UNIVERSITI PUTRA MALAYSIA

INCREASED BIOMASS PRODUCTION OF LETTUCE (Lactuca sativa L.) THROUGH NUTRIENT MANAGEMENT IN A RED HYBRID TILAPIA (Oreochromis spp.) BASED ON DECOUPLED RECIRCULATION AQUAPONICS SYSTEM

ABDEL RAZZAQ MOHAMMAD SAEED ALTAWAHA

FP 2021 43

INCREASED BIOMASS PRODUCTION OF LETTUCE (*Lactuca sativa* L.) THROUGH NUTRIENT MANAGEMENT IN A RED HYBRID TILAPIA (*Oreochromis spp.*) BASED ON DECOUPLED RECIRCULATION AQUAPONICS SYSTEM

By

ABDEL RAZZAQ MOHAMMAD SAEED ALTAWAHA

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

May 2021

DEDICATION

To my father's soul, and to my aunt Khadija. To my mother, who waited for me all the time through my doctorate studies and she counted each minute to return to her. To my wife and children, to my brothers, with special notice to Abdullah and Abdel Rahman, and to my sisters and my father and mother in law.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

INCREASED BIOMASS PRODUCTION OF LETTUCE (*Lactuca sativa* L.) THROUGH NUTRIENT MANAGEMENT IN A RED HYBRID TILAPIA (*Oreochromis spp.*) BASED ON DECOUPLED RECIRCULATION AQUAPONICS SYSTEM

By

ABDEL RAZZAQ MOHAMMAD SAEED ALTAWAHA

May 2021

Chairman : Puteri Edaroyati bt Megat Wahab, PhD
Faculty : Agriculture

Improved aquaponics systems (APS) by adopting the decoupled recirculating aquaponics system (DRAPS) that has two independent circulations where can be controlled the physical and chemical characteristics of the water for the fish and plant independently and ability to supply macronutrients and micronutrients at an optimum concentration for plants is one of the most effective solutions to address food security issues. Thus, this study was conducted, and it consisted of four experiments. The first experiment was conducted based on a randomized complete block design (RCBD) to determine the ideal stocking density among 8 kg m^{-3}, 10 kg m^{-3}, and 12 kg m^{-3} and its effects on water quality, weight gain of tilapia and butterhead lettuce in the DRAPS. The results of the first experiment showed that the highest stocking density produced the highest concentrations of ammonia-nitrogen (NH_3-N), ammonium (NH_4), nitrate-nitrogen (NO_3-N), and potassium (K). It was reported that DRAPS that relied solely on fish waste would have an insufficient concentration of nitrogen (N), phosphorus (P), K, and iron (Fe). However, the results also showed that while the lowest stocking density (8 kg m^{-3}) produced the highest yield of butterhead lettuce, they were lower than the marketable yield of 150 g $plant^{-1}$.

The lowest stocking density of 8 kg m^{-3} was subsequently used in the second experiment to evaluate the effects of three ratios of nitrate to urea±nickel (Ni) at (60:40–Ni, 60:40+Ni, and 100:0 as control) and two different seedling ages (14 days and 21 days) on the growth, yield, and the leaf nutrient content of the butterhead lettuce in DRAPS. The experimental design was based on an RCBD split-plot design with nitrate: urea ratio as the main plot, seedling age as the sub-plot, and three replicates for each treatment. The results showed that the shoot fresh weight of the butterhead lettuce transplanted at the seedling age of 21 days and supplemented with nitrate urea ratios of 60:40–Ni and 60:40+Ni decreased by 40.8% and 43.5%, respectively as compared to that

supplemented with nitrate urea at the ratio of 100:0. When the lettuce was supplemented with fertilizer at the ratio of 100:0, the total shoot weight of the lettuce transplanted at the seedling age of 14 days decreased by 20.8% as compared to that of the 21-day. It was observed that the lettuce that was supplemented with Ni produced higher leaf N, K, sodium (Na), and Fe contents than those without Ni. Controlling the pH and introducing inorganic fertilizer in the second loop of DRAPS had significantly increased the total fresh yield per unit area by 91% compared to that as reported in Chapter 3. The nitrate urea ratio of 100:0 and seedling age of 21 days were determined as the ideal treatments and they were used in the third experiment. It was observed from experiments 1 and 2 that Fe is one of the most limited micronutrients in APS. Therefore, the third experiment was conducted to evaluate the effects of Fe sources and nutrient solution on the growth, yield, and leaf nutrient content of the salad in DRAPS. The experiment was set up as a factorial with two factors (first factor: Fe-sources [Fe-DTPA and Fe-EDTA]; second factor: Nutrient solution [inorganic fertilizer and recycled nutrient solution]) based on an RCBD with three replicates for each treatment. The results showed that the highest total fresh weight of the salad was detected in the DRAPS treated with Fe-DTPA and complemented nutrient solution which was 6.2% higher than those in the DRAPS treated with Fe-EDTA from the same season.

The optimum planting density (PD) should be determined according to agronomic assessment, which takes growth performance, water use efficiency (WUE), and recycled nutrient solution use efficiency into consideration. In this context, the effects of two PD (16 plants m^{-2} and 32 plants m^{-2}) and two nutrient solutions on the salad in DRAPS were studied in the fourth experiment. The ideal stocking density (Experiment 1), nitrate urea ratio, seedling age (Experiment 2), and Fe source (Experiment 3) were used in this experiment. The highest shoot fresh weight of the butterhead lettuce was recorded in the interaction of PD of 16 plant m^{-2} and complemented nutrient solution, while the highest total fresh weight was recorded in the PD of 32 plants m^{-2} and Complemented nutrient solution. The results collected from all four experiments demonstrated the potential of DRAPS in optimizing nutrient availability and increasing the butterhead lettuce biomass production. In conclusion, this study had successfully used DRAPS to produce butterhead lettuce and tilapia, which has proven the sustainability of DRAPS with two independent loops as an agricultural production system capable of increasing WUE and minimizing the inorganic nutrient supplements by integrating the production of fish and plant.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENINGKATAN HASIL BIOJISIM SALAD (*Lactuca sativa* L.) MELALUI PENGURUSAN NUTRIEN DALAM TILAPIA MERAH HIBRID (*Oreachromis spp.*) BERASASKAN SISTEM AKUAPONIK EDARAN SEMULA NYAHGANDING

