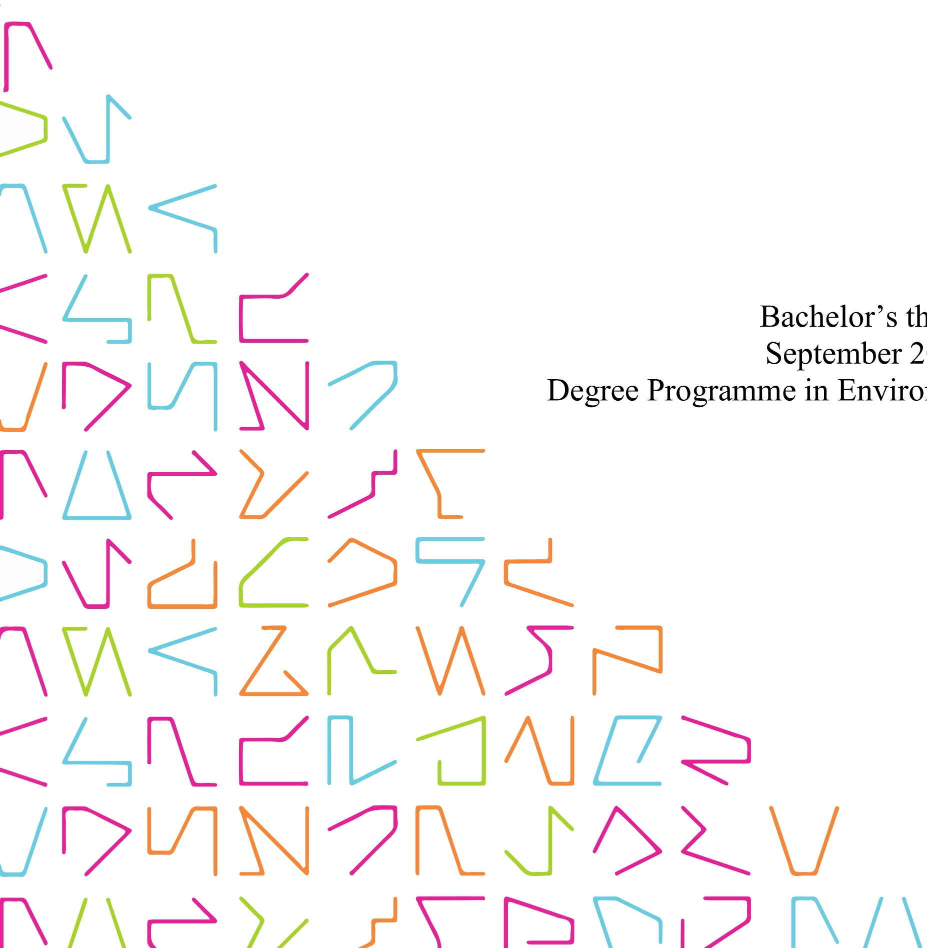
TAMPERE UNIVERSITY
OF APPLIED SCIENCES

EFFECTS OF AERATION ON LETTUCE *(Lactuca sativa)* GROWTH IN DEEP WATER CULTURE AQUAPONICS

Daniel Bodenmiller



Bachelor's thesis
September 2017
Degree Programme in Environmental Engineering

ABSTRACT

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Effects of Aeration on Lettuce *(Lactuca sativa)* Growth in Deep Water Culture Aquaponics

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The main objective of this thesis was to investigate the effects of increased aeration on lettuce (*Lactuca sativa*) growth in deep water culture aquaponics systems.

Oxygen levels play an important role in plant growth, especially in soilless systems a sufficient amount of oxygen needs to be supplied to the root zone to prevent oxygen depletion. Aeration, on the other hand, also represents a cost factor; therefore it is necessary to strike a balance between supplying enough oxygen to ensure good growth and avoiding energy wastage by supplying too much. Research on aeration of growbeds in aquaponics systems is very limited and the results of this study could help growers maximize outputs and resource efficiency.

The experiment was conducted in the TAMK greenhouse where a deep water culture aquaponics setup was installed. In the test setup lettuce (*Lactuca sativa*) was grown in 3 consecutive trials for a period of 6 weeks each. For the experiment six separate growbeds were available. Three were fitted with air supply systems pumping air into the beds at rates of 275 L/h, 550 L/h and 825 L/h while the other three beds served as control without additional aeration. Dissolved oxygen as well as other important water quality and environmental parameters were monitored throughout the experiment. The lettuce yield and several growth indicators were monitored biweekly and compared for different treatments.

All treatments showed dissolved oxygen levels above 5 mg/L, which should rule out oxygen depletion affecting the results. The average yield at harvest was 29% lower in the aerated beds compared to the controls but only 12% lower after drying the samples. The lower yield could be partly attributed to the higher pH readings that were accompanied by the added aeration.

The results show that heavy aeration can cause a pH shift in the system and even be a limiting factor to plant growth. Therefore it is highly recommendable to monitor and manage dissolved oxygen levels in deep water culture aquaponics.

Key words: aquaponics, lettuce, dissolved oxygen, aeration, growth

CONTENTS

1 INTRODUCTION

Growing plants in water culture requires a sufficient amount of oxygen to be present in the root zone in order to prevent oxygen depletion and poor plant growth. Especially in deep water culture (DWC), where plants sit on top of a floating raft, with their roots completely submerged in nutrient solution, auxiliary aeration of the nutrient solution is a recommended means of ensuring sufficient oxygen levels. With aquaponics as a relatively new technology though, little scientific evidence has been presented this far on how dissolved oxygen levels affect plant growth in this particular system. Also, in practice monitoring and managing DO levels is often overlooked, partly due to the high acquisition cost of measuring equipment and added labour.

To study different aeration treatments, an experiment is conducted with a small-scale aquaponics system in greenhouse conditions. The aim of the thesis is to study the effect of increased aeration on lettuce growth and key water quality parameters. The results could aid maximize outputs and energy efficiency.

1.1 Introduction to aquaponics

Aquaponics is a major area of interest in the field of integrated and sustainable cultivation practices. It has even been acknowledged by the European Union Parliament (van Woensel, et al., 2015) as one of the “ten technologies which could change our lives”. Aquaponics is able to reduce some of the negative impacts of food production on the environment by eliminating the need for additional fertilizers, herbicides and pesticides as well as reducing the need for water by 95% over traditional practices. Recovering nutrients from fish waste in a closed cycle as well as the ability to cultivate very densely makes aquaponics a great tool for more efficient food production. Furthermore, functioning independent of fertile soil, regional food security can be empowered in areas where arable land is lacking. (Nelson & Pade, 2008)

Aquaponics is a recirculating food production system that combines two methods: Aquaculture and Hydroponics; Aquaculture being the production of fish and Hydroponics being the use of a nutrient solution to grow terrestrial plants in a soilless environment. These two food production techniques working in conjunction creates a system that works relatively symbiotically with little need for extra inputs such as fertilizers, pesticides and herbicides. The three main parts to the system are fish, bacteria and terrestrial plants which each contribute to a closed loop system that is mutually beneficial to all three factors. The fish respire and excrete into the water, providing the system with a source of nutrients. Bacteria then convert the fish waste into usable nutrients for the plants and the plants uptake those nutrients enabling clean water to return to the fish tank.

Plants, fish and bacteria all have different requirements for optimum performance. In order for an aquaponics system to work effectively a number of parameters have to be monitored and balanced within acceptable limits. The most important parameters to monitor will shortly be described in the following section.

1.2 Important parameters

Given the intricacy of the thesis topic, the author assumes the reader has a basic understanding of how aquaponics systems work. Aquaponics systems only work efficiently in a narrow range of environmental conditions, which have to be carefully balanced. In the following section only the most important parameters and their interactions are summarised and explained. For more general information on aquaponics I would like to refer the reader to one of the most complete documents to date by Somerville et al. (2014), which can be found in the list of references.

1.2.1 Dissolved oxygen

Oxygen is essential to most of the processes occurring in aquaponics: fish need it for respiration, nitrifying bacteria need it during nitrogen conversion and the plants´ rootsystem need oxygen to respire and to avoid root-rot. (Somerville, et al., 2014)

The solubility of a gas, including oxygen, in water is dependent on temperature. The solubility of oxygen in water decreases as temperature increases. In practice this means that that warm water holds less dissolved oxygen and has less capacity to store oxygen than cold water. Air pressure is another factor to take into account when considering dissolved oxygen. According to Henry´s law the solubility of a gas in liquid is directly related to the pressure of the gas above the liquid. In this experiment though, oxygen dissolved from the atmosphere only has a minor effect on DO levels compared to the aeration system. (Timberlake & Timberlake, 2011)

Other factors influencing DO levels in aquaponics include fish stocking density, algae build up and decomposition of solids. Appropriate DO levels for aquaponics will be discussed in the next chapter.

1.2.2 pH

pH is a measure of acidity/alkalinity of a substance at a given temperature. The pH scale ranges from 0 (very acidic) to 14 (very alkaline). The pH value is determined by hydrogen ion activity, or in other words, the concentration of available hydrogen ions. It is important to highlight the logarithmic nature of the scale, as for example a solution of pH 5 has a ten times higher hydrogen ion concentration than a solution of pH 6. (Prichard & Lawn, 2003)

In aquaponics most processes such as nitrification and nutrient availability are pH dependant. Most plants grown in hydroponics perform best at a lower pH of 5,8 to 6,2, whereas nitrifying bacteria and fish often prefer higher pH ranging from about 7 to 9 (Rakocy, et al., 2006). The ideal pH range is a compromise, which allows all organisms to thrive. The optimum range lies, according to Somerville et al. (2014), between pH 6-7. Values below 5,5 or higher than 7,5 require buffering, as outside this range bacteria cannot function efficiently anymore and plants cannot access certain nutrients.

