels for leafy vegetables (for lettuce e.g. 3'500 mg nitrate per kg fresh weight). By adapting the amount of fertilizer, health issues connected to nitrate should be prevented. Further fruiting vegetables where the consumed plant parts do not accumulate nitrate as much as in leafy vegetables could be cultivated.

The analysis of the costs and the retail prices showed, that the monthly revenue was lower than the monthly input costs during data collection for each aquaponic system. The initial costs to start running the systems were with approx. EUR 776.- over hundred times higher than the running costs. Labour costs were not included in the analysis. The predicted expenses until the 100 fish are harvested (after 6-8 months) was expected to be EUR 202.- ±13.- and EUR 155.- ±4.- for the insect fed
fish and the conventionally fed fish, respectively. The value of the fish was estimated to be EUR 353.- for both systems.

Aquaponics was found to be a promising technique to increase food security in Palestine. By cultivating climate-adapted vegetables and fish species, large amounts of food can be produced locally. To also produce fish food locally, research of alternative protein sources should be expanded.
Zusammenfassung

Mit Aquaponik bezeichnet man die Kombination von Fischzucht (Aquakultur) und Gemüseanbau in Hydrokultur. Die Methode, mit welcher eine breite Vielfalt an Nahrungsmitteln produziert werden kann, ist sowohl platz- wie auch wassersparend. Um die Wachstumsraten von Pflanzen und Fischen in kleinskaligen Systemen zu untersuchen wurden in Bethlehem (Palästina) zwei Aquaponik-Systeme sowie ein Hydroponik-System zur Kontrolle gebaut. Alle Systeme wurden mit Mangold (Beta vulgaris subsp. vulgaris) bepflanzt und in den Aquaponik-Systemen wurden je ca. 100 Tilapia (Oreochromis niloticus) ausgesetzt.

Um Alternativen zu nicht nachhaltigem Fischmehl, welches heute zumeist als Proteinquelle für Fischfutter dient, zu untersuchen, wurde Fischfutter mit Insektenmehl produziert. Fische wurden in einem Aquaponik-System konventionell mit Fischmehl gefüttert während sie im anderen System mit Fischfutter aus dem Mehl der Larve der schwarzen Soldatenfliege (Hermetia illucens) gefüttert wurden.


Das Sammeln der Daten startete am 4. März, 2016 und endete am 1. Juni 2016. Zu Beginn war das monatliches Pflanzenwachstum in den Aquaponik-Systemen aufgrund von Nährstoffmangel mit 1.24 ±0.71 kg m\(^{-2}\) geringer als im Hydroponik-System (10.42 ±3.18 kg m\(^{-2}\)). Hitzestress war im weiteren Verlauf des Versuchs dann in allen drei Systemen der limitierende Faktor und die letzten drei Ernten unterschieden sich nicht signifikant voneinander. Das Wachstum der Fische, welche mit konventionellem Futter gefüttert wurden war signifikant höher (p<0.01) als das Wachstum der mit Insekten gefütterten Fische. Unterschiede bei der Amminosäurenzusammensetzung sowie der Chitingehalt im Insektenmehl werden als Gründe für das reduzierte Wachstum vermutet.


Die Analyse der Warenwerte sowie der Kosten der einzelnen Aquaponik-Systeme zeigte, dass während der Datenerhebung monatlich weniger Einnahmen generiert wurden als Ausgaben anfielen. Die anfänglichen Kosten bspw. für die Baumaterialien waren mit EUR 776.- um ein hundertfaches höher als die laufenden Kosten. Weiter wurden Arbeitskosten in der Analyse nicht integriert. Die prognostizierten Ausgaben
um in 6-8 Monaten 100 schlachtreife Fische zu produzieren belaufen sich auf EUR 202.- ±13.- für die insektenbasierte Fütterung und auf EUR 155.- ±4.- für die konventionelle Fütterung. Der Wert der Fische wurde auf EUR 353.- geschätzt.

Aquaponik-Systeme sind eine vielversprechende Technik um die Ernährungssicherheit in Palästina zu erhöhen. Durch die Kultivierung von ans Klima angepassten Fischen und Gemüsesorten können große Mengen an Nahrungsmitteln lokal produziert werden. Um auch das Fischfutter lokal zu produzieren, müssen weiter Alternativen untersucht und optimiert werden.
Acknowledgements

This master thesis was only made possible with the help of various people. First of all I want to thank Dr. Anett Hofmann for supporting me over the last year from the first days of organizing the experiment until the submission date. I want to thank Philip Jones and Mohammad Najajrah for building and maintaining the systems as well as for their technical advice. Mazin Qumsiyeh and Jessie Chang I want to thank for their generous hospitality and support throughout the planning phase and data collection.

For the advice with regard to planning and implementing the experiment I want to thank Prof. Dr. Johan Six. I was also greatly supported in the laboratory at the ETH by Muna Mergani Taha, Sabine Müller and Charlotte Decock and at Bethlehem University by Joseph Danho.

I further want to thank Christoph Sandrock and Timo Stadtlander from FiBL for providing the insect meal for this experiment, as well as for sharing their invaluable advice on making insect-based fish food and also knowledge of fish food ingredients in general.

Finally I want to thank all my supporters who include my family and girlfriend. The World Food System Center helped with financing the systems, whereas the Walter Hochstrasser-Stiftung provided support for my travel costs and living expenses in the West Bank. I further want to thank all the crowdfunding backers without whom this project would not have been possible.
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>API</td>
<td>Aquarium Pharmaceuticals; Provider of Aquarium Test Kits</td>
</tr>
<tr>
<td>df</td>
<td>Degrees of Freedom</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved oxygen</td>
</tr>
<tr>
<td>EC</td>
<td>Electrical conductivity</td>
</tr>
<tr>
<td>EUR</td>
<td>Euro</td>
</tr>
<tr>
<td>FCR</td>
<td>Feed conversion rate</td>
</tr>
<tr>
<td>FiBL</td>
<td>Research Institute of Organic Agriculture in Frick, Switzerland</td>
</tr>
<tr>
<td>GH</td>
<td>General hardness</td>
</tr>
<tr>
<td>ILS</td>
<td>Israeli new shekel</td>
</tr>
<tr>
<td>KH</td>
<td>Carbonate hardness</td>
</tr>
<tr>
<td>NFT</td>
<td>Nutrient film technique</td>
</tr>
<tr>
<td>$NH_3$</td>
<td>Ammonia</td>
</tr>
<tr>
<td>$NO_2^-$</td>
<td>Nitrite</td>
</tr>
<tr>
<td>$NO_3^-$</td>
<td>Nitrate</td>
</tr>
<tr>
<td>PMNH</td>
<td>Palestinian Museum of Natural History</td>
</tr>
<tr>
<td>$PO_4^{3-}$</td>
<td>Phosphate</td>
</tr>
<tr>
<td>ppm</td>
<td>parts per million</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
</tr>
<tr>
<td>TDS</td>
<td>Total dissolved solids</td>
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1 Introduction

People in the West Bank (Palestine) suffer from the decreasing availability of agricultural land. Population growth has led to increased urbanization and higher food demand [26]. The labile economical, ecological and political situation in Palestine makes it crucial to foster research on sustainable agricultural techniques. This background was my motivation to write a master thesis on the combination of fish farming and vegetable cultivation (aquaponics) in the West Bank.

Aquaponics is a water- and space-efficient technique that does not depend on synthetic fertilizer. It further helps decrease the dependency on imports of agricultural products from foreign countries and is therefore an ideal system to offer new opportunities for the people in the West Bank.

1.1 How aquaponics works

The principle of aquaponics combines two agricultural techniques: aquaculture, also known as fish farming, and hydroponics, which means growing fruit and vegetables in a system without soil. The combination of these two techniques is called aquaponics [56] [63]. In a circulatory system including a fish tank, a filter and growing beds, fish and plants grow together. Implementation is possible at low and high technological levels, which makes it interesting also for small-scale systems. The costs for such small-scale units at low technological levels can be kept low.

Bacteria, which colonise a filter media, are an invaluable component of aquaponics, as they transfer fish excretion into plant available nutrients. Water including these nutrients is pumped to the growing beds, where they are taken up by plants [56]. The water is then channelled back to the fish. Three main plant cultivation techniques can be distinguished: (1) floating raft, (2) nutrient film and (3) media-filled [63]. All three methods provide the roots with water, air and nutrients.

Plants in a floating raft system are held in place in floating sheets of e.g. Styrofoam, polystyrene boards or any other material that can float and hold plants in place [56] [63]. The roots dangle in the water that fills the growing bed. This water comes from the fish tank and is pumped back to the fish tank through an overflow [63].

When using the nutrient film technique (NFT), water is continuously pumped into pipes, which hold the plants in place. The roots grow suspended in a slow flowing current of water, through which they are provided with nutrients and moisture [56].

The third technique, which was in fact applied in this study and is also used in other projects in the West Bank, uses media-filled growing beds that often include a flood and drain mechanism [56]. Plants are grown in an inert media (e.g. volcanic
Introduction

Figure 1.1: Schematic illustration of a simple small-scale aquaponic system [56]

stones, clay balls, etc.) which acts as a substitute for soil [63]. Water from the fish tank fills the growing beds which are, after reaching a certain water level, quickly drained by a siphon. The water is subsequently collected in a sump tank, from where it is pumped back to the fish (cf. Figure 1.1).

Water in an aquaponic system circulates between fish and roots of the cultivated plants. Fish excretions enrich the water with solid and dissolved wastes. To clean the water, solids get removed mechanically. Dissolved waste in the form of ammonia ($NH_3$) gets transformed by a biofilter to nitrite ($NO_2^-$) and eventually to nitrate ($NO_3^-$) (cf. Subsection 1.6.2). While concentrations of 1 ppm of $NH_3$ and $NO_2^-$ are already toxic to fish, nitrate concentrations up to 150 ppm do not harm the fish [56] [63].

The biofilter is a crucial part of every aquaponic system. The bacteria involved in the transformation of the toxic materials are dependant on a big surface in order to colonize. In a media-filled system, the media in the growing beds can act as a mechanical and biological filter [63] [42]. This technique allows therefore a filtration without the addition of an extra tank solely needed for bacteria colonization which in turn makes it a preferable technique for small-scale systems. When using NFT or floating rafts a proper biological filtration can only be achieved with the help of an additional tank filled with filter media [42].

1.2 Hydro- and aquaculture in the West Bank

Due to the difficult political and economic circumstances in the West Bank new approaches are needed to increase food security. Several organizations have started projects to train farmers in the field of fish farming and hydroponic vegetable
1.2 Hydro- and aquaculture in the West Bank

cultivation. Some of these projects that are related to this master thesis are presented in this Section. The sites of these projects are shown in Figure 1.2.

1.2.1 Jericho: Aquaculture

The fish used in this research were provided by a fish farm in Jericho. The farm was established approx. 5 years ago by the Palestinian Ministry of Agriculture and the Arab Development Society [5]. It is specialized in growing Nile tilapia (*Oreochromis niloticus*) (cf. Figure 1.3). The water used in this project is pumped up from the ground and already has an optimal temperature of $26^\circ$C. Enriched with fish excretion it is then used to irrigate nearby fields. Fish are sold as fingerlings (the stage where they begin to eat solid food [56]) or for consumption by the Palestinian market.

1.2.2 Beit Qad: Aquaponics

The MA’AN permaculture center in Beit Qad near Jenin in the North of the West Bank serves as a demonstration site for various agricultural techniques [38]. The aquaponic systems were installed in 2012 and have been expanded continuously. By organizing meetings or workshops, MA’AN Development Center teaches local farmers and interested people about different kinds of aquaponic methods. A wide variety of vegetables and fruits

Figure 1.2: Map of the West Bank

Figure 1.3: Fish ponds with *O. niloticus* in Jericho

Figure 1.4: Media-filled growing beds in Beit Qad
are grown in their small-scale systems using media-filled growing beds (cf. Figure 1.4), floating rafts as well as a NFT system. Additionally fish are grown in an outside pond from which the nutrient-rich water is used to irrigate the surrounding fields.