Oleh

ABDEL RAZZAQ MOHAMMAD SAEED ALTAWAHA

Mei 2021

Pengerusi : Puteri Edaroyati bt Megat Wahab, PhD
Fakulti : Pertanian

Sistem akuaponik (APS) yang ditambah baik dengan menggunakan sistem akuaponik kitar semula yang terpisah (DRAPS) dengan dua kitaran tersendiri yang dapat mengawal ciri fizikal dan kimia air untuk ikan dan tumbuhan secara berasingan dan kemampuan untuk membekalkan makronutrien dan mikronutrien pada kepekatan optimum untuk tanaman adalah salah satu penyelesaian yang paling berkesan untuk mengatasi masalah keselamatan makanan. Oleh itu, kajian ini dijalankan dan ia terdiri daripada empat eksperimen. Eksperimen pertama dilaksanakan berdasarkan reka bentuk blok rawak lengkap (RCBD) untuk menentukan ketumpatan stok optimum antara 8 kg m^{-3}, 10 kg m^{-3}, dan 12 kg m^{-3} dan kesannya pada tilapia dalam DRAPS. Hasil eksperimen pertama menunjukkan bahawa ketumpatan stok tertinggi menghasilkan kepekatan ammonia-nitrogen (NH_3-N), amonium (NH_4), nitrat-nitrogen (NO_3-N), dan kalium (K) yang tertinggi. Dilaporkan bahawa DRAPS yang hanya bergantung pada sisa ikan akan mempunyai kepekatan nitrogen (N), fosforus (P), K, dan besi (Fe) yang tidak mencukupi. Meskipun demikian, hasil eksperimen juga menunjukkan bahawa walaupun hasil salada butterhead adalah tertinggi pada ketumpatan stok terendah (8 kg m^{-3}), hasil tersebut adalah lebih rendah daripada hasil yang dapat dipasarkan, iaitu 150 g $tumbuhan^{-1}$. Ketumpatan stok terendah, iaitu 8 kg m^{-3} digunakan dalam eksperimen kedua untuk menilai kesan-kesan tiga tahap nitrat (urea±nikel (Ni) pada 60:40–Ni, 60:40+Ni dengan 100:0 sebagai kawalan) dan dua umur anak benih yang berbeza (14 hari dan 21 hari) pada pertumbuhan, hasil, dan kandungan nutrien daun salad butterhead dalam DRAPS. Reka bentuk eksperimen didasarkan pada rancangan petak terpisah RCBD dengan nisbah nitrat:urea sebagai petak utama, umur anak benih sebagai anak petak, dan tiga ulangan untuk setiap olahan. Hasil eksperimen menunjukkan bahawa berat segar tunas salad butterhead yang ditanam dengan menggunakan anak benih berumur 21 hari dan dibaja dengan baja bernisbah 60:40–Ni dan 60:40+Ni masing-masing menurun sebanyak 40.8% dan 43.5% berbanding dengan salad butterhead yang dibaja dengan baja bernisbah 100:0. Apabila salad butterhead dibaja dengan baja bernisbah 100:0, jumlah berat tunas salad butterhead yang ditanam dengan menggunakan anak benih berumur 14

hari menurun sebanyak 20.8% berbanding dengan salad butterhead yang ditanam menggunakan anak benih berumur 21 hari. Salad butterhead yang dibaja dengan Ni diperhatikan menghasilkan kandungan N, K, sodium (Na), dan Fe daun yang lebih tinggi daripada yang tanpa Ni. Pengoptimuman pH dan penambahan baja sintetik pada lingkaran kedua DRAPS telah meningkatkan jumlah hasil segar bagi setiap unit kawasan sebanyak 91% berbanding dengan yang dilaporkan dalam Bab 3. Nisbah baja 100:0 dan umur anak benih 21 hari ditentukan sebagai olahan optimum dan digunakan dalam eksperimen ketiga. Dari eksperimen 1 dan 2, dapat diperhatikan bahawa Fe ialah salah satu mikronutrien yang paling terhad dalam APS. Oleh itu, eksperimen ketiga dijalankan untuk menilai kesan-kesan sumber Fe dan musim tanam pada pertumbuhan, hasil, dan kandungan nutrien daun salad butterhead dalam DRAPS. Eksperimen ini menggunakan reka bentuk faktorial dengan dua faktor (faktor pertama: sumber Fe [Fe-DTPA dan Fe-EDTA]; faktor kedua: musim tumbuh [baja sintetik dan larutan nutrien kitar semula]) berdasarkan RCBD dengan tiga ulangan untuk setiap olahan. Hasil eksperimen menunjukkan bahawa jumlah berat segar salad butterhead yang paling tinggi didapati daripada DRAPS yang diolah dengan Fe-DTPA pada musim tanam pertama dan ia adalah 6.2% lebih tinggi daripada jumlah berat segar salad butterhead dalam DRAPS yang diolah dengan Fe-EDTA pada musim yang sama. Fe-DTPA diperhatikan sedikit meningkatkan kepekatan N, K, kalsium (Ca), dan magnesium (Mg) dalam daun, sedangkan Fe-EDTA meningkatkan kepekatan Fe, kuprum (Cu), dan mangan (Mn) dalam daun. Ketumpatan penanaman (PD) optimum harus ditentukan dengan penilaian agronomi yang mempertimbangkan prestasi pertumbuhan, kecekapan penggunaan air (WUE), dan kecekapan penggunaan larutan nutrien kitar semula. Dalam konteks ini, kesan-kesan dua PD (16 tumbuhan m^{-2} dan 32 tumbuhan m^{-2}) dan dua musim tanam pada salad butterhead dalam DRAPS dikaji dalam eksperimen keempat. Ketumpatan stok (Eksperimen 1), nisbah baja, umur anak benih (Eksperimen 2), dan sumber Fe (Eksperimen 3) yang optimum digunakan dalam eksperimen ini. Berat segar tunas salad butterhead tertinggi dicatat pada musim tanam pertama dengan PD 16 tumbuhan m^{-2}, sementara jumlah berat segar tertinggi dicatat pada musim tanam pertama dengan PD 32 tumbuhan m^{-2}. Hasil yang dikumpulkan daripada keempat-empat eksperimen ini memperagakan potensi DRAPS dalam mengoptimumkan ketersediaan nutrien dan meningkatkan pengeluaran biomas salad butterhead. Kesimpulannya, kajian ini telah berjaya menggunakan DRAPS untuk pengeluaran salad butterhead dan tilapia. Hal ini telah membuktikan kelestarian DRAPS yang mempunyai dua lingkaran bebas sebagai sistem pengeluaran pertanian yang mampu meningkatkan WUE dan meminimumkan suplemen nutrien sintetik dengan mengintegrasikan pengeluaran ikan dan tumbuhan.