1.2.3 Electrical conductivity

Electrical conductivity (EC) is a good indication for plant available nutrients in aquaponics water. Plants take up nutrients mostly in inorganic form, in aquatic solutions these inorganic nutrients exist in a charged ionic form. These charged particles can be detected by an EC-meter by passing a current through the water column and measuring the conductance. The more charged ions in the solution the higher the EC reading and the higher the amount of plant available nutrients. The EC has limited significance because the amount of charged particles is measured only, no conclusions can be drawn about the presence and quantity of individual nutrients. (Lennard, 2012)

1.2.4 Nitrogen

Even though a large number of macro- and micronutrients are necessary for healthy plant growth, nitrogen compounds are often used in aquaponics as main indicator for nutrient load. The main source of nutrients in this closed system is fish excreta, which consists mostly of carbon dioxide and nitrogen compounds like ammonia. As it would be too cost and labour intensive to monitor concentrations for every single needed nutrient, nitrogen is often used as sole indicator for nutrient load. (Klinger-Bowen, et al., 2011)

Fish waste the water mostly as ammonia (NH_3), which is then converted by nitrifying bacteria into nitrite (NO_2^-) and then afterwards into nitrate (NO_3^-). Efficient conversion of ammonia into nitrate is of high importance because the main source of nutrients for plants in the system is also toxic to fish. Ammonia and nitrite are about 100 times more toxic to fish than nitrate, which can be filtered and taken up by the plants. Though being less toxic, it is recommended to keep nitrate levels below 150 mg/L, higher levels might require a water change. (Somerville, et al., 2014)

2 LITERATURE REVIEW

The following pages will establish a brief overview on the scientific research published relevant to this thesis with special focus on aeration in water culture.

2.1 Aeration studies in Hydroponics

The relation between plant growth and oxygen levels in water culture have been studied intensively for more than a century. Already in 1860 first experiments showed a strong correlation of increased plant growth and aeration in water culture. Aeration of the nutrient solution resulted, for some species, in improved plant growth. It was also shown that a lack of aeration can be a limiting factor for plant growth. (von Sachs, 1860) according to (Durell, 1941)

Stiles and Jörgensen (1917) investigated the effect of aeration on different plants cultivated in nutrient solution. Their findings showed significant improvements in root and shoot growth for Barley and Balsam in aerated solutions over their non-aerated counterparts. Their experiments also showed that the effect of aeration varies with environmental conditions and species; buckwheat growth for example remained unaffected by additional aeration.

A recent greenhouse study conducted by Roosta et al. (2016) compared eggplant growth in floating hydroponic cultures with different oxygen concentrations. The study found growth to increase with rising oxygen levels and reach optimum growth at their highest test concentration of 4 mg/L. The study does not assess however, whether even better results could be established with higher concentrations. Furthermore, higher oxygen levels seemed to alleviate signs of ammonium toxicity among the tested plants. The authors suggested that based on their findings oxygen levels and distribution in floating hydroponics systems should be managed and must not fall short of 4 mg/L.

To summarize these findings it can be said that oxygen depletion affects plant growth negatively and dissolved oxygen levels water culture should be kept no lower than 4 mg/L (Roosta, et al., 2016). While the effect of aeration on floating hydroponics cultures is already well established there has been little scientific evidence on whether additional aeration of plant beds in aquaponics has the same beneficial effect.

2.2 Aeration studies in Aquaponics

Modern-day aquaponics and first scientific research emerged in the 1970´s in an attempt to lower toxic nutrient loads in recirculating aquaculture systems. Starting from the early 1980´s, under the lead of Dr. James Rakocy, the University of the Virgin Islands (UVI) made the probably most significant contribution in research and development of DWC aquaponics system. They developed the first commercially viable DWC aquaponics system and many of their findings like plant-to-fish ratios, stocking ratios and viability studies still form the foundations for contemporary aquaponics system design. (Nelson & Pade, 2008)

Junge et al. (2017) clearly show in their paper that the amount of published aquaponics research is very limited; however there is a steady increase in published papers since 2010. Even though aquaponics systems are abundant all over the world the amount of published research is insufficient and many ecological, economic and social concepts are in need of further research and development (Junge, et al., 2017). The high popularity among private non-commercial systems is further contributing to the academic void; spreading of non-scientific information by self-titled experts has become prevalent phenomenon.

Dissolved oxygen is often stated as one of the most important parameters to control in aquaponics. Nevertheless, most publications do not discuss how to manage DO levels and proper aeration or only do so in very vague terms.

Lennard (2012) for example recommends aiming for oxygenation levels as high as possible, which in my conclusion would imply that there is no negative effect to expect from excessive air supply. Nelson and Pade (2008) claim optimal DO levels around 80% saturation or 6-7mg/L.

A report by Somerville et al. (2014) states the optimum DO levels for each organism, meaning plants, fish and bacteria, in an aquaponics system to be 5–8mg/L. Furthermore, instructions are presented for practical implementation; by installing air diffusors in the hydroponics bed and regulate the air flow to 240 Litres per hour for every 2-4 m^2 of raft area suitable DO levels will be created for the plants.

Another area of disagreement among growers is the necessity to aerate different system components. While many backyard systems only employ aeration in the fish tank and biofilter Lennard (2012) suggests to also aerate hydroponics beds. The UVI raft system and the raft system designs proposed by Nelson and Pade (2008) feature aeration in the fish tanks, the biofilter, the hydroponic tanks and an additional degassing tank. The degassing tank is a heavily aerated tank which is placed between the biofilter and the hydroponics tank. Its purpose is to vent out potentially harmful gases like carbon dioxide and nitrogen into the atmosphere (Rakocy, et al., 2011).

There seems to be a consent that the optimum DO level is near the saturation point and placing air stones directly into the DWC channels is highly encouraged. The recommendations for optimum DO levels though are rather vague and it remains unclear how these values where determined. I was unable to attain any scientific studies or experimental data concerning the optimum DO level in aquaponics systems, so it might be assumed that these values originate from hydroponics studies. Hydroponics and aquaponics however differ in many important aspects, such as the absence of organisms like fish and nitrifying bacteria as well as processes like respiration and nutrient conversion. Therefore findings from hydroponics studies are not necessarily always applicable to aquaponics.

2.3 Problem overview and aim of study

Constant monitoring and management of DO levels in aquaponics is often not realized due to the relatively high price of measuring equipment. Particularly in commercial scale operations optimal air flow should be managed and excess aeration kept to a minimum due to the higher energy demand and increased cost. Closing the research gap on dissolved oxygen levels could help growers reach higher resource efficiency and maximize outputs.

The aim of this study was:

1. to study the effect of increased aeration on plant and root growth of lettuce in DWC aquaponics
2. to establish an optimum dissolved oxygen concentration for lettuce cultured in DWC aquaponics.
3. to study the effect of increased aeration on key water quality parameters.

Hypothesis:

"Increased aeration of the hydroponics bed will lead to increased plant growth"

3 METHOD

3.1 Aquaponics system overview

The experiment was conducted on the first floor balcony of the TAMK greenhouse. The greenhouse´s glass facade is facing the south-west direction. The TAMK main campus and greenhouse is located in Tampere, Finland (latitude 61°30’12” N, longitude 23°48’30” E, altitude 112 m).

PICTURE 1. This picture shows the greenhouse at the Tampere University of Applied Sciences (TAMK). The aquaponics system was installed on the second floor balcony. (Daniel Bodenmiller 2015)

The aquaponics system was designed and constructed by Benjamin MacNab, Olli Soppela and Daniel Bodenmiller in early 2015 with the intention to be used as a pilot system for research purposes. The build was sponsored by the German company elobau GmbH as well as a small grant from Maa ja Vesitekniikan Tuki (MVTT); a suitable space was provided by TAMK. The system was operational from May 2015 onward and had 10 months to mature before the start of the experiment.