### 1.2.3 Al Fawar: Hydroponics

The 'Gesellschaft für Internationale Zusammenarbeit' (GIZ, German Federal Enterprise for International Cooperation) specializes in international development [28]. In spring 2016 they built several rooftop hydroponic systems in Al Fawar refugee camp near Hebron. Students and young farmers from the camp were educated on the construction and maintenance of floating raft systems, wicking beds and vertical NFT systems (cf. Figure 1.5). The project already attracted visitors, such as pupils and neighbours, during the construction phase.

### 1.2.4 Bethlehem area: Closed down aquaponics

The Applied Research Institute - Jerusalem (ARIJ) initiated a project to provide 10 households in Bethlehem Governorate with aquaponics [59]. This project was established in 2012 and financed by the Polish Center for International Aid (PCPM) [59].

Visiting two farmers in April 2016 in Beit Sahour, a town near Bethlehem, showed the failure of this project (cf. Figure 1.6). Both farmers were provided with small scale aquaponic units including a fish tank and four m² of growing area. At the time of this research the systems were no longer in use and upon their accounts active fish farming had only been practised for half a year and one and a half years, respectively. The farmers stated that fish did not grow fast enough to be harvested before winter and that extension service was insufficient.
1.3 Nile tilapia (*Oreochromis niloticus*)

Nile tilapia (*Oreochromis niloticus*, cf. Figure 1.7) is a species of tilapia, a cichlid fish native to Africa and the Middle East [46]. Cultivation of this omnivorous grazer can be traced back to ancient Egyptian times 4000 years ago. In the 1960s, *O. niloticus* was distributed in several parts of the world increasing its production to 3.5 megatons in 2013 [46]. This made it the predominant cultured tilapia species. By far the largest producer is China followed by Egypt and the Philippines [46]. After carp, the production of all tilapia species combined is the second most important group of fish cultured commercially [46]. Due to its commonly perceived good taste and affordability, tilapia is also popular in Palestine and is sold on fish markets all over the West Bank (cf. Section 3.6.1).

The popularity of *O. niloticus* for fish farming arises from its fast growth and its tolerance to poor water quality. Dissolved oxygen (DO) levels as low as 2-3 mg/l can be tolerated as well as slightly higher concentrations of $NH_3$ and $NO_2^{-}$ compared to other cultivated fish [56]. This can be an important feature in a circulatory system like aquaponics since $NH_3$ rich fish excretion remains in the system and is gradually converted to less toxic nitrate.

*O. niloticus’* good feed conversion rate (FCR) of 1.4-1.8 allows a high productivity with small amounts of fish food [56]. Due to its fast growth rate, *O. niloticus* can reach marketable size of 600 g already after 6-8 months [63]. This means that Nile tilapia can be cultivated in the warmer summer months in regions with cold winters. It is furthermore an easy breeder which makes constant purchase of fingerlings redundant [56].

During the first life stages of larvae and fingerling, fish are kept separate to prevent bigger fish from eating them [56]. Fish in an aquaponic system should be kept in their grow-out stage which is characterised by a high growth rate [56]. This stage ends with reaching sexual maturity after 5-6 months [56]. Water temperature has to reach $24^\circ$C to allow spawning [46]. *O. niloticus* are maternal mouth breeders and the female eats only little or nothing during brooding [46]. This biological feature has an important influence on the cultivation of Nile tilapia. Since reproduction starts before marketable size of 600 g is reached, growth rate is decreased due to the production of offspring. The development of hormonal sex-reversal techniques has been able to confront the decrease in production and eliminate related financial losses [46]. The male monosex populations produced with this technique allow the cultivation of fast-growing, uniform fish [46].
1 Introduction

1.4 Insects as fish food

The amount of fish produced in aquacultures increased from 50 million tons in 2007 to over 66 million tons in 2012 [25]. This production increase comes along with an enhanced demand for fish food which is mainly based on fish meal [56]. Several studies address the problem of the use of unsustainable fish meal as a protein source in fish food [67] [39]. A promising approach is the substitution of fish meal with insect meal as a protein source [33] [51] [39]. To build up fish biomass, protein is the most important but also most expensive component in fish food [56] [33]. The fish food commonly used to cultivate tilapia contains 25-35% protein [56]. For optimal growth in younger fish like fingerlings, protein content should be increased [56].

One of the most promising insects for the production of fish food is the larvae of the black soldier fly (Hermetia illucens) [33]. H. illucens can be fed with all kinds of organic waste such as plant residues, kitchen waste or animal manure [27] [33]. The meal of the pre-pupae stage of the black soldier fly is high in protein and fat and shows additionally a balanced profile of essential amino acids [33] [6].

The larvae of H. illucens should be harvested and processed into meal in their pre-pupal stage. At this stage the larvae have reached their maximum size and still have a low chitin content [33]. Chitin, a nitrogen-containing polysaccharide found in the exoskeleton of insects [8], can decrease digestibility of fish food [33]. The differences in the composition of amino acids and the chitin content in the insect meal may have a negative impact on fish growth.

1.5 Swiss chard (Beta vulgaris subsp. vulgaris)

Fast growth and relatively low nutrient requirements make Swiss chard (cf. Figure 1.8) an attractive plant for aquaponic systems [56]. Swiss chard can be harvested 6 weeks after planting and both nitrate and phosphorus requirements are lower compared to fruiting vegetables [56]. Additionally, it is a popular leafy green in many parts of the world including Israel and Palestine.

However a problem with leafy vegetables like Swiss chard is, that the edible plant parts tend to accumulate nitrate [60]. The compounds of nitrate that are synthesised in the digestive tract are assumed to be carcinogenic [18] [60]. The major source for human intake of nitrate are vegetables [60], especially from lettuce, Swiss chard and beetroot [50]. Therefore it is interesting to examine nitrate content of the Swiss chard cultivated in aquaponic systems in order to receive information on health issues.

![Figure 1.8: Swiss chard (B. vulgaris subsp. vulgaris)](image_url)
1.6 Choice of ideal conditions

The choice of the optimal conditions in a hydroponic system is straightforward. The amount of fertilizer, pH or optimum temperature can be adjusted for the needs of the plant. In contrast, the choices in an aquaponic system are more complicated. Simultaneously needs of plants, fish and bacteria have to be considered equally. Finally, the chosen conditions are always a trade-off of these different needs.

1.6.1 Temperature and pH

When it comes to the optimal temperature, Swiss chard and tilapia have slightly different requirements. While the fish thrive best in water temperatures between 25°C and 30°C [56] or even up to 36°C [46], Swiss chard prefers air temperatures from 18°C to 26°C [56]. At water temperatures of 20 – 22°C, growth rates for tilapia can be reduced by 70 percent [58].

pH requirements of Swiss chard (pH 6-7.5) do overlap with the ideal values for tilapia (pH 7-9) [56]. Therefore a pH of 7-7.5 was targeted in the aquaponic systems. At a pH level above 7.5 plants cannot absorb iron, phosphorus and manganese [56].

For the hydroponic system a slightly lower pH was chosen. Plants prefer a pH between 6.0 and 6.5 [56]. Other sources recommend a pH between 5.8 and 6.3 for nutrient solutions in hydroponic systems [54]. Therefore a pH around 6 was targeted in the hydroponic system in order to make all the necessary nutrients readily available for plant uptake [56].

1.6.2 Ammonia, nitrite and dissolved oxygen

As already mentioned in Section 1.1 the use of the media bed technique makes the use of an extra biofilter redundant [42]. The bacteria can colonize the surface of the porous volcanic stones and convert ammonia (NH₃) to nitrite (NO₂⁻) and nitrate (NO₃⁻). Ammonia is converted to nitrite mainly by the bacteria Nitrosomonas sp whereas Nitrobacter sp is the most common nitrite-oxidizing bacteria [56]. The process of nitrification is crucial for an aquaponic system, as concentrations as low as 1 ppm of NH₃ and NO₂⁻ can already be lethal to fish [63] [56].

Same as with plants and fish, bacteria have an optimal pH and temperature range. Both Nitrosomonas sp and Nitrobacter sp function adequately at temperatures between 17°C and 34°C and at pH levels between 6 and 8.5 (optimal pH-value: 7.2-7.8 for Nitrosomonas sp and 7.2-8.2 for Nitrobacter sp) [56].

Bacteria, plants and fish equally need dissolved oxygen (DO) in the water to survive. Optimum DO levels for the ammonia-oxidizing and nitrite-oxidizing bacteria are 4-8 ppm [56]. Plants prefer DO concentrations higher than 3 ppm [56]. For fish, DO concentrations of 3-5 ppm are in the longer-term rather stressful conditions. At concentrations above 5 ppm fish are not stressed and optimal growth rates can be achieved [56].
1.6.3 Nitrate and electrical conductivity

Concentrations of nitrate ($NO_3^-$) in aquaponic systems can be influenced by the addition of fish food. To fertilize one $m^2$ growing area planted with leafy vegetables at least 30 g of fish food should be fed per day (20-25 plants per $m^2$) [63]. Other sources recommend 40 to 50 g of fish food [56]. The amount of fish food in turn determines the amount of fish.

Common ranges for nitrate in hydroponic systems are much higher than in aquaponic systems. The nutrient solution in hydroponics should contain 100-250 ppm Nitrate-N [54], which is equivalent to 440 to 1’100 ppm $NO_3^-$ (molar mass N: 14 g/mol; $NO_3^-$: 62 g/mol [7]).

For the cultivation of leafy vegetables in hydroponic systems electrical conductivity (EC) between 1500 and 2500 $\mu$S should be chosen [48]. Higher EC decreases nutrient uptake whereas lower EC could reduce yield due to nutrient deficiencies [48].

1.7 Research question

Small-scale aquaponic systems are a cost efficient opportunity to produce fish and vegetables using only small amounts of space and water. Especially in the economically weak and densely populated West Bank [24], these advantages are important for increasing food security. However, the cultivation of fish remains dependent on the import of unsustainable and expensive fish food based on fish meal. Fish food based on locally sustainably produced insects could become a relevant alternative. This research therefore focuses on the question, if insect-based fish food in small-scale aquaponic systems can provide sufficient plant nutrients for healthy leafy vegetables.

To answer this question, several system parameters (pH, temperature, DO, etc.) were monitored and controlled. The harvested plant biomass and the fish growth in the different systems was quantified and compared. Nitrate accumulation in the plant tissue was measured to evaluate possible health concerns. Further the cost efficiency of the small-scale units was compared.
2 Materials and methods

Data collection took place at the Palestinian Museum of Natural History (PMNH) of Bethlehem University in Bethlehem, Palestine (located at 31° 42’ N, 35° 11’ E, 775 meters above sea level [45]). Three systems with a main (fish) tank, two growing beds and a sump tank were installed inside a greenhouse (cf. Figure 2.1). This composition of the tanks was the same for both aquaponic systems and also for the hydroponic system. They were built in one row next to each other alongside the plastic wall of the greenhouse (cf. Figure 2.2).

2.1 Building the systems

Before data collection began, the aquaponic and hydroponic systems had to be financed, built and stocked with fish and plants. Since aquaponic systems need time to establish a bacteria community and also the equilibrium between fish waste and nutrient uptake by the plants, the systems were already built by the project partners in December 2015.

Philip Jones, head of the sustainable community development organization Byspokes, proposed the idea of building an aquaponic system for research purposes in July 2015. He suggested a collaboration with the Bethlehem University to foster research on aquaponics. Prof. Mazin Qumsiyeh was willing to support the idea, providing space in a greenhouse on the land of the PMNH in Bethlehem.

In December 2015, a crowdfunding call was started for this master thesis project which collected over EUR 3’000.- within two weeks. Additional funding was provided by the World Food System Center of ETH Zurich and the Hochstrasser Stiftung.
2 Materials and methods

Collection of materials already started in November 2015, meaning the first two systems, later used as aquaponics, were put into operation by the end of December 2015. The third system without fish was filled with water and planted end of February 2016 before the first measurements on all three systems commenced. Measurements started in the beginning of March 2016 for a period of three months.