ACKNOWLEDGEMENTS

بسم الله الرحمن الرحيم

In the name of Allah the Merciful

Praise be to Allah, Lord of the Worlds, who gave me determination, high spirit, and Knowledge to serve humanity. By virtue of His ability, the Almighty, this study has become a reality

I would like to express my sincere gratitude and obligation to Dr. Puteri Edaroyati Bt Megat Wahab for her motivation and support, Associate Professor Dr. Hawa Binti Jaafar from the Department of Crop Science, Dr. Ali Tan Kee Zuan from the Department of land Management, and Dr. Mohd Zafri Bin Hassan from the Department of Aquaculture, Faculty of Agriculture, UPM.

My sincere thanks to members of my thesis committee for their contributions and constructive criticisms, much appreciated by Professor Dr. Uma Rani Sinniah, Associate Professor Dr.Yahya Bin Awang, Associate Professor Dr. Yuzine Bin Esa and External Examiner Prof. Dr. Mahfuza Begum (Bangladesh Agricultural University)

I would also like to extend my thanks for the financial, material and technical contributions from the Faculty of Agriculture, UPM.

I would like to thank all the lecturers, professors, staff members, technicians and workers of Faculty of Agriculture,UPM, for their kindness, help and cooperation which led to thesuccess of this research with special notice to Mr. Mazlan Bang, Mr. Azahar Othman, Mr. Mohd Norhaizan Saliudin and Mrs not forgetting the contributions from my brothers and colleagues. I would also like to thank all my friends Dr. Wael Alsultan, Mr. Mohammad Kamal, Mr. Laith Almarashdeh, Dr Akram Al-Mahrouk and Dr. Loay Abdulkareem for supporting and motivation.

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Puteri Edaroyati bt Megat Wahab, PhD
Senior Lecturer
Faculty of Agriculture
Universiti Putra Malaysia
(Chairman)

Hawa binti Jaafar, PhD
Associate Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

Ali Tan Kee Zuan, PhD
Senior Lecturer
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

Mohd Zafri bin Hassan, PhD
Senior Lecturer
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

____

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software

Signature: ____________________ Date: ____________________

Name and Matric No: Abdel Razzaq Mohammad Saeed Altawaha, GS48247

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

Signature: ______________________________
Name of Chairman of Supervisory Committee: Dr. Puteri Edaroyati bt Megat Wahab

Signature: ______________________________
Name of Member of Supervisory Committee: Associate Professor Dr. Hawa binti Jaafar

Signature: ______________________________
Name of Member of Supervisory Committee: Dr. Ali Tan Kee Zuan

Signature: ______________________________
Name of Member of Supervisory Committee: Dr. Mohd Zafri bin Hassan

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

APS	Aquaponic systems
AOA	Ammonia-Oxidizing Archaea
AOB	Ammonia-Oxidizing Bacteria
CNS	Complemented nutrient solution
DRAPS	Decoupled recirculation aquaponics system
DWC	Deepwater culture
DTPA	Diethylenetriaminepentaacetic acid
DO	Dissolved oxygen
EC	Electric conductivity
EDTA	Ethylenediaminetetraacetic acid
FCR	Feed conversion ratio
L	Liter
LAR	Leaf area ratio
LWR	Leaf weight ratio
NOB	Nitrite-oxidizing bacteria
WUE	Water use efficiency
NUE	Nitrogen use efficiency
NFT	Nutrient film technique
PWU	Product water use
RZT	Root zone temperature
SC	Substrate culture
RGR	Relative growth rate
RNS	Recycled nutrient solution

SRAPS	Single recirculation aquaponics system
SLA	Specific leaf area
SR	Survival rate
TDS	Total dissolved solids
T	Water temperature
WG	Weight gain

CHAPTER 1

INTRODUCTION

1.1 Background to the study

In the last three decades, the single recirculation aquaponics system (SRAPS) achieved extraordinary attention due to an influential and significant role in improving sustainable food production (Goddek et al., 2015) by providing sufficient plant and fish products (Rakocy et al., 2006) for human consumption, which has a direct impact on the future of global food security (Maucieri et al., 2019; Rakocy et al., 2006). However, managing SRAPS was anticipated to be a complicated process to achieve optimal conditions towards the sustainable production of three organisms: fish, bacteria, and plants, in terms of pH, nutrients, and water quality. Interestingly, an innovation was proposed by Kloas et al. (2015), who named this approach as decoupled recirculation aquaponics system (DRAPS) to address the issue.

DRAPS is an alternative approach (2-loop systems) and has been gaining a significant amount of interest among the community as a sustainable agricultural production since 2015. Moreover, this system received tremendous attention due to its many advantages over SRAPS (Suhl et al., 2016; Kloas et al., 2015). One of the most critical features is the separate and highly controlled conditions for fish, microbes, and plants, as reported by Suhl et al. (2016) and Kloas et al. (2015), where the imbalances can be managed accurately for various parameters such as pH, electrical conductivity (EC), dissolved oxygen (DO), root zone temperature (RZT), and N compounds (NH_3-N, NH_4-N, NO_2-N, NO_3-N). In addition, the significance of DRAPS is the ability to supply macronutrients and micronutrients at an optimum concentration as independent factors for maximizing the growth and yield of plants.