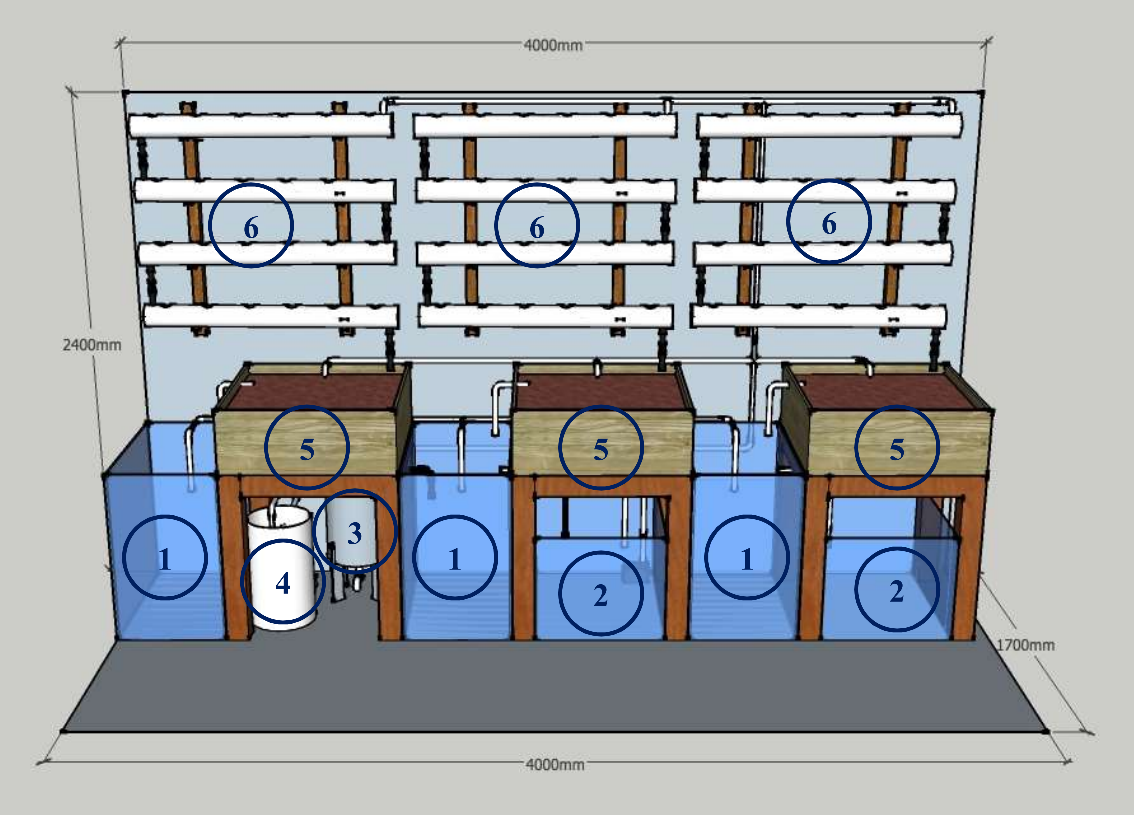


FIGURE 1. Schematic drawing of the aquaponics system used in the experiment. The components are labelled as follows: 1. Fish tanks, 2. Sump tanks, 3. Swirl filter, 4. Biofilter, 5. Growbeds, 6. NFT-tubes. (Benjamin MacNab 2015, modified)

The water flows, in a closed loop, from the fish tanks through the filtration unit to the sump tanks fed only by gravity. In the right sump tank a pump pumps the water up into the growbeds and Nutrient Film Technique (NFT) tubes before returning into the fish tanks. The NFT-tubes were filled with a constantly flowing, thin film of nutrient rich water, which supplied the roots with nutrients and water while leaving the roots enough space to respire. The NFT-tubes were disconnected from the system for the duration of the experiment as they were not relevant to the experiment and could possibly influence the results.

PICTURE 2. The aquaponics system during an earlier trial. The shelf in front houses the seedling trays and a smaller separate aquaponics unit. (Daniel Bodenmiller 2015)

Each of the three fishtanks had a total volume of 250L and was filled with 200L of water. The fishtanks were connected by bridge syphons. The water outlet to the filtration tanks is located in the middle tank.

The filtration stage was made up from two stages, first a mechanical filter followed by a biofilter. Due to space constraints the filter units had to be built using 30L cylindrical containers. The mechanical filter stage was a commonly used swirl filter design fitted with a bottom tap to flush out settled sludge. The biofilter was aerated and densely filled with foam cubes to create favourable conditions for bacteria growth. Apart from increased biological activity the filter also trapped a lot of smaller particles which did not settle in the swirl filter. To ensure proper function the filters were cleaned out at least once a week during the trial.

3.2 Experimental setup

There are several different practices available for growing plants in aquaponics. The three most commonly found are media-based beds, Nutrient Film Technique (NFT) tubes and deep water culture beds (DWC). DWC was chosen because it is most reliant upon auxiliary oxygen supply for the plants among these practices because the roots are almost completely submerged in water. Lettuce as a crop was chosen for this experiment because it is a popular vegetable to grow aquaponically, has a high demand and the environmental conditions in the TAMK greenhouse seemed to be appropriate.

Three trials were conducted between February and April 2016. In the test setup lettuce (*Lactuca sativa*) was grown in 3 consecutive trials for a period of 6 weeks each. For the experiment six separate growbeds were available. The pre-existing growbeds (see figure 1) were split into two, creating a total amount of six growbeds with separate water inlets and outlets. The dimensions of each growbed were 80x40 cm with a water level of 25 cm depth. Three growbeds were fitted with air supply systems pumping air into the beds at rates of 275 L/h, 550 L/h and 825 L/h while the other three beds served as control without additional aeration. The aerated beds were supplied with air by three sera 550 R air pumps.

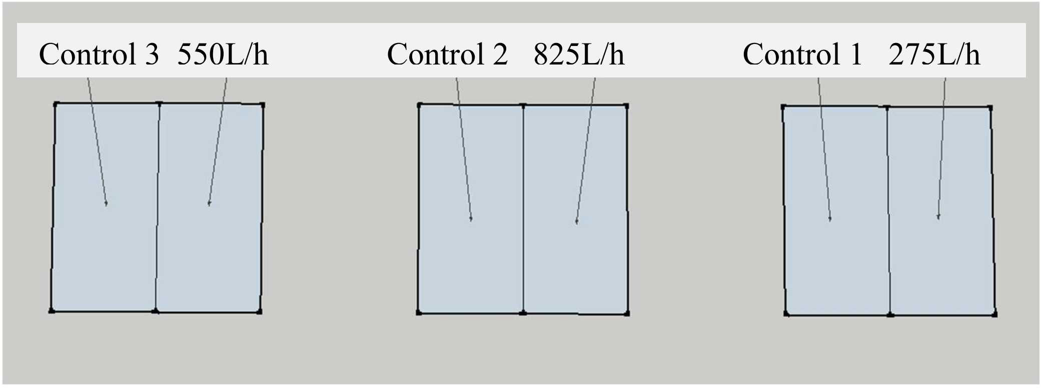


FIGURE 2. Layout of the aerated beds and their respective control beds. (Benjamin MacNab 2016, modified)

Given the small amount of daylight hours during winter days in Finland, it was necessary to install artificial lighting. Three generic 40W LED growlights with blue and red LEDs were installed 0,5m above the growbeds. One growlight was used to evenly illuminate two rafts at a time. The growlights were connected to a timer, which would turn the lights on for 18 hours during the day and off for six hours during the night from 10pm to 4am.

Dissolved oxygen as well as other important water quality and environmental parameters were monitored daily throughout the experiment. The lettuce yield and several growth indicators were monitored biweekly and compared for different treatments. More detailed information on monitoring can be found in section 3.4.

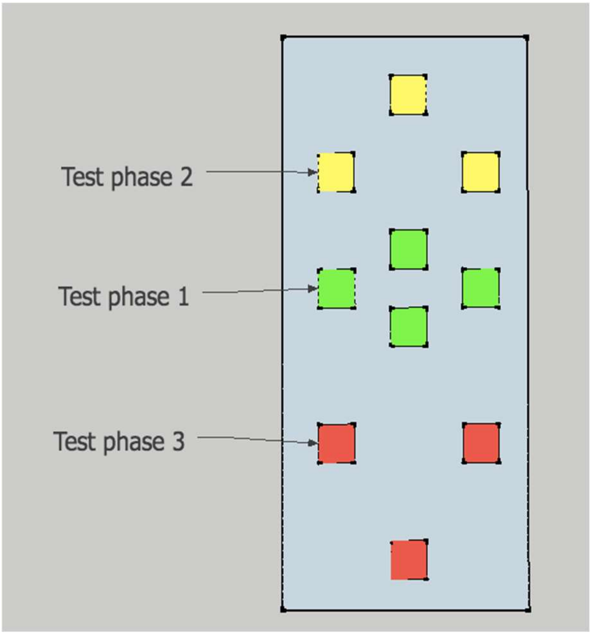
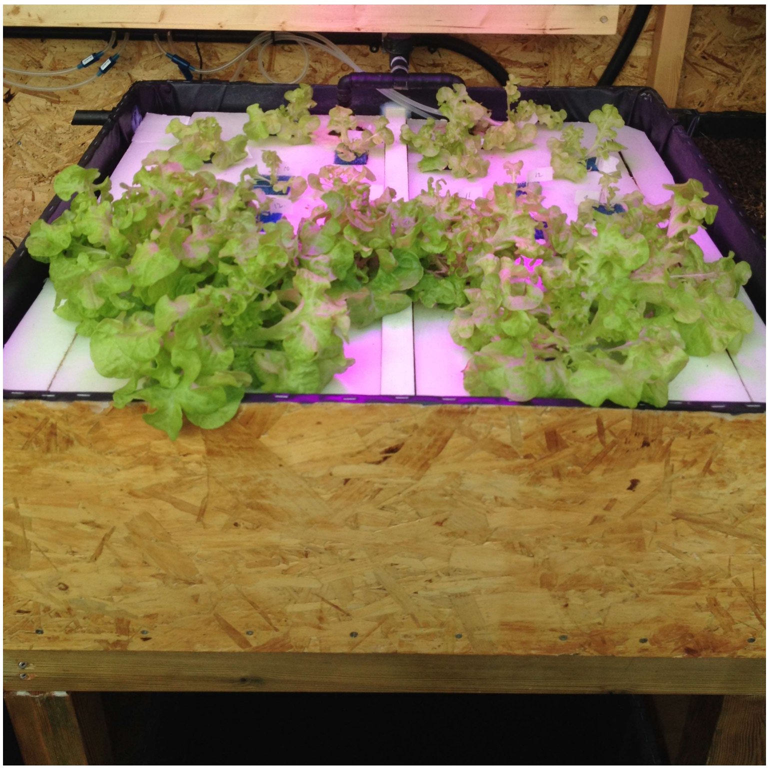


FIGURE 3. Schematic drawing of the raft layout. (Benjamin MacNab 2016)



PICTURE 3. Picture of the plant filled rafts during the experiment. (Daniel Bodenmiller 2016)

Each of the six DWC beds contain one floating raft and have a total of 10 plant spaces as illustrated in figure 3. The trials were set out to overlap in order to cut the experiment period from three trials lasting six weeks each to ten weeks. A new trial was started every two weeks while the earlier trials also remained in the system. Every two weeks the plants were moved to a new section with increased plant spacing to meet the changing needs of the plants during their growth phase.