Philip Jones, already having experience in aquaponics, supervised the building process with the help of the employees and volunteers at the PMNH, first and foremost by Mohammad Najajrah. Mohammad maintained the systems before the measurements commenced, fed the fish and began with planting of Swiss chard to be used for this research.

2.2 Experimental setup and replications

Two systems (System 1 and System 2) were stocked with fish (aquaponics) whereas System 3 was run as a hydroponic system (cf. Figure 2.3). The fish in the aquaponic systems were respectively fed with fish food based on insects (System 1, cf. Section 1.4) and fish meal (System 2).

The cultivation plan of each growing bed is shown in Figure 2.4. Each system consists of two equally treated growing beds (pseudoreplicates). Each growing bed was divided into four quarters and each quarter was planted with six Swiss chard plants. Planting started on Day 1 in Quarter 1. After 4 weeks, all growing beds were fully planted. Two weeks later Quarter 1 was harvested. Due to the fast growth of the plants in the hydroponic system, smaller plants in nearby quarters were shaded. Therefore it was decided to start harvesting the third quarter of the hydroponic system already after 30 days whereas plants in the third quarter of the aquaponics were harvested after 35 days. However, after the first cold period in March, plant
growth rate in all systems was similar, meaning harvesting took place on the same
day in all three systems again.

This shift of harvests in the third quarter caused also a shift in transplanting
seedlings. This means, that the Swiss chard in the hydroponic system had less time
to grow until the first harvest but more time until the second harvest. Therefore
growth periods for the hydroponic and the aquaponic systems were different for this
one quarter (Quarter 3). The results from Quarter 3 were therefore not included in
the evaluation of different growth rates of the three different systems (cf. Section 4.4).
Instead these results were only taken into account in the total amount harvested
over the whole data collection period (cf. Section 3.4). The remaining quarters
were harvested in total five times. For these five harvests, the growing period and
external factors like e.g. air temperature was the same in all systems. Each harvest
was therefore evaluated as a replicate.

The growing period for the harvests varied from 30 days (Harvest on Day 66), 35
days (Day 78, Day 85) up to 42 days (Day 43, Day 50).

![Figure 2.4: Arrangement of the four quarters in the growing beds](image)

2.3 System parameters

Aquaponic systems require the measurement of a wide variety of parameters. Some
parameters like the content of nitrite and ammonia in the water are crucial for the
survival of the fish. Then again, parameters like nitrate content do affect plant
growth.

2.3.1 Electrical conductivity and hardness

Electrical conductivity (EC) of water is measured in micro Siemens (=mho) and
can be used to determine the concentration of dissolved solids in water [55]. The
conductivity was measured on a daily basis with a digital meter (HM Digital,
Aquapro AP-2 water tester [29]). Since EC is affected by water temperature it has
to be adjusted via the following equation [55]:

\[
K_{18} = \frac{1000000}{R_t[1 + c(t - 18)]}
\]
2 Materials and methods

\[ K_{18} = \text{conductance in microsiemens} (\mu S) \]
\[ R_t = \text{resistance in siemens at temperature } t. \]
\[ c = \text{temperature coefficient.} \]
\[ t = \text{temperature at the time of measurement.} \]

The coefficient \( c \) varies depending on the water temperature [55]. The AP-2 Aquapro water tester features a thermometer and compensates the temperature automatically [29].

In Subsection 1.6.3 a target range of 1500-2500 \( \mu S \) for hydroponic systems was described. In the hydroponic system used in this research a value of 1700 \( \mu S \) was targeted to create ideal nutrient conditions for the Swiss chard. Fertilizer was added when values below 1700 \( \mu S \) were measured.

Both general hardness (GH) and carbonate hardness (KH) were measured every third day with a colorimetric method using a test kit (API, GH & KH Test Kit for freshwater [3]). The quantity of drops needed to induce a colour change of the 5 ml water sample determines the GH and KH [3].

2.3.2 Temperature and pH

The temperature (T) of the water in all three systems was measured with a thermometer (FarmTek, Outdoor/Indoor Min/Max Temperature Station [21]) several times a day. Additionally a temperature logger (Lascar, EL-USB-1 Temperature Data Logger [34]) was used in System 2. This logger was placed in the middle of the fish tank and recorded the water temperature every 30 minutes.

Air temperature was measured with the help of the Outdoor/Indoor Min/Max Temperature Station [21]. Two of these thermometers were placed on the growing beds of System 1 and 2 next to the plants. Since displayed air T was not always the same for the two thermometers, the average value was taken and rounded off to whole numbers.

To increase water temperature to over 25°C, the plastic side walls of the greenhouse were kept closed in the beginning of data collection in March 2016. This was the only possibility to increase water temperature since there was no heater available. Due to warmer air temperatures in April and May, water temperatures increased and the plastic walls were opened day and night. Due to the onset of the hot season, the greenhouse was shaded with a black net laid on top of the roof from Day 62 onwards (as of May 4, 2016).

A pH electrode (HM Digital, pH-80: pH HydroTester [30]) was used to measure the pH in the aquaponic and hydroponic systems on a daily basis. Furthermore a test kit (API, Freshwater Master Test Kit [2]) was used to determine the pH every third day. A chemical solution is added to a 5 ml water sample and the colour change is compared to a pH colour chart [2].

In the beginning of data collection, a pH of 8.4 was measured in the local tap water. This water was used to fill the tanks in the hydroponic system. After the addition of phosphoric acid, the pH dropped to the hydroponics’ target range between 5.8
2.3 System parameters

to 6.3 (cf. Subsection 1.6.1). During the first 20 days, 70 g of phosphoric acid was added. During the remaining period of data collection additional 300 g were added to keep the pH lower than 6.3 (cf. Figure 3.7).

The aquaponic systems were stocked with fish 6 weeks before data collection started. During that time pH was lowered to 7.5. In the beginning of the data collection, pH stayed above 7 (cf. Subsection 1.6.1). Starting on Day 38, small amounts of phosphoric acid were added to System 1 and System 2 to lower the pH to a range between 6.5 and 7 [54]. Acid addition was spread out over 3 days to avoid a sudden pH change, which could have harmed the fish. Since the pH stayed in the target range (cf. Figure 3.7) during the rest of the data collection, no additional acid was needed after Day 40.

2.3.3 Ammonia, Nitrite and Dissolved Oxygen

Ammonia (\(NH_3^+\)) and nitrite (\(NO_2^-\)) were measured with a test kit (API, Freshwater Master Test Kit [2]). To determine \(NH_3^+\) concentration two test solutions are added to a 5 ml water sample. After 5 minutes the sample develops a colour which can be compared to a colour chart to determine the \(NH_3^+\) content. The measurement of \(NO_2^-\) requires only one test solution. The subsequent procedure is the same as for \(NH_3^+\). Measurements took place every day from the start of data collection until Day 14, afterwards every third day.

DO was measured with a DO meter (Milwaukee Instruments, MW600 DO Meter [41]). This portable meter records oxygen concentration from 0.0 to 19.9 ppm at a resolution of 0.1 ppm [41].

2.3.4 Nitrate and Phosphate

The target nitrate concentration for the hydroponic system in this research was 600 to 900 ppm [54]. The fertilizer used contained 4 % nitrogen, 2.5 % phosphorous and 6 % potassium [36]. In the beginning of the data collection, nitrate (\(NO_3^-\)) was measured with a test kit (API, Freshwater Master Test Kit [2]). To determine the \(NO_3^-\) concentration, two nitrate test solutions are added to a 5 ml water sample. The subsequent procedure is the same as for the \(NH_3^+\) measurement (cf. Subsection 2.3.3). To obtain more exact results, nitrate was measured twice a week via the UV-Spectrophotometric method [65] in the laboratory at the Chemistry Department of Bethlehem University (cf. Laboratory protocol A.1.1). The absorption at 220 nm was used to determine the \(NO_3^-\) concentration. Since organic matter may also absorb at a wavelength of 220 nm, a second measurement was conducted at 275 nm. At this wavelength, \(NO_3^-\) does not absorb whereas organic matter still does. The \(NO_3^-\) concentration was then determined by subtracting the results from the measurement at 275 nm from the results at 220 nm.

The test kit (API, Phosphate Test Kit) for measuring phosphate (\(PO_4^{3-}\)) concentration uses a colour chart which displays concentrations up to 10 ppm [4]. Due to high \(PO_4^{3-}\) concentrations 5 ml water samples were diluted with 95 ml distilled
Materials and methods

2.4 Inputs

In order to start data collection right after arriving in Bethlehem in the beginning of March, insect-based fish food was previously produced in Switzerland and sent to Palestine. The meal of the larvae of the black soldier fly (*Hermetia illucens*) was provided by the Department of Livestock Sciences at the Research Institute of Organic Agriculture (FiBL) in Frick, Switzerland. The insects were harvested in a pre-pupal stadium and deep-frozen. Before the production of the pellets, the meal used was defatted at FiBL. The water content as well as the amount of ash in the insect meal was measured at ETH Zürich in the laboratory of the Animal Nutrition group of Prof., Dr. Michael Kreuzer. The dry matter minus the ash content resulted in the organic matter content.

To measure the fat content samples were added to an extraction apparatus called 'Büchi Extraktionsapparatur B-811’ and fat was extracted with petroleum ether. The solvent was vaporized and the fat content was determined by weighing.

To measure the protein content and the carbon content of the insect meal, samples were weighed into an oven where they were burned in a pure oxygen atmosphere. During the combustion, nitrogen and carbon is transformed into $CO_2$, $N_2$ and $NO_x$. Carbon content is measured in an infrared cell whereas nitrogen is determined in a TC-cell where the thermoconductivity is measured (LECO, Type CN-2000 Analyser).

The target composition of the insect-based fish food was determined with the support of Timo Stadtlander from FiBL [57]. A mixture of 68% insect meal, 27.5% wheat flour, 3% sunflower oil and 1.5% vitamin-mineral premix (provided by FiBL) was added to a mincer to produce pellets of 2 mm diameter. The sunflower oil was added after the pellets of the first attempt did not stick together. The conventional fish food used already contained such a premix in order to add the necessary vitamins and minerals to increase fish growth.

The final insect-based fish food had a crude protein content of approx. 38.2% and a fat content of approx. 19.2%. The content of carbohydrate and water was estimated to be 16.2% and 6.3%, respectively. For the conventional fish food, only the crude protein content (34%) and the fat content (6%) were known.

Furthermore the amount of fish food and fertilizer added was measured with a digital electric scale (JiangYin SuoFei Electronic Technology, SF400) [31]). From Day 45 on, nearly every day the planned amount of fish food (70 g) was fed. Only exceptions was a cold weather period in the beginning of May (Day 64-68).
The amount of water that was added continuously to the three systems was monitored with a water meter (Shandong Guanxiang Meter Co., Brass Body Water Meter (LXS) [52]). All systems contained approx. 900 liters of water in the beginning of data collection. At initiation of the experiment the meter was set to zero and the meter was read on the last day of data collection to determine the total amount of water used.

As mentioned before, small amounts of phosphoric acid to adjust the pH were needed. In total 16 g, 27 g and 372 g of phosphoric acid were respectively added to System 1, 2 and 3. Finally, for each system a small water pump consuming 45 Watt was used (Aqua One, Water Pump Maxi 105 [35]). Except for a half-day complete power blackout on April 4, 2016, these pumps were constantly running.

2.5 Fish weight and fish length

To monitor fish growth in the aquaponic systems, fish were caught from both systems in succession and kept in an additional barrel. An air pump was used to aerate the barrel. All fish were weighed, measured (length) and returned into their respective fish tank.

Fish were caught individually from the additional barrel with a small net. The net was drained from excess of water and the fish were put in a bucket on a scale (JiangYin SuoFei Electronic Technology, SF400 [31]). The accuracy of the scale was 1g. After weighing, fish were measured with a ruler to the nearest half of a centimeter. Standard length from snout to the caudal peduncle was recorded [44].

Fish were measured in total four times, namely on Day 1, Day 30, Day 59 and Day 88. There was only one fish tank (replication) per treatment. The feeding strategies were the two different treatments that were evaluated.