The first study for DRAPS was conducted by integrating tomato and tilapia under nutrient film technique (NFT) by Kloas et al. (2015). Then, Suhl et al. (2016) and Kloas et al. (2015) identified a research gap that required further improvement: optimising and adjusting the production of the nutrient solution generated from the fish culture to plant ratio for different species. Thus, the optimal red hybrid tilapia (*Oreochromis spp.*) stocking density to lettuce (*Lactuca sativa*) ratios were not comprehended because the majority of the past studies prioritized the evaluation of the efficiency of DRAPS for producing tomato and tilapia (Monsees et al., 2017; Suhl et al., 2016; Kloas et al., 2015). Optimizing fish stocking density is critical for producing optimum N level by converting ammonia to nitrate through nitrifying bacteria, with nitrate as the basic requirement for plant functions such as photosynthesis and regulating plant morphology, physiology, and mineral content.

The utilization of urea [$CO(NH_2)_2$] as a supplementary N source has become possible due to the two-loop design of DRAPS. Therefore, finding the optimal ratio of urea with inorganic nitrate will reduce fertilizer costs to produce leafy crops. Urea is well known for its potential as a reliable N source due to its high N content (46%). However, modern agricultural systems such as hydroponics and coupled APS seldom use urea as the source of N due to the concern in the build-up of NH_4-N. This is because urea will be broken down to NH_4-N, and if the concentration becomes 3 mg L^{-1} or higher, it can be toxic to the fish. Conversely, this would not be a concern in DRAPS due to the advantages of having two loops. In DRAPS, the fish culture is located in the first loop, which will not be affected by the application of urea or its conversion to NH_4-N. However, the utilization of urea is necessary for APS, especially DRAPS, because NO_3-N is the main product of the nitrification process and is the main source of N for most crops such as lettuce. Previous studies reported that urea supplied together with NO_3-N has reduced nitrate accumulation in leafy vegetables (Zhu et al., 1997). Gunes et al. (1994) also reported that the fresh or dry yield of lettuce under NFT was not affected by the replacement of 20% NO_3-N by urea in the nutrient solution.

Nickel (Ni) is one of the most effective micronutrients of urea in the nutrient solution as it is a component of the urease enzyme (Dixon et al., 1980) and other enzymes that are responsible for nitrate reduction. The urease enzyme was essentially used in urea assimilation by plant tissues to hydrolyze urea (Witte, 2011). Thus, Ni is needed to increase urease activity and avoid any urea toxicity symptoms in crop tissues (Marschner, 1995; Benchemsi-Bekkari and Pizelle, 1992). Moreover, Ni also plays a crucial role in N metabolism (Brown et al., 1990) in higher plants (Hansch and Mendel, 2009; Barker and Pilbeam, 2007). However, limited studies were available on urea optimization through the supplementation of micronutrients such as Ni in the nutrient solution for producing lettuce (Khoshgoftarmanesh et al., 2011).

Seedling age is an important agronomic factor and is a vital strategy to increase the plants' growth, development, and yield in APS. Numerous studies have reported on the production of lettuce under APS. However, the seedling age varied from ten to 21 days (Monsees et al., 2019; Pérez-Urrestarazu et al., 2019; Velichkova et al., 2019; Jordan et al., 2018b; Delaide et al., 2016). Therefore, the standardization of seedling age of lettuce with an ideal number of leaves, leaf area and root canopy in an APS plays a vital role in growth and yield in improving the uptake of nutrients, enhancing nutrient use efficiency, and preventing stunted growth of the plants. Furthermore, the seedling age at the time of transplantation is expected to have significant impacts on plant growth and yield. To date, the effect of seedling age at the time of transplantation on subsequent plant performance in DRAPS were not studied.

Iron (Fe) is one of the most limited micronutrients in APS (Kasozi et al., 2019) and is the third most limiting nutrient for plant growth and metabolism (Rout and Sahoo, 2015; Samaranayke et al., 2012; Zuo and Zhang, 2011). Fe is not released in an adequate concentration by the nitrification process in APS (Roosta and Hamidpour, 2011; Rakocy et al., 2006). Therefore, the Fe levels will be too low to sustain hydroponic vegetable production in APS that solely depends on fish metabolism to provide nutrients for plants

(Roosta and Mohsenian, 2012; Seawright et al., 1998). Nonetheless, Fe is an essential nutrient for crop production in APS and must be optimized to an adequate level (2-5 mg L^{-1}) in the hydroponic production unit (Kasozi et al., 2019; Roosta and Mohsenian, 2012; Tyson et al., 2011; Rakocy et al., 2006). The deficiency in Fe will result in poor yield and low nutritional quality (Rout and Sahoo, 2015), inhibit photosynthesis, cause lower stomatal conductance, and decrease the transpiration rate of plants (Larbi et al., 2006). Fe can be supplemented through different methods, such as chelated to water or as a foliar application. Different sources of chelated Fe can be used in APS, such as Fe-EDTA and Fe-DTPA. Consequently, Randall et al. (1999) reported the safe level of Fe concentration for aquatic culture as 1.69 mg L^{-1}. In a subsequent study, Phippen et al. (2008) endorsed a total Fe concentration at an optimum level of 0.35 mg L^{-1} to 1.0 mg L^{-1} for aquatic culture.

Using recycled nutrient solution (RNS) in aquaponics and hydroponic systems has become increasingly popular in ecosystems sustainability (Bugbee, 2004). Moreover, Paulus et al. (2012) reported the feasibility of using nutrient solutions prepared with low-quality water or RNS for producing lettuce in hydroponic systems, which possessed multiple benefits (Askari-Khorasgania and Pessarakl, 2020). Hence, the benefits of RNS as compared to conventional and hydroponic cultivation are promised by APS and DRAPS (Askari-Khorasgania and Pessarakl, 2020), which thereby increases the energy, water, and nutrient uptake efficiency, financial gains, and sustainability of plants and ecosystems (Askari-Khorasgania and Pessarakl, 2020). Previous studies by Zekki et al. (1996) reported that the RNS does not restrict crop yields. Bugbee. (2004) had also reported that there is a limited understanding of nutrient management in RNS. Thus, the management of RNS alongside fish nutrient solution is highly needed.