The seedlings were grown for two weeks under artificial light in a gravel bed next to the experimental setup before they were inserted into the system. The seedlings were supplied with water from the system in order to acclimate to the environmental conditions of the experimental setup. The seeds are organic and were sourced from the German supplier Bingenheimer Saatgut. The species was listed as oak leaf lettuce *(Lactuca sativa var. crispa)* type Piro.

Initially four seedlings were placed into the ‘Test phase 1’ position for a period of two weeks. After two weeks, the three healthiest looking plants were selected and moved into “Test phase 2”. Simultaneously, four new seedlings will be inserted into “test phase

1”. After another two weeks the same process will occur again with the plants from phase one going to two and phase two going to three.

3.3 Maintenance

3.3.1 Fish

At the time of the experiment the fish tanks were stocked with three different species: African catfish *(Clarias gariepinus)*, Common roach *(Rutilus rutilus)* and European perch *(Perca fluviatilis)*. The total number of African catfish *(Clarias gariepinus)* was 25, four Common roach *(Rutilus rutilus)* and seven European perch *(Perca fluviatilis)*.

The fish were weighed on the 2nd of February 2016 and the feeding ratio of 1% body weight per day was established. Accordingly, the fish were fed 28,6g/weekday for the first 6 weeks. The feeding rate was updated on the 15th of March 2016 according to the fish´s weight gain to 38,5g/weekday. Thereafter, taking the limited filtration capacity into consideration, the feeding rate was not increased anymore. The fish could only be fed during weekdays because the laboratory was not accessible during the weekend. The weekend feed input got compensated for by evenly distributing the weekend share over the weekdays.

The fish feed ratio is rather low compared to proposed guidance values of 60-100g/m^2 of plant area (Rakocy, et al., 2011) or 56g/m^2 with 25-30 lettuce plants/m^2 (Al-Hafedh, et al., 2008). Observations from earlier trials however showed good plant growth with even lower feed ratios, which lead to the conclusion that the feed input should be sufficient for the experiment.

3.3.2 Water and supplements

More water was added as required about 1-2 times a week, no exact volumes were recorded. Tap water was used as water source and no pre-treatment was deployed. The tap water during the trials was between pH 8,3 and pH 8,4 (Tampereen Vesi, 2016). Based on experience from earlier trials and signs of deficiency Epsom salt ($MgSO_4$) and chelated iron were supplemented. The exact dosage was not recorded but about one teaspoon of chelated iron and one tablespoon of Epsom salt were added every two weeks.

3.3.3 Filters

The filters were cleaned out once a week on no particular day. The swirl filter was emptied completely from the bottom drain and rinsed with water. The biofilter was cleaned by removing the media and rinsing it in a separate sink. The filter of the water pump was cleaned out as required; mostly after a drop in water pressure was observed.

3.4 Data collection

3.4.1 Water quality parameters

The water quality parameters measurements were taken from each of the growbeds as well as the fish tanks and biofilter. In the beginning of the experiment DO, pH and EC measurements were all conducted using the YSI Professional Plus handheld meter. The YSI Professional Plus meter failed unexpectedly on the 26th of February and was replaced by the YSI ProODO meter for DO measurement for the remaining duration of the experiment. The pH and EC measurements for the remaining time were conducted with Mettler Toledo FiveEasy meters. Temperature loggers were placed into one of the growbeds, one of the fish tanks, the biofilter and on the wall level with the growbeds. The following table summarises the monitoring measures during the experiment.

TABLE 1. Monitoring parameters, sampling frequency and equipment used during the experiment.

Parameter	**Unit**	**Sampling frequency**	**Measuring device**
Dissolved oxygen	%; mg/L	daily Monday-Friday	YSI Professional Plus; YSI ProODO
pH		daily Monday-Friday	YSI professional plus; Mettler Toledo FiveEasy pH
Electrical Conductivity	µs/cm	daily Monday-Friday	YSI professional plus; Mettler Toledo FiveEasy Conductivity
Temperature	°C	every 30 minutes	USB temperature logger
Nitrate	mg/L	weekly	HACH

It was planned to monitor the nitrate levels in the growbeds, therefore samples were taken weekly in triplicates and frozen to be analysed at a later point. Unfortunately, the laboratory´s freezer broke shortly after the experiment ended, melting and rendering the samples unusable for further analysis.

3.4.2 Vegetative growth parameters

The lettuce has a retention time of 6 weeks in the system. Every 2 weeks the plants are moved in order to keep the plant spacing adequate. While moving the plants leaf count, width of the widest leaf, shoot length, root length and weight are recorded. After 6 weeks the plants are harvested and additionally to the mentioned parameters wet and dry weight of the shoots and roots are documented. The lettuce is dried in an oven at 105 °C for 8 hours before it is ready to be weighed. For some of the bigger lettuces from the third trial 8 hours was insufficient to evaporate all the moisture therefore they were left in the oven overnight. Fresh and dry weight were measured and recorded using a Precisa XT220A precision scale.

3.4.3 Calibration

Calibrations were done on a regular basis. Frequency and type of calibration can be found in table 2.

TABLE 2. Parameters, frequency and type of calibrations performed during the experiment.

Parameter	**Calibration**	**Frequency**
dissolved oxygen	water-saturated air calibration	daily
pH	2-point calibration at pH4 and pH7	weekly
electric conductivity	using 1413 µS/cm standard calibration solution	monthly
temperature	no calibration	-

4 RESULTS

This section is reserved for the presentation of the most significant results. The scope of this work does not allow for all the acquired results to be presented in this section. Further data can be found in appendix 1. In most of the graphs there are two gaps due to missing data. The first gap from the 26th of February to the 6th of March was due to failure of the used measurement device YSI Professional Plus. The second gap from the 25th of March to the 31st of March was due to the laboratory being closed during Easter Holidays.

4.1 DO levels

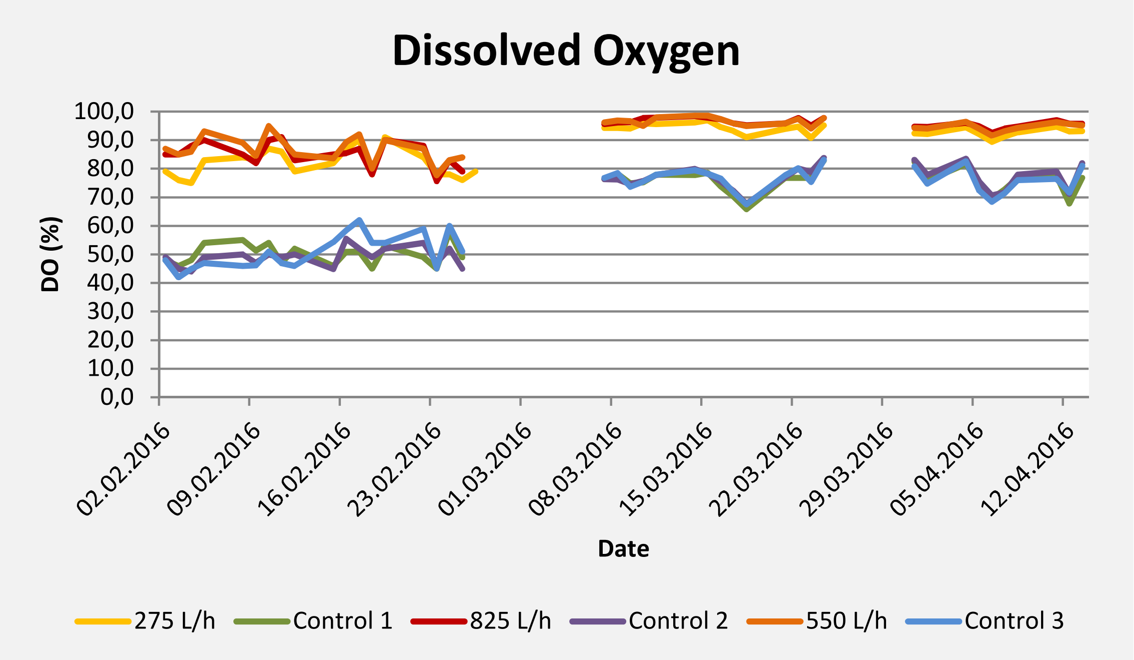


FIGURE 4. Dissolved oxygen levels in percent saturation for each different treatment.