To describe differences in weight and length between System 1 and System 2, a t-test has been conducted [47]. First, normal distribution of the values was examined with the help of a Kolmogorov-Smirnov-test, before conducting the t-test [47]. Also, variance homogeneity was examined with a Levene test [47] [68]. The hypothesis ($H_0$) was, that there was no significant difference between the fish weight/length of the two different systems. The alternative hypothesis ($H_1$) assumes a difference in weight/length of the two different feeding strategies.

2.6 Plant growth

To compare plant growth in the aquaponic and hydroponic systems, Swiss chard was planted weekly in a quarter of each growing bed. Due to this successive planting not all Swiss chard was harvested on the same date and the growing beds were therefore always stocked with some more mature plants. Harvest of all plants at the same time could disturb the equilibrium in an aquaponic system, meaning a continuous
nutrient uptake is essential. Also, a continuous harvest of leafy vegetables is a key objective for aquaponic systems in a non-research setting, when used for food supply.

The fast growth of Swiss chard (cf. Section 1.5) made multiple harvests possible in the rather short data collection period of three months. Plants were pulled out of the growing media and the roots were cut off. Above-ground fresh weight of each plant was determined with a digital electric scale (JiangYin SuoFei Electronic Technology, SF400) [31]).

To determine the most important factors influencing plant growth, correlation coefficients were compared and a multi linear regression analysis was conducted [69]. Before conducting a multi linear regression analysis, linear correlation that was assumed due to theoretical considerations were tested. A scatter plot with the criterion (e.g. ‘harvested biomass’) and the predictors (e.g. ‘nitrate concentration’, ‘temperature’) was used to examine linearity visually [47]. The normal distribution was tested with the help of a Kolmogorov-Smirnov-Test [47].

2.7 Plant nitrate concentration

Plant samples of all three systems were collected during the harvests on Day 85 and Day 92. Due to limited storage capacity, sample collection at an earlier date was not possible. Several outer leaves of plants in each system were weighed and mixed manually. The liquid extract containing plant parts was collected in tubes and deep-frozen [49]. The remaining parts of the sample were dried and the weight of the dry matter was recorded to calculate the amount of nitrate per kg plant fresh weight.

In total three different samples (replicates) were collected and tested per System 1 and 2. For System 3, four samples were collected and tested. All samples were measured twice. This repetition of the same samples can be described as pseudoreplicates. These pseudoreplicates of the same samples serve to control the measuring accuracy.

Liquid extract of the plants was analysed at the laboratory at ETH research station in Lindau-Eschikon. For this purpose containers with liquid extract were shipped from the research site in Bethlehem to Switzerland. They were transported in personal luggage and in a package sent by airmail and were defrosted during transport for 1 and 5 days, respectively.

Measurement took place on the 17th of June, 2016. Liquid plant samples were diluted by a factor of 100 and filtered. A Vanadium(III) chloride reagent was used to colour the samples (cf. Laboratory protocol A.1.2). Concentrations of $\text{NO}_3^-$ were determined colorimetrically on a VWR V1200 spectrophotometer [17].
3 Results

This chapter summarizes all data on system parameters, plant growth, fish growth, plant nitrate concentration and cost effectiveness gathered during the data collection period from March 4, 2016 to June 1, 2016. The most important results are described with the help of charts. The data is evaluated and discussed in Chapter 4.

3.1 System parameters

Measurements with respect to parameters relevant to the individual systems are presented in the following. These include in their respective order EC, GH, KH temperatures, pH values, ammonia, nitrite, DO, nitrate and phosphate.

3.1.1 Electrical conductivity and hardness

In the beginning of the data collection, electrical conductivity (EC) of the water in the tanks was similar in all three systems (cf. Figure 3.1). The value initially measured corresponds with the EC of 457 $\mu$S measured for tap water on April 13, 2016 (Day 41).

During the data collection period, EC for the aquaponics (System 1 and System 2) increased steadily. After 90 days it reached a value of over 1000 $\mu$S. This development is similar for System 3 during the first 10 days. After the addition of over 4 kg of fertilizer over a period of 20 days (cf. Figure 3.10), the target value of roughly 1700 $\mu$S was reached in the hydroponic system. This level was held constant over the measurement period.
General hardness (GH) increased heavily after the addition of over 4 kg of fertilizer in System 3 after 20 days. However, also in the aquaponic systems an increase was observed during the measuring period (cf. Figure 3.2). The development of the carbonate hardness (KH) however is similar for all three systems and remained at a value between 0 and 100 ppm after the first 10 days.

3.1.2 Temperature and pH

Figures 3.3 and 3.4 show the development of the water temperature in all three systems. Water T was increasing over the data collection period. Several fluctuations are visible at both measuring times. The average water T at 9 a.m. was 0.09°C and 0.24°C higher in System 1 than System 2 before the second and fourth measurement of the fish, respectively. Between the second and third measurement of the fish (between Day 30 and 59), the water at 9 a.m. was on average 0.22°C warmer in System 2 compared to System 1.

Air T values show strong variation from day to day. Clouds and wind can influence air T measurements in a greenhouse within minutes. Therefore, unlike water T, air
3.1 System parameters

Figure 3.7: Measured pH and target values for the aquaponic and the hydroponic systems

The daily fluctuation of the water temperatures in System 2 is shown in Figure 3.6. The data shown summarizes the temperature profile of one week in April 2016 (April 14 - 20, 2016). Lowest temperatures were measured in the morning at around 7 a.m. Water T subsequently increased during the day by 5 – 8°C until 6 p.m.

The measured pH is shown in Figure 3.7. The lines show the pH measured with the pH electrode (HM Digital, pH-80: pH HydroTester [30]) whares the points show the value measured with the API Freshwater Master Test Kit [2].

3.1.3 Ammonia, Nitrite and Dissolved Oxygen

Ammonia (\(NH_3\)) and nitrite (\(NO_2^-\)) concentrations never exceeded 0.5 ppm in the aquaponic systems during the data collection and therefore never reached critical values for fish (1 ppm [56] [63]). Especially after the first two weeks of data collection \(NO_2^-\) content was mostly at 0 ppm, with \(NH_3\) content mostly at 0.25 ppm.

Critical values below 3 ppm [56] for dissolved oxygen (DO) were also never reached. Measurements started on Day 35 when the DO meter had finally been delivered to Bethlehem. The concentration varied with the water temperature, i.e. the warmer the water the lower the DO [41]. This was also observed in the water of all three systems. Figure 3.8 shows the water temperature together with the DO concentration in System 2. Measuring points for the other aquaponic system were similar. The hydroponic system showed slightly higher values (cf. Figure 3.9).
3 Results

![Figure 3.8: DO concentration and water T at the measurement](image1)

![Figure 3.9: Critical values for DO concentrations](image2)

3.1.4 Nitrate and Phosphate

The target value for nitrate of 600 to 900 ppm in the hydroponic system was reached after the addition of over 4 kg of fertilizer in the first 20 days (cf. Figure 3.10). During the remaining data collection period this concentration was held constant by adding small amounts of fertilizer periodically.

Nitrate concentrations in the aquaponic systems were low in the first half of data collection. As shown in Figure 3.12 the concentration then increased slowly up to 250 ppm.

Figure 3.11 shows the results for the phosphate concentrations in the aquaponic and hydroponic systems. Results for the two aquaponics were similar whereas the concentration was higher in the hydroponic system.

3.2 Inputs

The results for the composition of the fish food are listed in Table 3.1. Some of the contents were estimated by consulting the nutrition information table delivered with the purchased wheat flour [12] and sunflower oil [13].

![Figure 3.10: Nitrate concentration and fertilizer added in System 3](image3)

![Figure 3.11: PO$_4^{3-}$ concentrations in all three systems](image4)
3.3 Fish weight and fish length

Figure 3.12: Added fish food and nitrate concentrations in the aquaponic systems

Fertilizer and fish food as main inputs are shown in Figures 3.10 and 3.12. Total amount of fish food used was 4.54 kg for both aquaponic systems. The total amount of fertilizer used in the 90 days of data collection was 7.72 kg.

Table 3.1: Content of individual ingredients of insect-based fish food

<table>
<thead>
<tr>
<th>Content (%)</th>
<th>Hermetia meal</th>
<th>Wheat flour</th>
<th>Sunflower oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude protein</td>
<td>50.10</td>
<td>13.40</td>
<td>n.d.</td>
</tr>
<tr>
<td>Fat</td>
<td>24.40</td>
<td>1.25</td>
<td>92 *</td>
</tr>
<tr>
<td>Ash</td>
<td>5.55</td>
<td>1.73</td>
<td>n.d.</td>
</tr>
<tr>
<td>Carbohydrates</td>
<td>n.d.</td>
<td>60 *</td>
<td>n.d.</td>
</tr>
<tr>
<td>Water</td>
<td>4.86</td>
<td>10.80</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

* estimated

Beside fish food and fertilizer, the amount of water used was recorded. The total amount of water added during the measuring period was 1.11 m³, 1.05 m³, 1.13 m³ for System 1, System 2 and System 3, respectively.

3.3 Fish weight and fish length

The number of fish measured on Day 1 was 101 in each system. However, due to high turbidity especially in System 1, not all fish were caught. In the second measurement 106 and 102 fish were counted in System 1 and System 2, respectively. Occasionally fish died during the data collection period. Of the seven fish that died in System 1, two jumped out of the fish tank unnoticed after the measurement. The cause of death of the five remaining fish is unknown. In System 2, one fish died during the entire data collection period of 90 days. On Day 88, when the last measurement took place, 104 and 99 fish were counted in System 1 and System 2, respectively.

The differences in weight and length between the first and the second measurement were very small. Third and fourth measurements however showed increased fish weight and fish length in both aquaponic systems (cf. Table 3.2).
3 Results

Table 3.2: Comparison of fish parameters

<table>
<thead>
<tr>
<th>Period (Days)</th>
<th>Aquaponic 1</th>
<th>Aquaponic 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average weight increase (g)</td>
<td>1-30: -0.70</td>
<td>30-59: 7.55</td>
</tr>
<tr>
<td></td>
<td>30-59: 2.43</td>
<td>10.04</td>
</tr>
<tr>
<td>Average length increase (cm)</td>
<td>1-30: 0.22</td>
<td>30-59: 1.23</td>
</tr>
<tr>
<td></td>
<td>30-59: 0.27</td>
<td>1.37</td>
</tr>
<tr>
<td>Average monthly weight gain</td>
<td>30-88: 41.5 ±7.3 %</td>
<td>49.1 ±4.6 %</td>
</tr>
<tr>
<td>Absolute growth (kg)</td>
<td>1-90: 1.58</td>
<td>2.47</td>
</tr>
<tr>
<td>Fish food used (kg)</td>
<td>30-88: 2.36 ±0.18</td>
<td>1.69 ±0.06</td>
</tr>
<tr>
<td>FCR</td>
<td>30-88: 4.54</td>
<td>4.54</td>
</tr>
</tbody>
</table>

In the beginning of the data collection, a total fish weight of 1634 g and 1645 g was recorded in System 1 and System 2, respectively (cf. Figure 3.13). The last measurement resulted in 3214 g and 4114 g total fish weight which is an increase of 1580 g and 2469 g, respectively. Average weight in System 1 increased from 16.18 ±13.06 g to 30.90 ±19.80 g whereas in System 2 it increased from 16.29 ±11.30 g to 41.56 ±26.40 g. The increase of the average fish weight in all measurements is discussed in Section 4.3 and shown in Table 4.2.

The FCR and the percentage of the average monthly weight gain shown in Table 3.2 were calculated with the weight gain and feed used in the period from Day 30-88. Average weight gain was very low and even negative in the first measuring period from Day 1-30. Reasons for this decreased growth in the beginning will be discussed in Section 4.3.

Figure 3.14 shows the average fish length which increased from 6.62 ±2.15 cm to 8.8 ±2.18 cm and from 7.09 ±2.23 cm to 9.67 ±2.28 cm in System 1 and System 2, respectively.