Planting density (PD) is one of the most crucial agronomic factors for optimizing the quality and quantity of lettuce yield (Maboko, 2013) in APS and hydroponics (Makhadmeh et al., 2017). PD plays a vital role in promoting the efficient use of sunlight for photosynthesis, water, and nutrients. PD is an effective crop management factor that affects productivity by regulating growth, development, and yield. Moreover, high PD will result in intense competition between plants for radiation needed for leaf photosynthetic capacity (Ma et al., 2014), water, and nutrients (Bugbee, 2004). Thus, the optimization of PD is a vital step towards improving lettuce performance.

1.2 Statement of the Problem

Managing a single recirculation aquaponics system was anticipated to be a complicated process; it is a complex system due to needing to optimize the physical and chemical properties such as pH, EC, DO, and temperature of the water for three types of organisms, which are fish, nitrifying bacteria, and plants in a single loop. In addition, it is challenging to apply a mineral salt without adversely impacting the fish and nitrifying bacteria. Therefore, the decoupled recirculation aquaponics system with a two-circulation design is the key advantage that optimizes water's physical and chemical parameters such as pH, EC, DO, root-zone temperature, and N compounds to maximize the yield of plants and fish. Also, its capability to supply the plants with the optimal concentrations of inorganic macronutrients and micronutrients in producing the highest quantity and quality of crops without toxifying the fish culture and causing adverse effects on the nitrifying bacteria.

1.3 Objectives of the study

The general aim of this study was to optimize the DRAPS as a sustainable food production system through the integration of tilapia (*Oreochromis spp*) and lettuce (*Lactuca sativa* L.) in small-scale production. The specific objectives of this study to improve and optimize DRAPS were as follow.

1. To determine the ideal stocking density of tilapia (*Oreochromis spp*) for enhanced water quality, the growth performance of both fish and lettuce (*Lactuca sativa*) yield without the addition of fertilizers in DRAPS.
2. To evaluate the potential of different nitrogen form/ratios with and without Nickel and seedling ages on biomass production, relative growth rate and leaf nutrient contents of lettuce in DRAPS.
3. To evaluate the effect of different chelated iron and planting densities with recycled nutrient solutions on the growth, yield, water use efficiency and leaf nutrients contents of lettuce in DRAPS

REFERENCES

Abdel-Tawwab, M., Hagras, A. E., Elbaghdady, H. A. M., & Monier, M. N. (2014). Dissolved oxygen level and stocking density effects on growth, feed utilization, physiology, and innate immunity of Nile Tilapia, *Oreochromis niloticus*. *Journal of Applied Aquaculture*, 26(4), 340-355. https://doi.org/10.1080/10454438.2014.959830

Abdel-Tawwab, M., Hagras, A. E., Elbaghdady, H. A. M., & Monier, M. N. (2015). Effects of dissolved oxygen and fish size on Nile tilapia, *Oreochromis niloticus* (L.): growth performance, whole-body composition, and innate immunity. *Aquaculture International*, 23(5), 1261-1274. https://doi.org/10.1007/s10499-015-9882-y

Adams, P., Graves, C. J., & Winsor, G. W. (1978). Effects of copper deficiency and liming on the yield, quality and copper status of tomatoes, lettuce and cucumbers grown in peat. *Scientia Horticulturae*, 9(3), 199-205. https://doi.org/10.1016/0304-4238(78)90001-8

Adler, P. R., Summerfelt, S. T., Glenn, D. M., & Takeda, F. (2003). Mechanistic approach to phytoremediation of water. *Ecological engineering*, 20(3), 251-264. https://doi.org/10.1016/S0925-8574(03)00044-2

Adler, P., Takeda, F., Glenn, D., & Summerfelt, S. (1996). Utilizing byproducts to enhance aquaculture sustainability. *World Aquaculture*, 27(2), 24–26.

Ahmad, M. S. A., & Ashraf, M. (2012). Essential roles and hazardous effects of nickel in plants. In *Reviews of environmental contamination and toxicology* (pp. 125-167). Springer, New York, NY.

Ahmad, M. S. A., Hussain, M., Saddiq, R., & Alvi, A. K. (2007). Mungbean: a nickel indicator, accumulator or excluder?. *Bulletin of environmental contamination and toxicology*, *78*(5), 319-324.

Ajitama, P., Effendi, H., & Hariyadi, S. (2018). Usage of fisheries rearing waste for butterhead lettuce (Lactuca sativa L. var. capitata) cultivation in recirculation. *Nature Environment and Pollution Technology*, 17(1), 145-151.

Alam, S. M. (1981). Effects of solution pH on the growth and chemical composition of rice plants. *Journal of Plant Nutrition*, *4*(3), 247-260. https:// doi.org/ 10.1080/01904168109362916

Albano, J. P., & Miller, W. B. (2001). Photodegradation of FeDTPA in nutrient solutions. I. Effects of irradiance, wavelength, and temperature. *HortScience*, 36(2), 313-316. https://doi.org/10.21273/HORTSCI.36.2.313

Albornoz, F., & Heinrich Lieth, J. (2015). Over fertilization limits lettuce productivity because of osmotic stress. *Chilean journal of agricultural research*, 75(3), 284-290. http://dx.doi.org/10.4067/S0718-58392015000400003

Al- Hafedh, Y.S., Alam, A. and Beltagi, M.S. (2008). Food production and water conservation in a recirculating aquaponic system in Saudi Arabia at different ratios of fish feed to plants. *Journal of the world aquaculture society*, 39(4), 510-520. https://doi.org/10.1111/j.1749-7345.2008.00181.x

Alibakhshi, M., & Khoshgoftarmanesh, A. H. (2015). Effects of nickel nutrition in the mineral form and complexed with histidine in the nitrogen metabolism of onion bulb. *Plant growth regulation*, 75(3), 733-740.