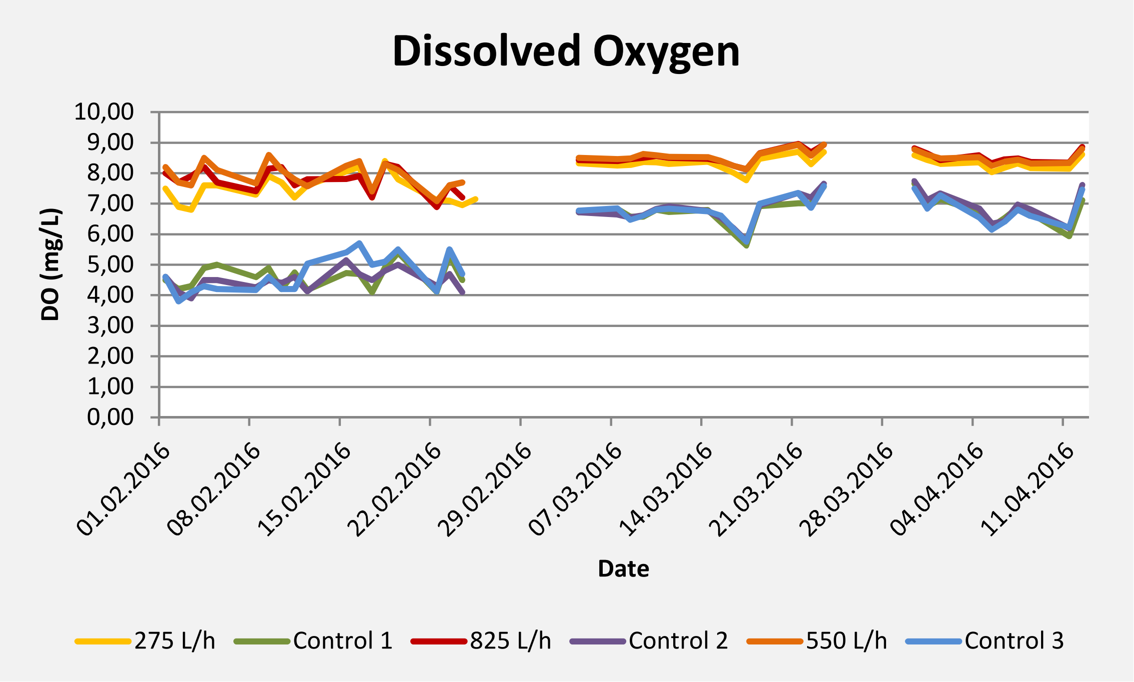


FIGURE 5. Dissolved oxygen levels in mg/L for different treatments.

Both figures, 4 and 5, show that all of the aerated beds operate very close to saturated oxygen levels while the control beds were around 70-80% saturation. These high readings suggest that the heavy aeration of the aerated beds did also affect the control beds, a phenomenon that is mainly owed to the small size of the system and the closed water loop. All beds retained oxygen levels above the recommended minimum of 4 mg/L (Roosta, et al., 2016), which means that oxygen depletion can be ruled out as a limiting growth factor.

For the period before the 26th of February the YSI Professional Plus meter was used, equipped with a Pro series Polarographic sensor with a 1.25 mil PE membrane. The meter had to be exchanged because of failure and from the 7th of March on a YSI ProODO meter with an optical sensor was used for measurements. The notably lower readings for the control beds from the YSI Professional Plus stand out when comparing the readings from the two meters. The artificially low readings from the control beds before the 26th of February can be disregarded because of their evolvement from a shortcoming in the measurement method, which will be discussed further in the discussion section.

4.2 pH levels

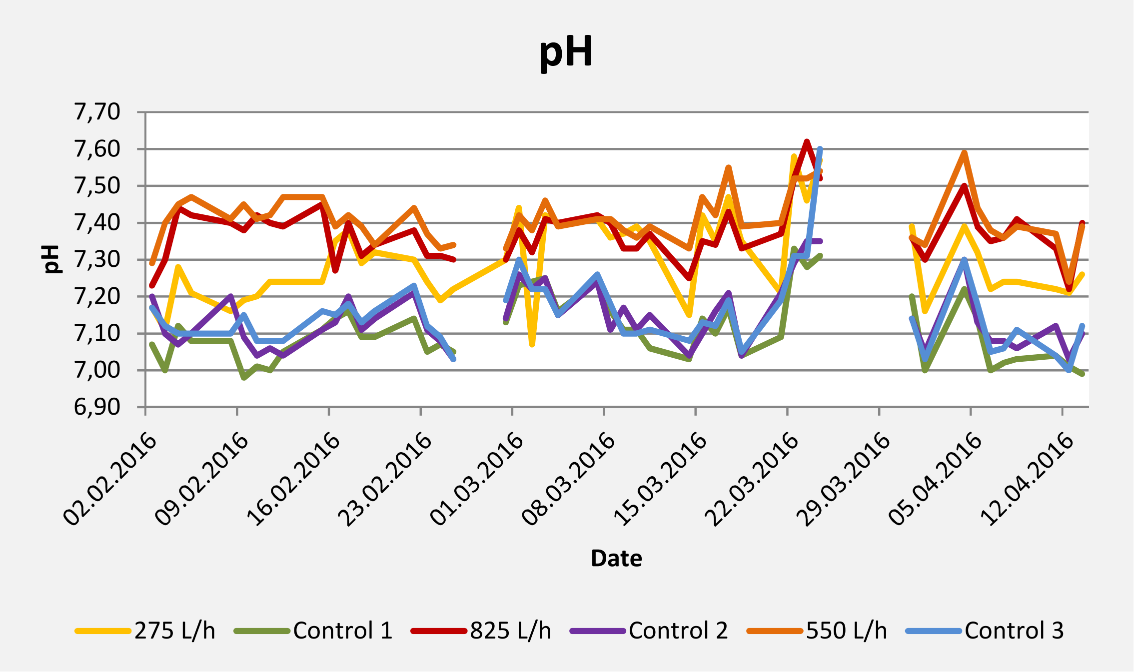


FIGURE 6. pH levels in the different growbeds during the experiment.

The graph shows a clear divide between the aerated and the control beds. The aerated beds had a higher pH throughout the testing phase. Considering the dissolved oxygen results, this could suggest that pH and aeration are linked; the increased pH could be caused by increased aeration. The 275 L/h treatment showed a slightly lower pH than the 550 L/h and 825 L/h ones, which were very close. Interestingly, not the bed with the highest aeration though but the 550 L/h treatment resulted in the highest pH levels.

4.3 EC levels

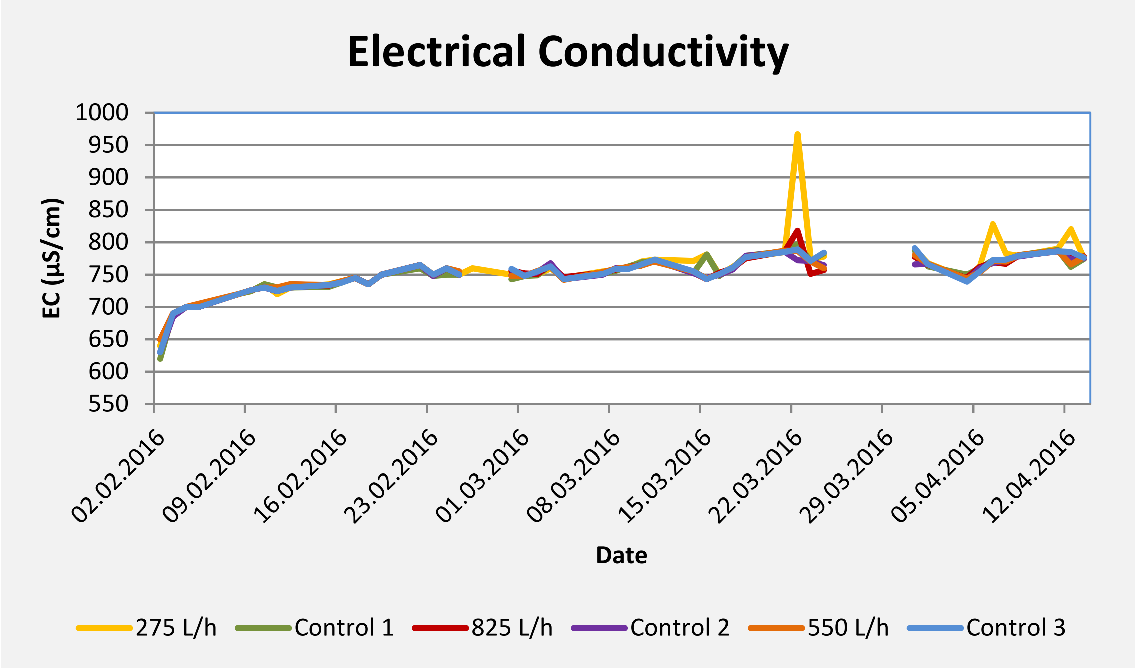


FIGURE 7. Electrical conductivity in the different growbeds during the experiment.

Before the beginning of the experiment also the NFT tubes on the wall were used to grow plants. The higher nutrient uptake due to more plants is most likely the reason for the low EC readings at the very beginning of the experiment. The readings, except for a couple negligible outliers, were quite uniform across the board and stabilized by the end of February between 750-800 µs/cm.