The results for the Kolmogorov-Smirnov-tests and the Levene-tests are shown in Appendix A.2. The t and p values as well as the degrees of freedom (df) of the t-tests are shown in Table 3.3. A t-test was conducted for the first measurement on Day 1 and the last measurement on Day 88.
### 3.4 Plant growth

Table 3.3: Results of the t-tests

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Weight</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Measurement</td>
<td>t</td>
<td>-0.063</td>
</tr>
<tr>
<td></td>
<td>df</td>
<td>196</td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>0.9498</td>
</tr>
<tr>
<td>Fourth Measurement</td>
<td>t</td>
<td>-3.224</td>
</tr>
<tr>
<td></td>
<td>df</td>
<td>182</td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>0.0015</td>
</tr>
</tbody>
</table>

**3.4 Plant growth**

Fresh weight per $m^2$ is shown in Figure 3.15. Especially due to more biomass harvested in the first two harvests on Day 43 and 50, total amount of Swiss chard harvested in the hydroponic system is much higher compared to the aquaponic systems. The growth rates (kg per $m^2$ and 30-day period) of the different systems are summarized in Table 3.4. As mentioned in Section 2.2, harvests from Quarter 3 were not included due to different growing periods in the three systems.

Table 3.4: Comparison of the monthly growth rates

<table>
<thead>
<tr>
<th></th>
<th>Aquaponic I</th>
<th>Aquaponic II</th>
<th>Hydroponic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest 1 and 2</td>
<td>1.53 ±0.88</td>
<td>0.95 ±0.26</td>
<td>10.42 ±3.18</td>
</tr>
<tr>
<td>Harvest 4,5 and 6</td>
<td>2.95 ±1.02</td>
<td>2.54 ±1.50</td>
<td>3.29 ±0.98</td>
</tr>
<tr>
<td>All harvests</td>
<td>2.43 ±1.11</td>
<td>2.11 ±1.37</td>
<td>5.23 ±3.90</td>
</tr>
<tr>
<td>all data per 30-day period</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The harvests as well as the nitrate concentration in the water of the hydroponic system are shown in Figure 3.17. The amount of Swiss chard harvested on the first two dates (Day 43 and 50) was more than twice the amount of the following harvests.

Harvests in the aquaponic systems together with air T is shown in Figure 3.18. Biomass increases until the 4th harvest on Day 66 for both aquaponic systems. From that day on, harvested biomass decreased.

![Figure 3.15: Total plant biomass harvested per $m^2$](image1.png)

![Figure 3.16: Plants nitrate content and standard deviation](image2.png)
3 Results

3.5 Plant nitrate concentration

The measured nitrate content in the Swiss chard show higher values for the plants grown in the hydroponic system (cf. Figure 3.16). Values for the aquaponic system with insect-based fish food (System 1) were higher than the values measured in System 2 (conventional fish food).

The pseudoreplicates were not included in Figure 3.16. The repetition of the measurements showed that the measuring process produced accurate results. Differences between the first and the second measurement were below 5% for all three systems.

3.6 Cost effectiveness

To evaluate the cost effectiveness of small-scale aquaponic and hydroponic systems, the market prices of Swiss chard and tilapia in the West Bank were gathered. These results were used to calculate the value of the Swiss chard and fish produced in the small-scale systems. Further all expenses were collected and grouped into construction costs, measuring costs and input costs (cf. Table 3.6).

3.6.1 Retail prices

The revenues per system (one fish tank, 2 m² growing area) are summarized in Table 3.5. Calculations were performed with the gathered information on harvested plant
3.6 Cost effectiveness

Figure 3.18: Harvest in System 1 and 2 and air T at 5 p.m. with a linear regression

Biomass and fish growth as well as the retail prices. Swiss chard can be purchased for EUR 0.94 on the market in Bethlehem (1.- Euro is roughly equivalent to 4.26 Israeli New Shekel (the currency in Israel and the West Bank), July 2016 [70]). Farmers in the West Bank are paid EUR 0.71 per kg. Prices on the market in Ramallah and Beit Sahour are the same. Tilapia sold in Bethlehem is imported from the Mediterranean harbour town Tel Aviv-Jaffa and therefore has to pass the border between Israel and Palestine. It is sold for EUR 8.93 in Beit Jala, a town near Bethlehem. The purchasing price for the fish shop is EUR 8.23. Two other fish shops that were surveyed in the region do not sell tilapia. The selling price for imported carp for example was with EUR 8.23 per kg in a similar range. Tilapia can be purchased much cheaper (purchasing price: EUR 5.17 per kg) in East Jerusalem. This area belongs to the West Bank according to the agreement in 1948 [14] but it lies outside the separation wall.

Table 3.5: Revenues per system

<table>
<thead>
<tr>
<th></th>
<th>Aquaponic 1</th>
<th>Aquaponic 2</th>
<th>Hydroponic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenue from Swiss chard</td>
<td>6.86</td>
<td>6.04</td>
<td>17.79</td>
</tr>
<tr>
<td>Revenue from fish</td>
<td>9.28</td>
<td>14.50</td>
<td>-</td>
</tr>
<tr>
<td>Monthly revenue</td>
<td>5.38</td>
<td>6.84</td>
<td>5.92</td>
</tr>
<tr>
<td>Total revenue (Day 1-90)</td>
<td>16.14</td>
<td>20.54</td>
<td>17.79</td>
</tr>
</tbody>
</table>

All amounts in EUR
The tilapia from the fish farm in Jericho (cf. Subsection 1.2.1) that is sold for consumption to the Palestinian market realizes a price of 5.88 EUR per kg for the fish farmer. This is the price before transport and gutting [10].

### 3.6.2 Expenses

At the fish farm in Jericho the conventional fish food is purchased for EUR 1.18 per kg. The fish food used in the experiment was bought in Israel for EUR 2.82 per kg. The fertilizer that was used in the hydroponic system was purchased for EUR 2.35 per kg.

Furthermore the costs for the other inputs were gathered. Water costs including taxes amount to approx. EUR 1.65 per m$^3$. Phosphoric acid can be purchased for EUR 3.53 per kg and the electricity costs approx. EUR 0.12 per kW.

The total costs to build the systems used for this research was EUR 655.- per unit. As their designs are identical and they were built at the same time, the amount spent on tanks, pipes, volcanic stones, etc. was the same for all three systems. The costs for the measuring equipment shown in Table 3.6 do differ slightly since parameters like hardness or ammonia content does not need to be measured in hydroponic systems.

<table>
<thead>
<tr>
<th></th>
<th>Aquaponic I</th>
<th>Aquaponic II</th>
<th>Hydroponic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction costs</td>
<td>655</td>
<td>655</td>
<td>655</td>
</tr>
<tr>
<td>Measuring equipment</td>
<td>81.30</td>
<td>81.30</td>
<td>66.70</td>
</tr>
<tr>
<td>Initial inputs</td>
<td>36.40</td>
<td>36.40</td>
<td>11.80</td>
</tr>
<tr>
<td>Monthly input costs</td>
<td>6.90</td>
<td>6.90</td>
<td>7.70</td>
</tr>
<tr>
<td>Total money spent (Day 1-90)</td>
<td>794</td>
<td>794</td>
<td>757</td>
</tr>
</tbody>
</table>

all amounts in EUR

The initial inputs (cf. Table 3.6) summarize the costs for fish, plants and inputs like fertilizer and phosphoric acid to reach the ideal conditions. These values are higher for the aquaponic systems due to the purchase of the fish (EUR 35.30 for 100 fish). The monthly costs include water and electricity costs as well as fish food, fertilizer and phosphoric acid used per month. The labour costs were omitted.
4 Discussion

The results shown previously shall be evaluated in this chapter. Differences between the aquaponics and the hydroponic systems as well as differences between the two feeding strategies will be discussed. Furthermore influences of external factors on the results will be evaluated.

4.1 System parameters

This section covers the results from Section 3.1. All water parameters as well as the air temperature will be discussed.

4.1.1 Electrical conductivity and hardness

The EC meter is measuring the concentration of certain ions [54]. The exact concentration of dissolved solids cannot be determined with this measurement. However, the electrical conductivity serves as a straightforward approximation to determine the amount of nutrients dissolved in the water [54].

With higher EC values in the hydroponic system shown in Figure 3.1, an increase of the nitrate concentrations can also be observed (cf. Figure 3.10). This increase can also be observed in Figure 4.1 where nitrate concentrations and EC in System 1 and 2 are combined. Yet, it is still assumed that an increasing EC can not only be ascribed to higher nitrate contents.

Since the aquaponics and the hydroponic used in this thesis are closed systems, there is no water leaving the systems except through evapotranspiration. The water used to refill the systems had an EC value of about 450 µS and a nitrate content of about 17 ppm. Dissolved solids are lost through plant uptake. It is therefore assumed that over time, certain salts that are not taken up by plants accumulate in the systems. Somerville et al. mention the limit of 2000 µS at which plant growth may be reduced [56]. Another study used shoots of *Spathiphyllum* to evaluate plant growth in hydroponic systems [15]. EC values of 600 µS up to 2400 µS were examined. An EC of 1200 µS of the nutrient solution was found to be the optimum. Samarakoon et al. (2006) reported highest harvests of leafy lettuce for the lowest examined
EC of 1400 µS [48]. The study was done under tropical greenhouse conditions in a hydroponic system [48]. These two studies ([15] and [48]) look at ideal EC of nutrient solutions in open hydroponic systems. It is assumed that accumulation of other dissolved solids is marginal. For a small-scale aquaponic system it is therefore recommended that if the EC should reach permanently a value of over 2000 µS actions like replacing part of the water should be taken.

For cichlids, the recommended value for general hardness (GH) in aquaculture ranges from 50 to 100 ppm [3]. In an experiment where O. niloticus of 15-20 g in fish weight were exposed to a herbicide, a general hardness of 50-70 ppm (as CaCO₃) was reported [32]. Naturally occurring values for GH ranges from 10 ppm in certain rivers up to 500 ppm in rift valley lakes of East Africa [23]. The higher values found in this study (cf. Figure 3.2) probably did not harm the fish. Other studies used a similar range of 340 ± 29 ppm to grow O. niloticus [43]. Further juvenile fish and breeding fish are far more sensitive [23] than fish in their grow-out stage like the ones cultivated in this study.

The carbonate hardness (KH) describes the buffering capacity of the water [23]. This means that the pH is more stable in water with a higher KH [23]. A KH range of 50-100 ppm is recommended [3]. As shown in Figure 3.2, after the first 20 days KH values were stable at a rather low range of 30-60 ppm.

Both GH and KH did not need to be adjusted actively in this study. Nevertheless, with increasing GH values it may be necessary to exchange part of the water in the system in future with tap water with a lower GH. The rather low KH could also be increased by exchanging water, but also with the use of a buffer such as sodium bicarbonate [23].

### 4.1.2 Temperature and pH

Due to low water temperatures in the beginning of the data collection feeding was reduced and fish growth as well as plant growth therefore decreased (cf. Subsection 4.3 and Section 4.4). Even by keeping the greenhouse closed during the first weeks of data collection, water T could not be increased above 25°C, which would have been ideal for the fish. From Day 50 on, water T was above 20°C regularly and reached temperatures of up to 30°C in the evening.

Whereas the fish suffered from low temperatures in the beginning of the data collection, the Swiss chard grew much faster in this period. This can be seen by the high amounts of biomass harvested on Day 43 and Day 50 in System 3 (cf. Figure 3.17). Optimum air temperature for Swiss chard was only measured in the beginning of the measuring period (cf. Figure 3.18). The different effects on plant growth will further be discussed in Section 4.4.

Except for the first 20 days, the pH in the hydroponic system stayed close to the targeted value of 6 (cf. Figure 3.7). The plants had therefore ideal pH conditions. The target value for the two aquaponic systems was decreased after 38 days to 6.5-7. It was assumed that plant growth could be decreased at higher pH levels due to inaccessibility of certain nutrients like iron [56]. Nonetheless, the pH values that
were measured initially were also acceptable for the plants. The initial values were even better for the bacteria (optimum above 7.2 [56]) and the fish (optimum above 7 [56]). This choice of the target value shows the trade-off that has to be made in an aquaponic system. Since the pH was always in the acceptable range for both fish and plants it was assumed that it only had a minor influence on their growth rate.