Alibakhshi, M., & Khoshgoftarmanesh, A. H. (2016). The effect of nickel supply on bulb yield, urease and glutamine synthetase activity and concentrations of urea, amino acids and nitrogen of urea-fed onion plants. *Archives of Agronomy and Soil Science*, 62(1), 37-51.

Al-Tawaha, A., Al-Karaki, G. and Massadeh, A. (2016). Effects of planting density and cutting height on herbage and water use efficiency of thyme (*Origanum syriacum* L.) grown under protected soilless and open field conditions. *Research on Crops*, 17(1), 118-128. https://doi.org/10.5958/2348-7542.2016.00022.X

Al-Tawaha, A.R., Al-Karaki, G., Al-Tawaha, A.R., Sirajuddin, S.N., Makhadmeh, I., Wahab, P.E.M., Youssef, R.A., Al Sultan, W. and Massadeh, A. (2018). Effect of water flow rate on quantity and quality of lettuce (*Lactuca sativa* L.) in nutrient film technique (NFT) under hydroponics conditions. *Bulgarian Journal of Agricultural Science*, 24(5), 791-798.

Alu'datt, M.H., Rababah, T., Alhamad, M.N., Al-Tawaha, A., Al-Tawaha, A.R., Gammoh, S., Ereifej, K.I., Al-Karaki, G., Hamasha, H.R., Tranchant, C.C. and Kubow, S. (2019). Herbal yield, nutritive composition, phenolic contents and antioxidant activity of purslane (*Portulaca oleracea* L.) grown in different soilless media in a closed system. *Industrial Crops and Products*, *141*, p.111746. https://doi.org/10.1016/j.indcrop.2019.111746

Álvarez-Fernández, A., García-Laviña, P., Fidalgo, C., Abadía, J. and Abadía, A. (2004). Foliar fertilization to control iron chlorosis in pear (*Pyrus communis* L.) trees. *Plant and Soil*, 263(1), 5-15. https://doi.org/10.1023/B:PLSO.0000047717.97167.d4

Anderson, T. S., De Villiers, D., & Timmons, M. B. (2017). Growth and tissue elemental composition response of butterhead lettuce (*Lactuca sativa*, *cv*. Flandria) to hydroponic and aquaponic conditions. *Horticulturae*, *3*(3), 43. https://doi.org/10.3390/horticulturae3030043

Askari-Khorasgani, O., & Pessarakli, M. (2020). Tomato (Solanum lycopersicum) culture in vermi-aquaponic systems: I. Cultural practices. *Journal of Plant Nutrition*, 1-14. https://doi.org/10.1080/01904167.2020.1739306

Assunção, A. G., Bookum, W. M., Nelissen, H. J., Vooijs, R., Schat, H., & Ernst, W. H. (2003). Differential metal‐ specific tolerance and accumulation patterns among Thlaspi caerulescens populations originating from different soil types. *New Phytologist*, 159(2), 411-419.

Avnimelech, Y. (2006). Bio-filters: the need for an new comprehensive approach. *Aquacultural Engineering*, *34*(3), 172-178. https:// doi.org/ 10.1016/j.aquaeng. 2005. 04.001

Azad, A. K., Ishikawa, K., Diaz-Perez, J. C., Eaton, T. E. J., & Takeda, N. (2013). Growth and development of komatsuna (*Brassica rapa* L. Nothovar) in NFT (nutrient film technique) system, as influenced by natural mineral. *Agricultural Sciences*, 4(7A), 1-7. http://dx.doi.org/10.4236/as.2013.47A001

Badi, H. N., Yazdani, D., Ali, S. M., & Nazari, F. (2004). Effects of spacing and harvesting time on herbage yield and quality/quantity of oil in thyme, Thymus vulgaris L. *Industrial crops and products*, *19*(3), 231-236. https://doi.org/ 10.1016/ j.indcrop. 2003.10.005

Badiola, M., Mendiola, D., & Bostock, J. (2012). Recirculating Aquaculture Systems (RAS) analysis: Main issues on management and future challenges. *Aquacultural Engineering*, *51*, 26-35. https://doi.org/10.1016/j.aquaeng.2012.07.004

Bader, N. R. (2011). Sample preparation for flame atomic absorption spectroscopy: An overview. Rasayan Journal of Chemistry, 4(1), 49–55

Barber, S.T. 1984. "Nutrient balance and nitrogen use". In *Nitrogen in Crop Production*, Edited by: Hauck, R.D. 87–95. Madison, Wisconsin: ASA, CSSA, SSSA.

Barbosa, G.L., Gadelha, F.D.A., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G.M. and Halden, R.U (2015). Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. *International journal of environmental research and public health*, 12(6), 6879-6891.

Barceló, J. U. A. N., & Poschenrieder, C. (1990). Plant water relations as affected by heavy metal stress: a review. *Journal of plant nutrition*, 13(1), 1-37. https:// doi.org/ 10.1080/ 01904169009364057

Barker, A.V., Pilbeam, D.J., 2007. Handbook of Plant Nutrition. Taylor and Francis Group Press, Boca Raton, FL.

Bartelme, R. P., McLellan, S. L., & Newton, R. J. (2017). Freshwater recirculating aquaculture system operations drive biofilter bacterial community shifts around a stable nitrifying consortium of ammonia-oxidizing archaea and comammox Nitrospira. *Frontiers in microbiology*, *8*, 101. https://doi.org/ 10.3389/ fmicb. 2017. 00101

Bartelme, R. P., Oyserman, B. O., Blom, J. E., Sepulveda-Villet, O. J., & Newton, R. J. (2018). Stripping away the soil: plant growth promoting microbiology opportunities in aquaponics. *Frontiers in microbiology*, 9, 8. https:// doi.org/ 10.3389/ fmicb. 2018. 00008

Bartholomew W Green (2010). Effect of channel catfish stocking rate on yield and water quality in an intensive, mixed suspended-growth production system. *North American journal of aquaculture*, 72(2), 97-106. https://doi.org/10.1577/A09-020.1

Bar-Yosef, B. (2008). Fertigation management and crops response to solution recycling in semi-closed greenhouses. Soilless Culture: Theory and Practice. Elsevier, Amsterdam, 343-424.