4.4 Temperature

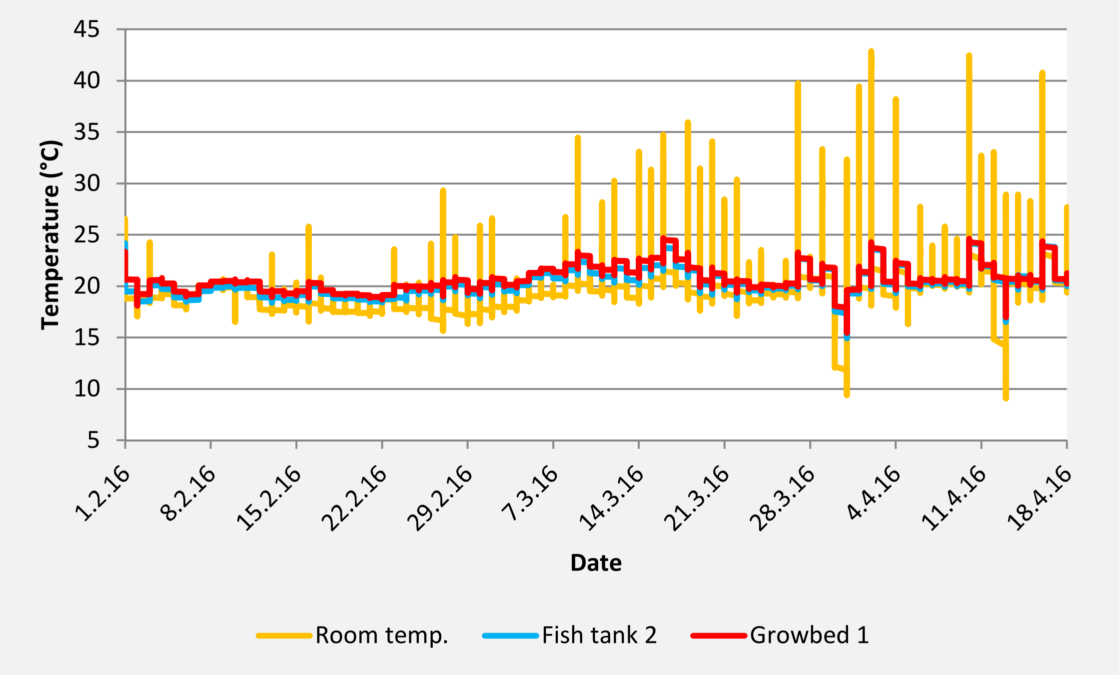


FIGURE 8. Temperature readings throughout the test period. Monitored were room temperature, fish tank number two and one growbed (275 L/h treatment).

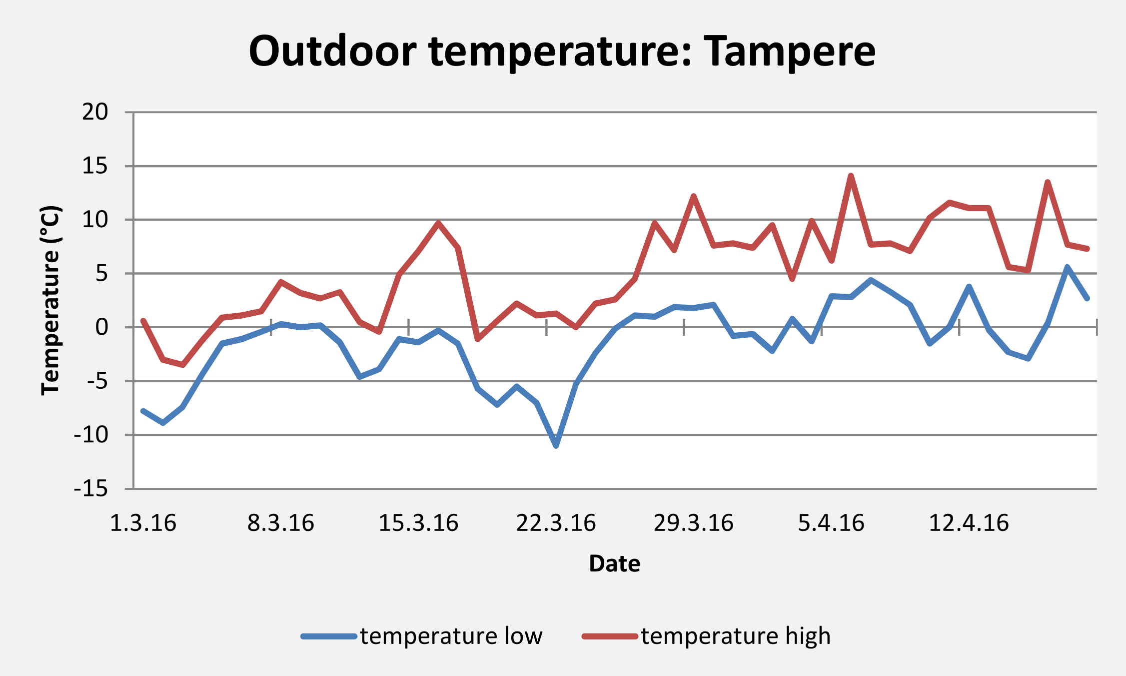


FIGURE 9. Minimum and maximum recorded temperatures in Tampere during the testing period**.** Data from (Suomen Sääpalvelu , 2017). Note that temperature readings for February were not available.

From figure 8 it is apparent that the water temperature remained mostly within an acceptable range, for both plants and fish, between 20-25 °C. Approaching 25 °C, the thermostat of the water heater in the sump tank was adjusted from its maximum threshold of 35 °C to 25 °C on the 17th of March. As a consequence a slight decrease in water temperature can be observed. The indoor room temperature on the balcony shows significant temperature variations of over 20 °C, over the cause of 24 hours. In addition, temperature peaks close to 45 °C with relatively moderate corresponding outdoor temperatures of less than 15 °C indicate that the greenhouse is less suitable to host trials under controlled conditions than expected. In order to create a more tolerable climate for the lettuce during warmer days the windows were kept open. The windows were closed during the weekends and outside the opening hours of the laboratory. Figure 8 indicates however, that the windows were accidentally left open twice during the night as the room temperature fell under 10 °C.

4.5 Vegetative growth

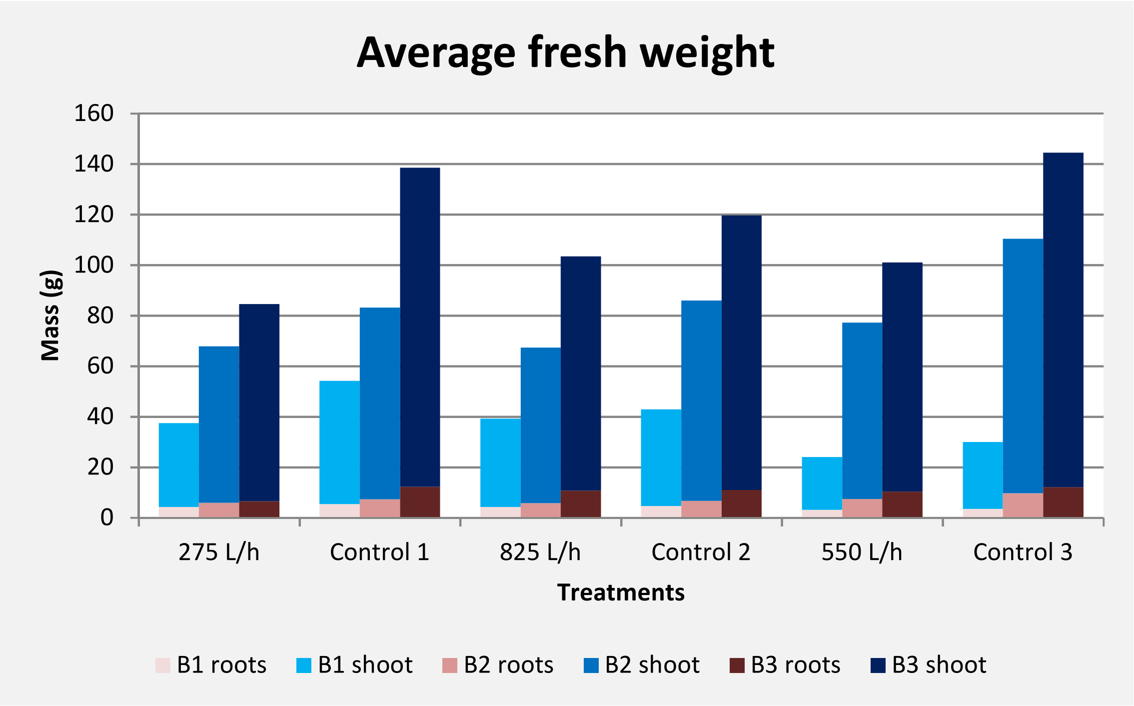


FIGURE 10. Average lettuce fresh weight by batch and treatment.

A significant difference in growth was found between trials. The yield increased significantly from batch to batch. This can be explained by varying environmental conditions, especially longer day hours and higher temperature towards the later trials.

Also, conductivity was low during the first trial which could indicate lower nutrient availability.

The control beds showed an overall higher yield than their aerated counterparts. The average fresh mass at harvest was 29% lower in the aerated beds compared to the controls. The average plant mass in the control beds was 89,9 g. The aerated beds showed lower average plant masses of 63,3g in the 275 L/h treatment, 67,4 g in the 550 L/h treatment and 70,0 g in the 825 L/h treatment.

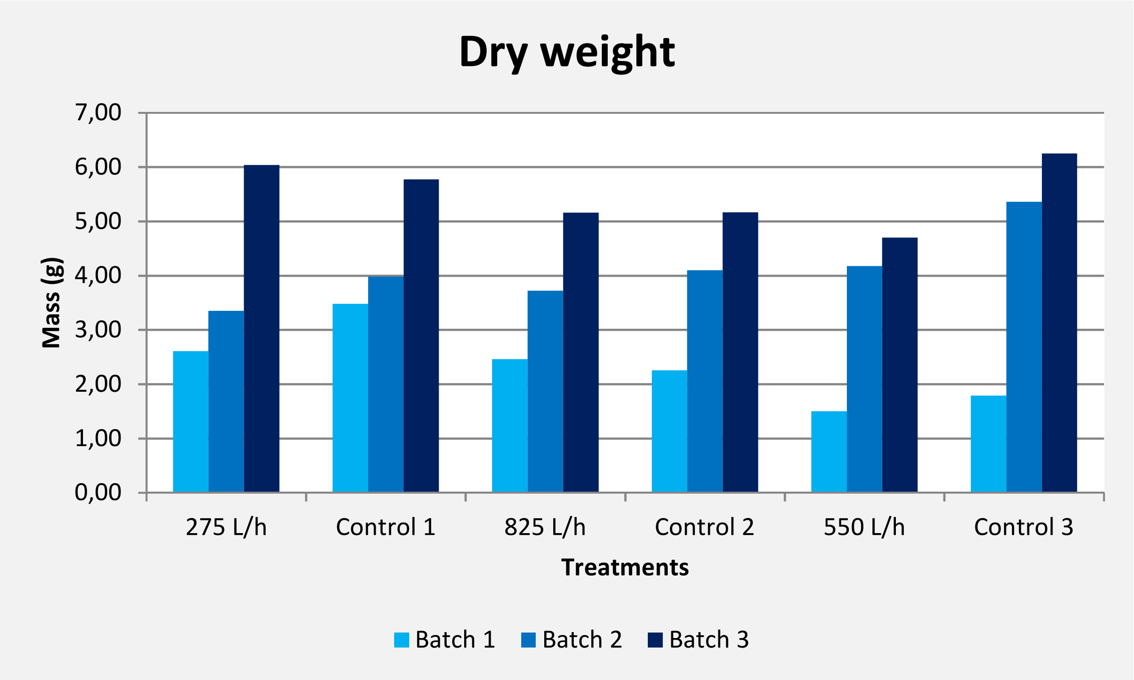


FIGURE 11. Average dry mass per plant by batch and treatment.