4.1.3 Ammonia, Nitrite and Dissolved Oxygen

The low concentrations of ammonia ($NH_3$) and nitrite ($NO_2^-\$) demonstrate the stability of the aquaponic systems. Fish excretion was converted into nitrate immediately. Thus it can be assumed, that the colonization with bacteria was already advanced when data collection began. Over the 3 months, both Nitrosomonas sp and Nitrobacter sp colonies seemed to be resilient.

Evaluating the gathered data of the concentration of dissolved oxygen (DO) primarily shows that this small-scale systems provide enough oxygen for bacteria, fish and plants (cf. Figure 3.9). The water was in fact pumped into the fish tank through several small holes in the pipe to increase oxygen concentration. Further water is siphoned to the sump tank, which also increases oxygen content of the water through splashing into the sump tank below the growing beds. The circulation is achieved by using only one small 45 Watt water pump (Aqua One, Water Pump Maxi 105 [35]). This amount of energy input was therefore sufficient to get enough oxygen into the water for all living organisms in the system. However, as shown in Figure 3.8, higher temperatures may decrease the concentration of DO. When reaching critical levels, an air pump/additional aerator should be used to increase DO concentration.

Finally, the difference between the hydroponic system and the two aquaponic systems can be seen in Figure 3.9. It shows, that a small amount of DO is in fact consumed by the fish and bacteria in the aquaponic systems, leading to lower DO concentrations.

4.1.4 Nitrate and Phosphate

Lower temperatures in the beginning did influence nitrate concentrations in the aquaponic systems. Figure 3.12 shows that with higher feeding rates nitrate concentrations increased. As mentioned in Subsection 4.1.2 due to low water T in the beginning of the data collection, the feeding rate had to be decreased, then again influencing the nitrate concentrations and therefore plant growth (cf. Section 4.4).

Since fertilizer was used in System 3, water temperature did not influence nitrate concentration (cf. Figure 3.10). Although measured nitrate concentrations showed strong variation they only fell below the target value twice. It was therefore assumed that nitrate did not limit plant growth in the hydroponic system.

Phosphorus (P) concentrations of 30 to 50 ppm are ideal in hydroponic systems [54]. Zekki et al. (1996) used a complete nutrient solution with a P content of 36 ppm to grow tomatoes in a hydroponic system [71]. Other suggested P contents of hydroponic
fertilizers for lettuce, herbs and leafy greens range from 16 to 50 ppm [40]. Phosphorus requirements of Swiss chard are lower compared to fruiting vegetables [56] and the target value for phosphorus was therefore chosen at around 30 ppm. In this study, phosphorus concentration was increased by respectively adding phosphoric acid as well as fertilizer or fish food to the hydroponic or aquaponic systems.

Both, test kit data and laboratory measurements, quantified the phosphate ($PO_4^{3-}$) concentration (cf. Figure 3.11). The recommended range for phosphate concentration is due to its higher molar mass approximately 90-150 ppm (atomic mass O: 16.00 g/mol; P: 30.97 g/mol [7]). For Swiss chard it was assumed that at $PO_4^{3-}$ concentrations of 90 ppm phosphate will not limit plant growth. In the hydroponic system, this threshold was reached 20 days after the start of the data collection. $PO_4^{3-}$ concentrations were at least 100 ppm at every measuring date.

The instructions for the test kit (API, Phosphate Test Kit) used to measure the phosphate in the beginning of the data collection recommends a concentration of 0 ppm for an aquarium [4]. Phosphate does not directly harm fish, but increases the growth of algae can be fostered by high phosphate levels [4]. It was assumed that without algae growth higher phosphate levels do not harm the fish. Studies with aquaponics also reported phosphate levels of 53 ppm in water from intensive recirculating fish culture systems [22]. However, Bright Agrotech, a company partnering with farmers to build vertical farms and hydroponics, recommends a phosphate concentration in aquaponics of 10-20 ppm for light feeders (e.g. leafy vegetables) [9].

It can be summarized that the lowest phosphate levels used in studies with hydroponic systems were 49 ppm (16 ppm phosphate [40]) and the highest levels mentioned in aquaponics were 53 ppm [22]. The phosphate concentrations measured in this study’s aquaponics were approx. 50 ppm (cf. Figure 3.11). They were therefore rather low for plants and rather high for fish. However, they still lie in the acceptable range of the recommended levels for hydroponics and aquaponics. It was therefore assumed that these phosphate levels only marginally influenced both plant growth and fish health.

Additionally, only marginal algae growth was observed in this study. The main reason for this reduced growth is that the water was never exposed to full sunlight. Media in the growing beds was not completely flooded and the fish tank as well as the sump tank was covered. Additionally O. niloticus as an omnivorous grazer [46] can prevent algae growth.

### 4.2 Inputs

The amount of water added was similar in all three systems. It was therefore assumed that the use of an aquaponic or a hydroponic system did not influence the amount of water used significantly. Differences may have occurred due to different water levels in the growing beds at the moment of reading the water meter. Whereas water consumption of circulatory hydroponic and aquaponic systems was found to
be similar, aquaponics may help decrease water use in fish production. Al-Hafedth et al. (2008) state that only 1.4 % of the total water in an aquaponic system was added daily compared to 20-25 % in extensive and semi-intensive aquacultures [1]. The water use per kg tilapia produced in these aquacultures is with 2.5 to over 5 $m^3$ much higher than the 0.32 $m^3$ recorded in the aquaponic system [1].

The higher amount of phosphoric acid used in the hydroponic system did not only decrease the pH but also increase the phosphate concentration (cf. Figure 3.11). It is assumed that the data measured with the test kit (API, Freshwater Master Test Kit [4]) were underestimating the actual phosphate concentration in the hydroponic system. This assumption is based on the fact that phosphoric acid was already added during the first 20 days and that laboratory data shows higher concentrations in System 3. However, these inaccurate $PO_4^{3-}$ measurements in the beginning were still mostly above 90 ppm and it was therefore assumed that phosphate was not limiting plant growth (cf. 4.1.4).

As another important input, mineral liquid fertilizer is used as a nutrient solution in hydroponic systems. Techniques used in organic agriculture like increasing of organic matter (e.g. through mulching) or the use of solid manure are no options in soilless systems. Using fish as a producer of fertilizer is one way to avoid the use of non-sustainable liquid mineral fertilizer. However, even products in aquaponics can not be labelled as ‘organic’ since typically no soil is used in the production [20].

The most complex input to evaluate is the fish food. The protein content of the conventional fish food was with 34 % within the recommended range of 25-35 % [56]. Other factors like the amino acid composition, the vitamin or the mineral content are assumed to be optimal for fish growth. This conventional fish food is in fact widely used to grow fish [37]. The growth rate of the fish fed with the conventional fish food was therefore assumed to be optimal in the given setting.

The insect-based fish food however was not widely used before and therefore not optimized to maximize fish growth. The production of this alternative fish food aimed at a similar composition as in the conventional fish food. As mentioned in Section 1.4 the amino acid composition of the larvae of *H. illucens* appears to be the most similar to fish meal [6] [33]. Furthermore a vitamin-mineral premix was added to the insect-based fish food to cover the requirements of vitamins and minerals for the fish.

An important disadvantage of insects as fish food is their chitin content which decreases digestibility of fish food [33]. Crude protein content was determined by measuring nitrogen content of the insect meal (cf. 2.4). Since chitin also contains nitrogen, crude protein content of the insect meal was overestimated. Kroeckel et al. (2002) measured a chitin content of 96 g per kg dry matter *Hermetia* meal [33]. Crude protein content was chitin-corrected for example by 28.2 to 42.5 % in a study by Diener et al. [16]. Another study observed a weight gain of 292.77 % in *Oreochromis niloticus* x *O. aureus* fed with a diet that contained 10 % chitin [53]. This weight gain was significantly (P<0.05) lower than the weight gain of 455.53 % of the fish fed with a diet that did not contain chitin.
4 Discussion

It was attempted to compensate for the overestimation of the crude protein content by choosing an increased protein content in the insect-based fish food (38.2 %) compared to the conventional fish food (34 %). Negative effects on the fish growth and potential solutions are discussed in Section 4.3.

4.3 Fish weight and fish length

The water T has a major influence on the growth rate of the fish [19]. As shown in Subsection 3.1.2 the T differences of the two fish tanks were small. Therefore it was assumed that this difference did not lead to differences in growth rates in the two Systems. Instead the only reason for varying growth rates is assumed to be the different feeding strategies.

The average fish weight of all four measurements is shown in Figure 4.2. Due to lower water temperatures (cf. Figure 3.3), the growth was marginal in the first 29 days. With increasing water temperatures, third and fourth measurement showed an increased average fish weight in both systems.

As shown in Appendix A.2, some results for the Kolmogorov-Smirnov-test for the fish weight/length were significant and normal distribution of the measured data points can therefore not be assumed. However, a t-test can still be conducted without normal distribution [47]. Requirements are more than 30 data points per group and similar group sizes [47]. None of the results of the Levene-tests were further significant meaning that variance homogeneity can be assumed [47].

The results of the t-tests show, that there was no significant difference in the two systems neither in fish weight nor in fish length in the beginning of the data collection period (cf. Table 3.3). The results for the last measurement on Day 88 look different: Both fish length and fish weight is significantly increased (p<0.01) in System 2. This means that the alternative hypothesis (H₁), describing different growth rates for the two feeding strategies, can be assumed. The significantly higher weight of the fish in System 2 can be explained with the different qualities of the fish foods used. Insect-based fish food has therefore a negative impact on the growth rate compared to conventional fish food. The fish will require larger amounts of insect-based fish food to reach marketable size of 600 g.

![Figure 4.2: Average fish weight and standard deviation in the aquaponic systems](image-url)
The different growth rates were assumed to derive from several characteristics of the insect-based fish food. First of all, the pellets, compared to the conventional pellets, did not float on the water surface. This might have decreased food uptake since fish food lying on the bottom of the fish tank is normally not eaten after about 30 minutes [56]. Further chitin content (cf. Section 1.4) or deficiencies of certain amino acids [6] might have decreased fish growth. A possible solution could be an increase of the protein content of the fish food. Since the measured crude protein content of the insect meal was 50.1 % (cf. Table 3.1), an increase in the insect-based fish food would be feasible. Even with a chitin-corrected crude protein content of 42.5 % [16], the protein content in the fish food would still be close to 30 %. This increase could be reached by decreasing the amount of wheat flour and by increasing the amount of insect-meal to produce the fish food pellets (cf. Table 3.1),

4.4 Plant growth

As mentioned before, the evaluation of the plant growth will focus on the harvests on Day 43, 50, 66, 78 and 85. On these dates, growth period was the same for all three systems and data for all growing beds is available. Moreover, the two first harvests (on Day 43 and 50) as well as the three last harvests (on Day 66, 78 and 85) will be evaluated separately.

Plant growth was influenced by a wide variety of factors. Most of them were already mentioned in previous sections. It can be summarized that the system parameters EC, GH and KH as well as concentrations of \( \text{NH}_3 \), \( \text{NO}_2^- \) and DO did not influence plant growth directly.

Other parameters including pH and \( \text{PO}_4^{3-} \) were assumed to have only marginal influence on differences in Swiss chard biomass in the three systems. The pH was also included in the multiple linear regression analysis conducted for the last three harvests. And pH had no significant influence on the harvested biomass (cf. Appendix A.3.2). For \( \text{PO}_4^{3-} \) concentration optimum values were only reached in the hydroponic system. Levels in the aquaponics could not be adjusted since the fertilizer was added in form of fish food, allowing no exact addition of \( \text{PO}_4^{3-} \). However, as shown in Subsection 4.1.4, levels in both aquaponic systems were also in a range where it was assumed that plant growth was not stunted.

Figures 4.3 and 4.4 show the average harvested fresh weight per plant on different dates. As explained in Section 2.6, Swiss chard was planted weekly in one quarter of each growing bed. Since each system is composed of two growing beds, each with six Swiss chard plants, this meant that per harvest 12 plants were harvested per system. The average plant weight was higher for the hydroponic system (664 ± 361 g) compared to the average weight of the plants in the aquaponic systems (79 ± 78 g) for the first two harvests. The high standard deviations come from huge weight differences between individual plants.