Baßmann, B., Harbach, H., Weißbach, S., & Palm, H. W. (2020). Effect of plant density in coupled aquaponics on the welfare status of African catfish, Clarias gariepinus. *Journal of the World Aquaculture Society*, *51*(1), 183-199. https:// doi.org/ 10.1111/jwas.12574

Benchemsi-Bekkari, N., & Pizelle, G. (1992). In vivo urease activity in Robinia Pseudoacacia. *Plant physiology and biochemistry (Paris)*, *30*(2), 187-192.

Bergheim, A., Gausen, M., Næss, A., Hølland, P. M., Krogedal, P., & Crampton, V. (2006). A newly developed oxygen injection system for cage farms. *Aquacultural Engineerin*g, 34(1), 40-46. https://doi.org/10.1016/j.aquaeng.2005.04.003

Blackburne, R., Vadivelu, V.M., Yuan, Z., Keller, J. (2007). Kinetic characterisation of an enriched Nitrospira culture with comparison to Nitrobacter. *Water Res*. 41,3033e3042. https://doi.org/10.1016/j.watres.2007.01.043

Blanchard, C., Wells, D. E., Pickens, J. M., & Blersch, D. M (2020). Effect of pH on Cucumber Growth and Nutrient Availability in a Decoupled Aquaponic System with Minimal Solids Removal. *Horticulturae*, 6(1), 10. https://doi.org/ 10.3390/ horticulturae6010010

Bohl, M. (1977). Some initial aquaculture experiments in recirculating water systems. *Aquaculture*, 11(4), 323-328. https://doi.org/10.1016/0044-8486(77)90081-3

Borowski, E. and Michalek, S. (2011). The effect of foliar fertilization of French bean with iron salts and urea on some physiological processes in plants relative to iron uptake and translocation in leaves. *Acta Sci. Pol. Hortorum. Cultus*, 10(2), 83-193.

Boyd, C. (1997). Progressive fish culturist: Water quality in warm water fishponds. London: Taylor and Francis.

Briat, J. F., Curie, C., & Gaymard, F. (2007). Iron utilization and metabolism in plants. *Current opinion in plant biology*, 10(3), 276-282. https://doi.org/10 .1016/ j.pbi. 2007.04.003

Brown, P. H., Welch, R. M., & Cary, E. E. (1987). Nickel: A micronutrient essential for higher plants. *Plant physiology*, 85(3), 801-803.

Brown, P.H., Welch, R.M., Madison, J.T. (1990). Effect of nickel deficiency on soluble anion, amino acid, and nitrogen levels in barley. *Plant and Soil*, 125, 19-27. https://doi.org/10.1007/BF00010740

Brown, S., McIvor, K., & Snyder, E. H. (Eds.) (2016). Sowing seeds in the city: Ecosystem and municipal services. Dordrecht: Springer

Bugbee, B. (2004). nutrient management in recirculating hydroponic culture. Acta Hortic. 648, 99-112. https://doi.org/10.17660/*ActaHortic*.2004.648.12

Burzyn´ski, M. Buczek, J. (1994) The influence of Cd, Pb, Cu and Ni on NO3 - uptake by cucumber seedlings. I. Nitrate uptake and respiration of cucumber seedlings roots treated with Cd, Pb, Cu and *Ni. Acta* Physiol Plant, 16:291–296

Buzby, K. M., & Lin, L. S. (2014). Scaling aquaponic systems: Balancing plant uptake with fish output. *Aquacultural Engineering*, 63, 39-44. https://doi.org/ 10.1016/ j.aquaeng .2014. 09.002

Capkin, E., Kayis, S., Boran, H., & Altinok, I (2010). Acute toxicity of some agriculture fertilizers to rainbow trout. *Turkish Journal of Fisheries and Aquatic Sciences*, 10(1), 19-25. https://doi.org/10.4194/trjfas.2010.0103

Cartelat, A., Cerovic, Z. G., Goulas, Y., Meyer, S., Lelarge, C., Prioul, J. L., et al. (2005). Optically assessed contents of leaf polyphenolics and chlorophyll as indicators of nitrogen deficiency in wheat (*Triticum aestivum* L.). *Field Crops Res.* 91, 35–49. https://doi.org/10.1016/j.fcr.2004.05.002

Casillas-Hernández, R., Magallón-Barajas, F., Portillo-Clarck, G., & Páez-Osuna, F. (2006). Nutrient mass balances in semi-intensive shrimp ponds from Sonora, Mexico using two feeding strategies: trays and mechanical dispersal. *Aquaculture*, 258(1-4), 289-298. https://doi.org/10.1016/j.aquaculture. 2006.03.027

Chatzistathis, T. (2014). *Micronutrient deficiency in soils and plants*. Bentham Science Publishers. pp. 38-55

Chen C, Huang D, Liu J. (2009). Functions and toxicity of nickel in plants: recent advances and future prospects. *Clean* 37:304–313

Chen, D., Martell, A.E. and McManus, D. (1995). Studies on the mechanism of chelate degradation in iron-based, liquid redox H2S removal processes. *Canadian Journal of Chemistry*, 1995, 73(2): 264-274, https://doi.org/10.1139/v95-036

Chen, Y., Clapp, C. E., & Magen, H. (2004). Mechanisms of plant growth stimulation by humic substances: The role of organo-iron complexes. *Soil Science and Plant Nutrition*, 50(7), 1089-1095. https://doi.org/10.1080/00380768.2004.10408579

Chohura, P., Kołota, E., & Komosa, A. (2012). The effect of the kind of Fe chelate on yielding and quality of greenhouse tomato fruits. *Folia Horticulturae*, 24(2), 109-114.