Already by visually comparing figure 10 and 11 it becomes apparent that there is a notable difference between the fresh and dry mass of the lettuce. The lettuce from the control beds averaged only 12% more weight over their aerated counterparts. This is significantly less than the 29% difference measured for fresh lettuce.

Figure 11 shows a steady mass decline in batch 1 and 3 towards the right hand side. The same can be seen when looking at batch 1 in figure 10. Interestingly the beds in the graph are arranged by their position in the system; getting fed from the same water line, the beds on the left are first in line of the water supply from the fish tank. The beds first in line of the water supply might receive nutrient solution of different composition with more settleable solids. This could be due to particles with higher density settling in the beds first in line of the water supply. Visual observations support this assumption as the first two beds (275L/h and Control 1) increased turbidity.

4.6 Visual observations

Visual observations showed higher occurrence of tip burn in plants grown in beds with added aeration. A total amount of 5 plants was affected by significant tip burn, whereas a total of 19 plants were affected in the aerated beds. This means that plants in aerated beds were almost 4 times more likely to be affected by tip burn.

PICTURE 4. An example of a lettuce plant from the third batch affected by tip burn. (Daniel Bodenmiller 2016)

Tip burn can occur for a number of reasons, among others calcium deficiency, poor plant transpiration, salt accumulation and low relative humidity (Mattson, 2015). The exact cause for increased tip burn in the aerated beds is unclear and would have to be examined further.

In the control beds sediment build up was observed in the bottom of the beds. Due to induced movement by the air bubblers sediments were not allowed to settle in the aerated beds but remained in the water column. In the aerated beds some of the sediment got caught in the root zone, as can be seen in the picture below.

PICTURE 5. Solid build-up in the root system of a lettuce taken from the 275L/h growbed. (Daniel Bodenmiller 2016)

5 DISCUSSION

5.1 Aims and hypothesis

Based on earlier findings and recommendations it was hypothesised that aeration of the root zone in DWC beds would lead to higher yields. The results of this experiment however showed that intense aeration can also have the opposite effect and become a limiting factor to plant growth. The initial objectives of this study were to determine the effect of aeration in DWC aquaponics on plant growth and key water quality parameters. While these objectives were met to a satisfactory degree the author's aspiration of establishing an optimum DO concentration goes well beyond the scope of this study.

5.2 Discussion of results

The results show sufficient DO levels throughout all beds; oxygen depletion can therefore be precluded as influencing factor. As expected, aeration of other system compartments supplied the control beds indirectly with oxygen, simulating conditions often present in DWC aquaponics systems without added growbed aeration.

The results showed a clear distinction between the two treatments, both in growth and water quality. The average yield at harvest was 29% lower in the aerated beds compared to the yield from the control beds. The lower yield in the aerated beds remained consistent throughout all three trials. Surprisingly the weight difference after drying the samples was significantly lower, only 12%. One plausible explanation is that plant composition was affected by the different treatments and therefore the samples show a difference in dry weight and water content.

The lower yield could be partly attributed to the higher pH readings that were accompanied by the added aeration, as pH plays an important role in bioavailability of nutrients. Plants can absorb nutrients best in the range of pH 6,0-6,5. A pH of 7,5 and higher can cause nutrient deficiencies for iron, manganese and phosphorus (Somerville, et al., 2014). Although no direct signs of nutrient deficiency showed during visual inspections, it is highly likely that reduced bioavailability of nutrients did contribute to the lower yields measured in the aerated beds. Surprisingly, the bed aerated at a rate of 275 L/h showed significantly lower pH readings with no increased performance over the other aerated beds. This suggests that increased pH is not the only factor contributing to the growth deficit monitored in the aerated beds. A number of other factors could be influencing the difference in growth like induced turbulence into the water column, root movement and solids not being able to settle. These variables need to be studied further.

From the results it is apparent that heavy aeration of the growbeds lead to elevated pH readings. The increase in pH could be attributed not solely to oxygen levels but most likely are due to increased diffusion of carbon dioxide into the atmosphere. Unfortunately, there are no measurements for dissolved carbon dioxide levels available during the experiment to support this claim. Hargreaves and Brunson (1996) point out that there is a relation between dissolved oxygen, carbon dioxide and pH in a fish pond environment. The dissolved oxygen and carbon dioxide concentrations follow an inversely proportional pattern; when oxygen levels are high, carbon dioxide levels are low and vice versa. The pH will increase as oxygen levels increase carbon dioxide is removed because carbon dioxide acts as an acid in water.

The same principal can also be applied to aquaponics. Rakocy et al. (2006) point out the same relationship of low DO levels corresponding with high carbon dioxide concentrations in aquaponics. Carbon dioxide is released into the water via respiration from fish and microbes ; free CO_2 released via respiration reacts with water forming carbonic acid (H_2CO_3) and consequently lowers the pH (Wurts & Durborow, 1992).

5.3 DO measurements

For the period from the 2nd to the 26th of February a YSI Professional Plus handheld meter was used for DO measurements. The meter was equipped with an electrochemical sensor; more exact a polarographic sensor with a 1.25 mil PE membrane. Unknown to the author at the time of the experiment was the fact that this sensor is flow dependant and requires sample movement to produce reliable readings. Water movement, especially in the control beds, was quite low and in retrospective stirring would have been necessary during sampling. Without sufficient water flow the sensor will deliver artificially low readings, which explains the significant difference in DO readings between the two meters. The replacement meter used an optical sensor which does not require sample movement and thus delivered correct readings. The readings from the aerated beds correspond better with the later YSI ProODO readings because the air bubbles cause movement in the water column. (YSI Inc., 2009)

5.4 Implications in commercial aquaponics

The results of this experiment clearly showed the interaction of aeration and other important environmental parameters. Because of the complex relation between oxygen levels and other parameters, especially pH, it is hard to draw general conclusions for best practices in commercial aquaponics. While in small scale aquaponics it is often hard to justify the cost of a professional DO meter, negligence or mismanagement can become very costly in bigger commercial systems. Aeration was found to play an important role in plant yield and energy efficiency. In order to maximise both case specific assessments and trials are necessary.

Another important insight gained from this experiment is the ability to locally manipulate pH through aeration adjustments. Fish, bacteria and plants all have different requirements. An increase in performance could be achieved by individually adjusting the air flow in different system compartments to match the optimum pH for each organism. Aeration should be seen as only one of many tools that can be used to manipulate pH and should be assessed carefully upon feasibility for specific cases.

After gaining some experience in this experiment with DO measurements, in aquaponics, I would recommend an optical over an electrochemical measurement system. While electrochemical sensors are a bit cheaper, they need constant flow or stirring to give reliable readings. Furthermore, higher accuracy, less frequent calibrations and no need to wait for the sensor to warm up might be worth considering the more expensive optical sensor. (YSI Inc., 2009)

If continuous monitoring in numerous locations in a commercial system is required, the price for an automated dissolved oxygen monitoring system could lie within the fivedigit to lower six-digit range. Most likely though, a professional handheld meter will meet the needs of most commercial growers. The meter used in this experiment for example, theYSI ProODO, in a Kit with an optical probe costs about 1500 $. The sensor cap has a lifetime of about one year and costs another 105 $ to replace (YSI Inc., 2017). A commercial grower should consider the added labour with the handheld meter which might outrun the cost of an automated system in the long run.

5.5 Limits of the test setup and further research

The results showed some of the limitations of the experimental setup, for example the different aerated treatments turned out to display little variance in oxygen levels. Unfortunately, given the limited amount of beds, system size and oxygen distribution throughout the system it was not possible to create a greater variety of oxygen levels. Additionally to the control beds which fell into the normal range it would have been beneficial to the study to also create low oxygen conditions and to monitor the effect on plant growth and pH. Another phenomenon, which cannot be simulated in a small scale system, is the gradual loss in dissolved oxygen occurring in long, non-aerated commercial DWC beds.

The significant difference in yield between trials suggests that the lighting was not sufficient enough during the dark Finnish Winter months. Furthermore, the temperature variation during the trials inside the greenhouse, peaking at almost 45 °C and going as low as 10 °C, could have potentially had impacts on plant growth. Better controlled conditions as well as continuous monitoring would be desirable for further studies.