The most important factors influencing plant growth were assumed to be the temperature and subsequently the nitrate concentrations. On the one hand the
cold weather led to low water temperatures which reduced feed intake of the fish in the aquaponic systems. This again led to lower fish excretions and lower nitrate concentrations (cf. Figure 4.5). On the other hand, nitrate concentration in the hydroponic system was not effected by these lower water temperatures. This was assumed to be the main reason for the significantly higher harvests in the hydroponic system compared to the two aquaponic systems on Day 43 and Day 50 (cf. Figure 4.3). Conducting a multi linear regression analysis to show the strong influence of the nitrate concentration was not possible. The reason was that the criterion ‘Biomass’ was not normally distributed (tested with a Kolmogorov-Smirnov-test [47]). Instead the correlation coefficients were calculated to compare the influence of the predictors on the criterion ‘Biomass’. It was found, that the correlation of the nitrate concentration was higher (correlation coefficient r=0.77) than the correlation of the average air temperature at 9 a.m. and 5 p.m. (r=0.07) during these first two harvests. The correlation coefficient between the harvested biomass and system specific treatment (aquaponic/hydroponic, insect-based/conventional fish food) was 0.64 and therefore also higher than the coefficient of the air temperature (r=0.07). As mentioned above, treatment and nitrate concentration can be linked. The nitrate concentration in the hydroponic system for example was much higher due to the addition of fertilizer. This explains why both factors, 'Treatment' and 'Nitrate concentration', have a similar correlation coefficient with the harvested biomass.

The increase of the air temperature (cf. Figure 3.5) led on the one hand to higher water temperatures and an increase of nutrients and harvested biomass in the aquaponic systems (cf. Figure 4.5 until Day 66). On the other hand optimum air temperature for Swiss chard was exceeded mostly from Day 40 onwards as can be seen in Figure 3.18. Assumingly, these high temperatures were the reason for the decreased harvests as seen in Figure 4.5 after Day 66. As shown in Figure 4.4, the average weight of the Swiss chard plants in the aquaponic and hydroponic systems was similar. A multiple linear regression analysis including individual plant fresh weight showed, that the days with heat stress significantly (p<0.001) decreased the amount of harvested biomass (cf. Appendix A.3.2). Other predictors like 'nitrate concentration' or 'treatment' had no significant influence on the biomass.

Figure 4.3: Average plant weight on Day 43 and 50

Figure 4.4: Average plant weight on Day 66, 78 and 85
4.5 Plant nitrate concentration

In summary it can be said that the temperature is the most important factor to consider when optimizing plant growth. Plant growth in aquaponic systems was decreased by the low temperatures in the beginning of the data collection as well as by the high temperatures in April and May. Plants in hydroponics were only decreased due to the higher temperatures in the end of data collection. With ideal temperatures it can be assumed that with increasing nitrate concentrations in the aquaponics, harvested plant biomass would become similar to the harvests in the hydroponic system. To prevent a decrease in harvest, more heat-resistant plants like peppers or cucumbers should be cultivated [56].

Parameters like pH or the $PO_{4}^{3-}$ concentrations could only become the limiting factors of plant growth in a greenhouse with controlled temperature. However, the building and maintenance of such greenhouses would be very cost intensive and would stand in no relation to the examined low-cost small-scale systems.

4.5 Plant nitrate concentration

The nitrate content found in vegetables is regulated by the Commission of the European Communities [60]. There are no maximum levels mentioned for Swiss chard in the Commission Regulation (EC) No 1881/2006 [60], but there are maximum values for similar leafy vegetables. Fresh spinach (summer months) for example should not exceed a maximum level of 2500 mg $NO_{3}^{-}$ per kg fresh plant biomass. The limit for lettuce grown under cover is 3500 mg $NO_{3}^{-}$/kg [60]. The concentrations measured in the hydroponic system exceed both of these thresholds whereas the amount of nitrate in the plants from System 1 only exceeds the threshold for fresh
spinach (cf. Figure 3.16). These rather high values correlate with findings in a study from Santamaria et al. (1999), where nitrate concentrations in Swiss chard samples ranged from 1299 up to 4220 mg per kg fresh weight [50]. The reason for the differences in nitrate concentration in the plants can most certainly be ascribed to the different nitrate concentrations in the water. This concentration was much higher in the hydroponic system during the growing period when samples were taken (Day 50 - Day 90) but also slightly higher in System 1 compared to System 2 (cf. Figure 3.10 and Figure 3.12).

As mentioned in Section 1.5, the problem is not nitrate itself. It is the toxicity of its compounds that are synthesised in the digestive tract [18]. However, Walker (1990) summarizes in a meta-analysis findings on the correlation of nitrate exposure and cancer [64]. A link between cancer incidence and nitrate intake was not found [64].

Although effects of nitrate uptake are controversially discussed, the European Union considers it necessary to state nitrate concentration limits in vegetables. Plants in System 1 and System 3 both show critically high nitrate concentrations. The easiest way to avoid exceeding these critical limits would be by planting fruiting vegetables where the consumed plant parts do not accumulate as much nitrate as in leafy vegetables [60]. In conclusion, when planting leafy vegetables, nitrate levels in the water would have to be reduced.

4.6 Cost effectiveness

First the costs for a small-scale unit like the ones used in this thesis will be discussed in Subsection 4.6.1. This evaluation is important for people in the West Bank that are interested in building such a small-scale system. The conditions in other nearby regions may vary strongly which made it only possible to predict costs and revenues in the West Bank.

Moreover the cost effectiveness of hydroponic and aquaponic systems and the potential differences between the two feeding strategies will be evaluated in Subsection 4.6.2. To get a good overview, data and calculations of the revenues and costs are summarized in Tables 3.5 and 3.6.

4.6.1 Costs for a small-scale aquaponic

The costs for one small-scale aquaponic unit are relatively high compared to the input costs (cf. Subsection 3.6.2). The costs to start running an aquaponic system amount to approx. EUR 773.- per system including the purchase of the materials, measuring tools, fish and plant seedlings. Monthly expenses for water and electricity amount to approx. EUR 4.70. The monthly costs for fish food depends on the biomass of the fish and amounted to EUR 0.94 in the first 30 days and to EUR 2.35 in the last 30 days of this study.

The total amount that has to be spent over the whole growing period of the fish is depending on the feed conversion rate (FCR). The FCR measured after the cold
4.6 Cost effectiveness

The amount of harvested plants in a small-scale aquaponic system is difficult to predict since a wide variety of plant species may be used. The value of the Swiss chard in the aquaponic systems in this study was EUR 1.60 ±0.89 per m² after a 30-day period. This value was calculated with the observed average daily growth rate in the aquaponic systems of 76 g ±42 g per m² and a price of EUR 0.71 per kg Swiss chard (cf. Section 3.6). These growth rate shows strong deviations which arise from different growth periods with different air temperatures and nitrate concentrations (cf. Section 4.4). The observed daily growth rate of the Swiss chard planted in the study in Beit Sahour was with almost 140 g per m² fairly higher [62].

Since the experimental setup for this study was designed for a research purpose, several modifications should be made when planning the setup of a small-scale aquaponic system for private use. The costs for example can be reduced dramatically by the use of recycled materials. Figure 4.6 shows a small-scale aquaponic system built of recycled barrels. Costs for the tanks were compared to this study decreased by 80 %. Furthermore, for the sake of diversification a wide variety of plants should be cultivated. The value of the different plants harvested per month in the study in Beit Sahour for example amounted to EUR 10.10 per m² [62] compared to EUR 1.60 ±0.89 per m² in this study.

Tilapia usually require 6-8 months to reach marketable size [56]. In the Bethlehem region, average maximum air temperatures of 20°C to 30°C can be expected from April to October [11]. Growing period should not extend over these 7 months.

Figure 4.6: Low-cost aquaponic system
4 Discussion

4.6.2 Cost effectiveness of the different systems

As shown in Table 3.6, costs before running the system were with approx. EUR 734.- (construction, measuring equipment and stocking) slightly lower for the hydroponic system than for the aquaponic systems (EUR 773.- for each system). At this point it is important to mention that the use of media-filled growing beds is not typical for small-scale hydroponics. Floating raft or NFT (cf. Section 1.1) is preferred since both systems can easily be scaled up which makes these techniques financially more viable [56]. NFT systems can furthermore use the vertical space which is especially interesting when space is limited [63]. The main reason to use the media-filled growing technique for small-scale aquaponics is that the filter and the growing beds are combined [56]. In contrast, hydroponic systems do not require a filter since the added nutrients can be taken up directly. The further cost analysis will therefore focus on future costs and revenues of media-filled small-scale aquaponic systems.

The price for insect-based fish food is not known since it is not produced commercially in Israel and Palestine. Same as for the commercial feed used in Jericho (cf. Subsection 1.2.1), a price of EUR 1.18 per kg was chosen for the insect-based fish food in all the calculations. This assumption might be too low since the industry to produce this sustainable fish food would need time to develop and initially this new fish food would be more expensive. However, after establishment, replacing fish proteins with insect proteins might cut costs in the long-term perspective.

The revenue derived from Swiss chard and fish is calculated hypothetically assuming it would have been sold for EUR 0.71 and EUR 5.88 per kg, respectively. To estimate the value of the fish, the same selling price as in the fish farm in Jericho (cf. Subsection 1.2.1) was chosen. This price was, compared to the researched prices in the Bethlehem region (cf. Subsection 3.6.2), relatively low or in other words pessimistic. When comparing Table 3.5 and Table 3.6, it can be seen that the monthly income was slightly lower than the monthly expenses. However, this calculation considers only the results from the observations during the data collection period when fish were small and absolute growth was low. Temperatures were further not ideal for the chosen plants. Other factors like higher selling prices or volatile water and electricity prices will also have a strong influence on the monthly in- and outputs.

To get a better idea of the relationship between the expenses and the income from the fish, a time frame from starting the systems until harvesting the fish will now be evaluated. Predictions will not include income generated from plants since the examined Swiss chard growth rates are not applicable for the summer temperatures in the West Bank. Data for other, more heat resistant crops (e.g. cucumbers or pepper [56]), is not available for small-scale aquaponic systems in this climate. Predictions made here should always be adjusted when external factors are influencing the growth of the fish. Overfeeding for example due to lower temperatures can easily be observed and should be avoided to reduce costs. Underfeeding on the other hand could extend the growing phase to November when water temperatures may be too low.
Table 4.1: Predicted expenses and income from fish

<table>
<thead>
<tr>
<th></th>
<th>Aquaponic I</th>
<th>Aquaponic II</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCR</td>
<td>2.36 ±0.18</td>
<td>1.69 ±0.06</td>
</tr>
<tr>
<td>Amount of feed needed (kg)</td>
<td>141 ±11</td>
<td>101 ±3</td>
</tr>
<tr>
<td>Input costs (EUR)</td>
<td>201.60 ±12.70</td>
<td>154.50 ±4.6</td>
</tr>
<tr>
<td>Revenue (fish only)</td>
<td>353.-</td>
<td>353.-</td>
</tr>
</tbody>
</table>

The costs for fish food are the biggest part of the input costs (EUR 166.20 and EUR 119.20 for System 1 and System 2, respectively). Other expenses like electricity or water costs did not include a standard deviation which is why only the standard deviation of the fish food costs is included in the input costs.

It can be seen that the value of the fish exceeds the costs for inputs. This prediction however does not include several important factors. Labour costs for example were not measured during this study and are therefore not included in the input costs. Since fish should be fed on a daily basis and problems may occur unexpectedly, aquaponic systems should be maintained on a regular basis, which may increase the presented input costs significantly. However, as already mentioned, revenue from plants grown simultaneously are not included in Table 4.1. In the study by Viladomat & Jones (2011) it was shown that, depending on the chosen crop, a significant part of the revenue generated in small-scale aquaponic system actually derives from crops [62].