It would be of interest to further study the impact of aeration on nutrient uptake and plant composition. The difference in dry and fresh weight suggests that a measurable difference in plant composition between different aeration treatments is possible. More testing with different crops would be needed to establish a better understanding of how different crops tolerate different oxygen levels and also to confirm the findings of this thesis. Another upcoming field of interest are recent multi-loop aquaponics design with semi-detached loops for aquaculture and plant production. Aeration of the plant beds are of special interest because other than in closed loop systems the oxygen levels will not be influenced much by aeration units in the fish tanks and filtration units.

6 CONCLUSION

Aquaponics research is still in its early stage of development and only during the last couple years scientific papers are being published in bigger numbers (Junge, et al., 2017). With this thesis the author wanted to contribute to fill in the scientific gaps which are still present in commercial aquaponics. Whilst the importance of sufficient aeration and DO levels is being widely recognized, interactions and management of DO levels are often disregarded. The results gathered from this experiment show that negligence of DO management can prove a costly mistake.

Oxygen depletion is known to be a limiting factor to plant growth but also heavy aeration, other than expected, had a negative effect on lettuce yields. Lettuce plants with added air supply in their growbeds did on average yield 29% less fresh mass than lettuce plants grown under controlled normal conditions. After drying the lettuce plants the difference in dry mass shrunk to only 12%. It is unclear to what extent aeration alone contributed to these results because simultaneously in the aerated test beds a shift in water pH was observed. Lower bioavailability of some nutrients as a consequence of the elevated pH readings in the aerated beds could explain the lower yields.

The significant difference between wet and dry mass suggests that the plant composition differs between the aerated and non-aerated treatments. The effect of aeration on plant composition and nutrient uptake should be further studied to not only assess the quantity but also the quality of grown produce. Further scientific studies and testing a variety of crops under different environmental conditions, also on commercial scale, is needed in order to confirm the results of this thesis and to draw profound conclusions.

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APPENDICES

Appendix 1. Supplementary graphs

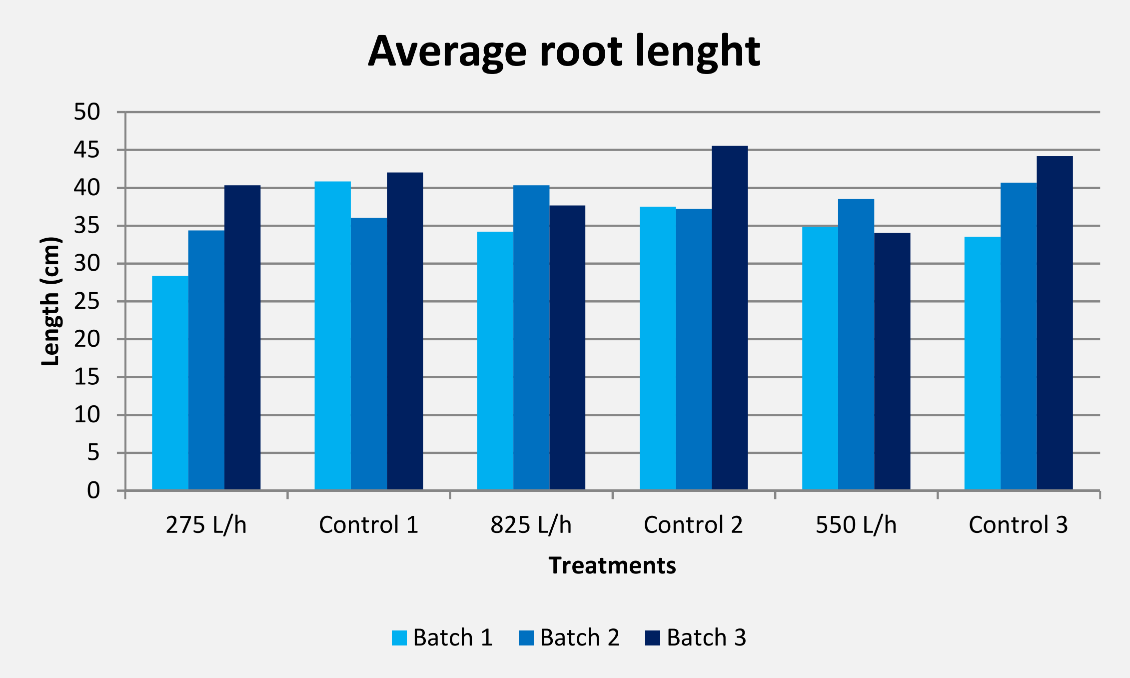

FIGURE 1. Average lettuce root length weight by batch and treatment

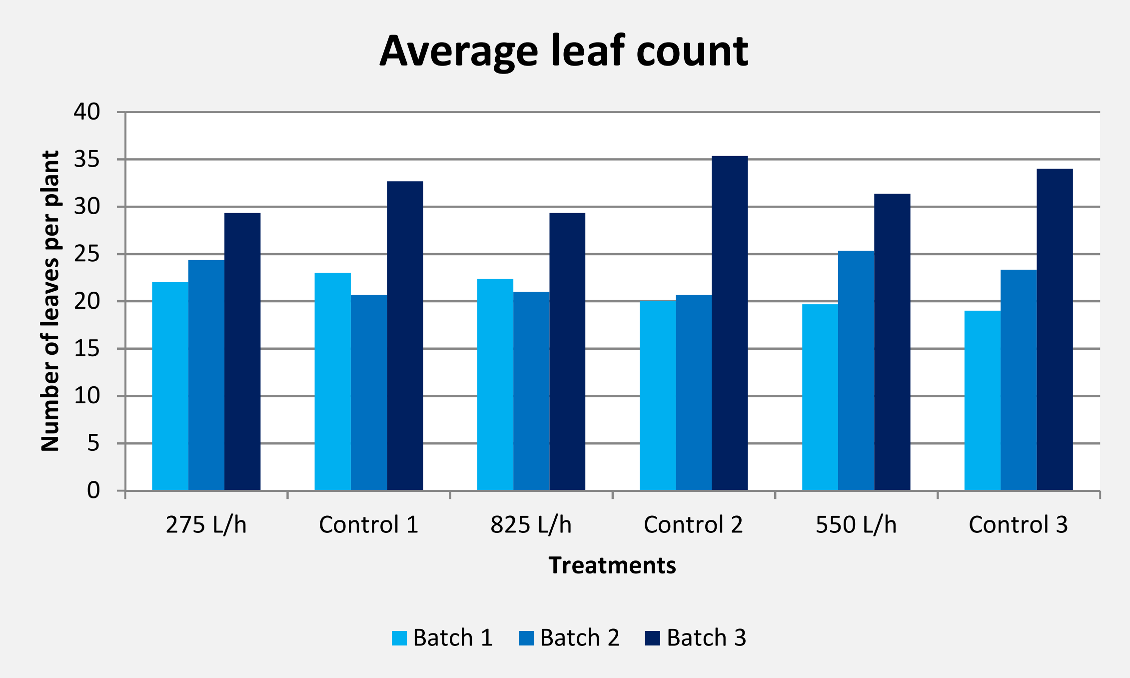

FIGURE 2. Average leaf count per lettuce by batch and treatment

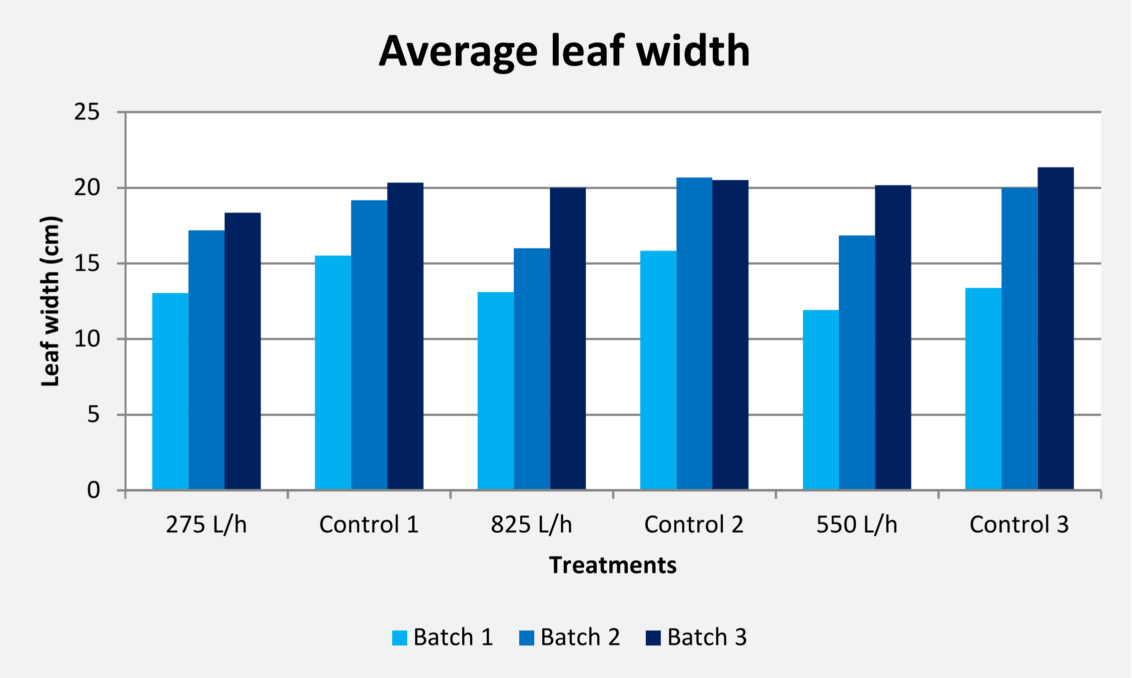

FIGURE 3. Average leaf width of the lettuce by batch and treatment