4.7 Future outlook and recommendation

Aquaponic is mostly unknown in the West Bank and communities like Bedouins are difficult to reach. Expanding research on small-scale units could therefore enhance the acceptance of the local community. This type of research should be open to the public and focus on the needs of the local community. Booklets and information brochures can be a useful tool to draw attention to this innovative agricultural technique. However, using small-scale research units also as demonstration sites (cf. Figure 4.7) will be the most efficient way to convince people in the West Bank of the advantages of these systems.

Although not all scientific details of aquaponics have to be known when building
Discussion

A small-scale unit, handling various problems concerning bacteria, fish or plants require a basic knowledge. By providing support and advice for owners of small-scale units over a long period of time, failed systems like the ones presented in Subsection 1.2.4 can be prevented.

The use of alternative fish food has been discussed in several publications [27] [33] [51] [63]. The results gathered in this study indicate a negative impact when using insect-based fish food exclusively. To meet all the nutritional requirements of the fish, Sommerville et al. (2014) recommend the use of high-quality manufactured fish food [56]. As supplemental fish food the authors mention duckweed (Lemma spp), the nitrogen fixing water fern Azolla, Moringa spp or insects. Future research examining growth rates of fish fed with alternative fish food should focus on the entire growing period to reveal nutrient deficiencies of each individual alternative. All in all, a combination of the afore mentioned alternatives may help decrease the share of fish meal used in the fish food diet.
5 Conclusion

The work with small-scale aquaponic systems reveals its resilience over a long period of time. Toxic compounds like ammonia or nitrite are efficiently converted into nitrate and a safe level of dissolved oxygen can be maintained simply with a small water pump. This resilience is an important prerequisite to prevent sudden fish death and collapse of the system. The comparison with a hydroponic system on the other side showed the strong influence of external factors. Requirements of bacteria, fish and plants have to be met simultaneously in one system. Due to this complexity in an aquaponic system, trade-offs have to be made when choosing the ideal conditions. Decreased bacteria activity as well as reduced plant and fish growth can be the consequence.

The harvested plant biomass was decreased in the beginning of the data collection period due to the low nitrate concentration in the aquaponic systems. In a hydroponic system, this nutrient deficiency can easily be corrected by adding fertilizer. In an aquaponic system, the dependency on the right conditions for the fish and the bacteria makes an increase of the nitrate concentration much more complicated.

The reduced plant growth in the end of the data collection period because of the high air temperatures can be prevented by choosing more heat-tolerant crops. In particular fruiting vegetables like peppers or cucumbers could still generate high yields in the summer months. Since nitrate concentrations were increasing in the hydroponic systems it can be assumed, that harvested biomass of heat-tolerant species would be similar in aquaponics and hydroponics.

The use of insect-based fish food revealed the advantages of the conventional fish food based on fish meal. Ever since fish have been cultivated the composition of the fish food has been investigated to optimize fish growth. Achieving the same optimization with fish food based on insect meal will require years of research. However, since fish meal is unsustainable [67] [39] and can not be produced locally the search for alternatives has to be promoted.

In the West Bank, new ways have to be found to increase food security and decrease dependency on imports. The idea of urban farming in this urbanized and densely populated region [24] could contribute to the local production of food. By producing a wide variety of vegetables and fish with little use of space and water, small-scale aquaponic systems are particularly suitable to increase food security.
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A Appendix

A.1 Laboratory protocols

A.1.1 Water parameters (Bethlehem University)

Phosphorus ($PO_4$)

Apparatus:
A. Spectrophotometer
B. Graduated pipettes, 1, 5, 10, 25 ml
C. Volumetric flasks 100 ml, 1000 ml
D. Erlenmeyer flasks or beakers (100, 250 ml)

Reagents:
1. Ammonium molybdate solution (5 %)
2. Stannous chloride
3. Stock phosphate solution
4. 20 N $H_2SO_4$
5. Standard phosphate solution

Calibration Curve:
1. Prepare solutions of 0.5, 1, 1.5, 2, 2.5 ppm ($PO_4$) by diluting 1, 2, 3, 4, 5 ml of the standard phosphate solution to 100 ml.
2. Apply the sample procedure to prepare the calibration curve.

Sample Procedure:
1. To 25 ml of water sample of standard add 1 ml of a mixture of equal volumes of 5 % ammonium molybdate and 20N $H_2SO_4$.
2. After 5 min add 1 ml of stannous chloride $SnCl_2$. If phosphate is present a blue color will develop.
3. After 20-45 min read the absorbance and plot a curve of absorbance vs. ppm phosphate.

Nitrogen (Nitrate)

Apparatus:
1. Spectrophotometer (spectronic 21D)
2. Quartz cells of 1 cm bath length
3. Filter papers (ashless or acid-washed)

Reagents:
1. Nitrate-free water
2. Stock nitrate solution
3. 1 N Hydrochloric acid (HCl)

Treatment of sample:
1. Add 1 ml of 1 N HCl to 50 ml volumetric flask.
2. Complete the volume to 50 ml with clear sample, filtered if necessary.
3. Zeroing: run a blank to which 1 ml of 1N HCl is added.
4. Pour the solution into absorption cell of spectrophotometer and measure the absorbance at 220 nm to obtain \( NO_3 \) reading.
5. If sample absorbance is greater than 1.0 so a sample dilution must be done.
6. Change wavelength to 275 nm.
7. Run blank for zeroing.
8. Read the absorbance at 275 nm to determine the interference due to organic matter.

Calibration curve:
1. Prepare 1,2,3,...,20 ppm of the standard Nitrate solution
2. Measure absorbance by applying the above procedure
Note: Check reliability of the curve by running a standard every 3-4 samples.

A.1.2 Nitrate in plants (ETH Zurich)

Measurement of soil inorganic nitrogen concentration (\( N_0_3 \) and \( N H_4 \)) for CEC/- Packard project:

1. Extraction for \( N H_4 \) and \( N_0_3 \)

1.1 Equipment
- Whatman 42 filter paper
- Funnels and holder cups
- Mechanical shaker box
- Polyethylene scintillation vials with poly-lines caps
- 2M KCl

1.2 Procedure
1. Place 5 g wet-weight soil into individual specimen cups. Add 50mL 2M KCl solution to each cup and attach lid.
2. Put samples in box shaker and shake for one hour on low speed.
4. If not using immediately, cap and place in refrigerator until ready, up to 24 hrs.

2. Nitrate Analysis

2.1 Materials
- Vanadium (III) chloride
- 0.5 M HCl
- 100 µl pipette
- Sulfanilamide
- N-(l-naphthyl)ethylenediamine dihydrochloride
- Cuvettes

2.2 Preparation of reagents
1. Pour 200 mL 0.5 M HCl into a bottle
2. Weigh 0.5g vanadium (III) chloride into bottle
3. Shake gently until vanadium (III) chloride is dissolved. If there are still undissolved particles, filter through a syringe filter
4. Add 0.2g sulfanilamide and 0.01g N-(l-naphthyl)ethylenediamine dihydrochloride and dissolve

2.3 Preparation of Standards
1. Prepare standards from 1000 ppm NO$_3$ found in refrigerator
2. Mix following standard dilution protocol using 2M KCl instead of DI water

2.4 Analysis
- Sample volume: 100 µl
- Add the sample into semimicro cuvets
- Add 1000 uL of reagent to all cuvets
- Cap cuvette (or do the Bob mixing method - THIS IS PREFERRED)
- Invert cuvettes to mix
- Note the time
- After 6-8 hours (and up to 2 days), read absorbance at 540 nm against a KCl blank standard (100 µl 2M KCl + 1000 µl NO$_3$ reagent) to correct for background N, (This means one KCl cuvette in the back and one in the front and then auto-zeroing the machine).

Measure absorbance of samples and record

3. Ammonium analysis

3.1 Prepare reagents:
Reagent A:
In approximate 100mL water, dissolve:
- 0.05 g sodium nitroprusside (sodium nitroferricyanide)
- 13 g sodium salicylate
- 10 g sodium citrate
- 10 g sodium tartrate

Reagent B: Dissolve 6 g sodium hydroxide in 100 mL water and add 2 mL sodium hypochlorite (bleach)

Note: Reagents A and B may be stored for several months at 40°C

3.2 Prepare standards:
- Weigh 0.2965 g NH₄Cl and dissolve into 100 mL 2M KCl to make 1000 ppm NH₄ standard
- Dilute to 10 ppm, 5 ppm, 1 ppm, and 0.5 ppm from the 100 ppm working solution

3.3 Analysis
- For samples in 0-1 ppm N (low range): Put 800 µL sample into semimicro cuvets
- Add 250 µL Reagent A to all cuvets
- Add 250 µL Reagent B to all cuvets
- Cap cuvets (or Bob method)
- Invert cuvets to mix
- Note the time
- After 1 hour, read adsorbance at 650 nm against a KCl blank standard (the color is stable for 1-2 hours) to correct for background N (same method as NO₃)
- Measure absorbance of samples and record

Note: Before reading samples in spectrophotometer, tap each cuvette on table to release trapped bubbles which could affect absorbance reading.

A.2 Fish parameters

A.2.1 Kolmogorov-Smirnov-test

System 1, 1st measurement
One-sample Kolmogorov-Smirnov test
data: Weight
D = 0.21941, p-value = 0.0001196
alternative hypothesis: two-sided
One-sample Kolmogorov-Smirnov test
data: Length
D = 0.15804, p-value = 0.01288
alternative hypothesis: two-sided

System 2, 1th measurement
One-sample Kolmogorov-Smirnov test
A.2 Fish parameters

data: Weight
D = 0.12873, p-value = 0.07033
alternative hypothesis: two-sided
One-sample Kolmogorov-Smirnov test
data: Length
D = 0.13223, p-value = 0.05849
alternative hypothesis: two-sided

System 1, 4th measurement

One-sample Kolmogorov-Smirnov test
data: Weight
D = 0.12389, p-value = 0.08215
alternative hypothesis: two-sided
One-sample Kolmogorov-Smirnov test
data: Length
D = 0.14902, p-value = 0.01973
alternative hypothesis: two-sided

System 2, 4th measurement

One-sample Kolmogorov-Smirnov test
data: Weight
D = 0.11958, p-value = 0.1179
alternative hypothesis: two-sided
One-sample Kolmogorov-Smirnov test
data: Length
D = 0.080079, p-value = 0.5494
alternative hypothesis: two-sided

A.2.2 Levene test

1st measurement
modified robust Brown-Forsythe Levene-type test based on the absolute deviations from the median
data: Weight Test Statistic = 0.9976, p-value = 0.4914
modified robust Brown-Forsythe Levene-type test based on the absolute deviations from the median
data: Length Test Statistic = 0.73181, p-value = 0.7619

4th measurement
modified robust Brown-Forsythe Levene-type test based on the absolute deviations from the median
A Appendix

data: Weight Test Statistic = 1.1264, p-value = 0.3477
modified robust Brown-Forsythe Levene-type test based on the absolute deviations from the median
data: Length Test Statistic = 1.1812, p-value = 0.293

A.3 Plants

A.3.1 First harvests

ks.test(Biomass, pnorm, mean(Biomass), sd(Biomass))
One-sample Kolmogorov-Smirnov test
data: Biomass
D = 0.27585, p-value = 3.485e-05
alternative hypothesis: two-sided

A.3.2 Last harvests

> ks.test(Biomass, pnorm, mean(Biomass), sd(Biomass))
One-sample Kolmogorov-Smirnov test
data: Biomass D = 0.10205, p-value = 0.2107
alternative hypothesis: two-sided

Table A.1: Multi linear regression analysis of the last harvests

|                | Estimate | Std. Error | t value | Pr(>|t|) |
|----------------|----------|------------|---------|----------|
| Intercept      | 30.7781  | 57.7663    | 0.533   | 0.595    |
| ln(nitrate)    | -0.3467  | 1.4740     | -0.235  | 0.815    |
| Growth stress  | -6.9420  | 1.2308     | -5.640  | 1.5e-07  |
| pH             | -2.4358  | 6.5940     | -0.369  | 0.713    |
| Treatment      | -0.3283  | 0.4914     | -0.668  | 0.506    |

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1