Commercial aquaponics production and profitability: Findings from an international survey. *Aquaculture*. 435. 67–74. https://doi.org/10.1016/j.Aquaculture.2014.09.023

Colt, J. (2006). Water quality requirements for reuse systems. *Aquacultural Engineering*, 34(3), 143-156. https://doi.org/10.1016/j.aquaeng.2005.08.011

Colt, J., Watten, B., & Rust, M. (2009). Modeling carbon dioxide, pH, and un-ionized ammonia relationships in serial reuse systems. *Aquacultural Engineering*, 40(1), 28-44. https://doi.org/10.1016/j.aquaeng.2008.10.004

Conversa, G., Santamaria, P. and Gonnella, M. (2004). Growth, Yield, And Mineral Content Of Butterhead Lettuce (*Lactuca sativa* var. *Capitata*) Grown In NFT. *Acta Hortic*. 659, 621-628. https://doi.org/10.17660/ActaHortic.2004.659.80

Costa, Â., Roubach, R., Dallago, B.S.L., Bueno, G.W., McManus, C. and Bernal, F.E.M. (2017). Influence of stocking density on growth performance and welfare of juvenile tilapia (*Oreochromis niloticus*) in cages. *Arquivo Brasileiro de Medicina Veterinária e Zootecnia*, 69(1), 243-251. https://doi.org/10.1590/1678-4162-8939

Costa, Â., Roubach, R., Dallago, B.S.L., Bueno, G.W., McManus, C. and Bernal, F.E.M (2017). Influence of stocking density on growth performance and welfare of juvenile tilapia (*Oreochromis niloticus*) in cages. *Arquivo Brasileiro de Medicina Veterinária e Zootecnia*, 69(1), 243-251. https://doi.org/10.1590/1678-4162-8939

Da Silva Cerozi, B. and Fitzsimmons, K. (2016). The effect of pH on phosphorus availability and speciation in an aquaponics nutrient solution. *Bioresource technology*, *219*, 778-781. https://doi.org/10.1016/j.biortech.2016.08.079

Daims, H., Lebedeva, E.V., Pjevac, P., Han, P., Herbold, C., Albertsen, M., Jehmlich, N., Palatinszky, M., Vierheilig, J., Bulaev, A., Kirkegaard, R.H., Von Bergen, M., Rattei, T., Bendinger, B., Nielsen, P.H., Wagner, M. (2015). Complete nitrification by Nitrospira bacteria. *Nature* 528, 504e509. https://doi.org/10.1038/nature16461

Davis, M., Ichikawa, I., Williams, E. J., & Banker, G. S. (1986). Comparison and evaluation of enteric polymer properties in aqueous solutions. *International journal of pharmaceutics*, *28*(2-3), 157-166. https://doi.org/10.1016/0378-5173(86)90241-3

Dawood, M. A. (2020). Nutritional immunity of fish intestines: important insights for sustainable aquaculture. *Reviews in Aquaculture,*1-22. https://doi.org/10.1111/raq.12492

De Kreij, C., Sonneveld, C., Warmenhoven, M. G., & Straver, N. A (1992). Guide values for nutrient element contents of vegetables and flowers under glass. Voedingsoplossingen glastuinbouw, 15.1–59.

Dediu, L., Cristea, V., Docan, A., & Vasilean, I. (2011). Evaluation of condition and technological performance of hybrid bester reared in standard and aquaponic system. *Aquaculture, Aquarium, Conservation & Legislation*, 4(4), 490-498.

Delaide, B., Delhaye, G., Dermience, M., Gott, J., Soyeurt, H., & Jijakli, M. H. (2017). Plant and fish production performance, nutrient mass balances, energy and water use of the PAFF Box, a small-scale aquaponic system. *Aquacultural Engineering*, *78*, 130-139.

Delaide, B., Goddek, S., Gott, J., Soyeurt, H. and Jijakli, M. (2016). Lettuce (Lactuca sativa L. var. Sucrine) growth performance in complemented aquaponic solution outperforms hydroponics. *Water*, 8(10), 467. https://doi.org/10.3390/w8100467

DeLong, P.D., Losordo, M.T. and Rakocy, J.E (2009). Tank Culture of Tilapia. SRAC Publication, No. 282, Texas, USA, 7 pp

De La Guardia, M. D., & Alcántara, E. (2002). Bicarbonate and low iron level increase root to total plant weight ratio in olive and peach rootstock. *Journal of Plant Nutrition*, 25(5), 1021-1032. https://doi.org/10.1081/PLN-120003936

Diver, S. (2006). Aquaponics-integration of hydroponics with aquaculture. National Center for Appropriate Technology (NCAT), Butte, p. 28

Diver, S., & Rinehart, L (2010). Aquaponics Integration of hydroponics and aquaculture. National Sustainable Agriculture Information Service, 1–28. Retrieved from http://attra.ncat.org/attra-pub/aquaponic.html

Dixon, N.E., Hinds, J.A., Fihelly, A.K., Gazzola, C., Winzor, D.J., Blakeley, R.L., Zerner, B. (1980). Jack bean urease (EC 3.5.1.5). IV. The molecular size and the mechanism of inhibition by hydroxamic acids. Spectrophotometric titration of enzymes with reversible inhibitors. *Canadian Journal of Biochemistry*, 1980, 58(12): 1323-1334, https://doi.org/ 10.1139/o80-180

Domingues, D. S., Takahashi, H. W., Camara, C. A., & Nixdorf, S. L. (2012). Automated system developed to control pH and concentration of nutrient solution evaluated in hydroponic lettuce production. *Computers and electronics in agriculture*, 84, 53-61. https://doi.org/ 10. 1016/j.compag.2012.02.006

Duan, Y., Dong, X., Zhang, X., & Miao, Z. (2011). Effects of dissolved oxygen concentration and stocking density on the growth, energy budget and body composition of juvenile Japanese flounder, Paralichthys olivaceus (*Temminck et Schlegel*). *Aquaculture Research*, 42(3), 407-416. https://doi.org/10.1111/j.1365-2109.2010.02635.x

Durborow, R. M., Crosby, D. M., & Brunson, M. W (1997). Nitrite in fish ponds. Southern Regional Aquaculture Center. SRAC Publication No. 462. http://www.aces.edu/ dept/ fisheries/ aquaculture/pdf/462fs.pdf

Ebeling, J. M., Timmons, M. B., & Bisogni, J. J (2006). Engineering analysis of the stoichiometry of photoautotrophic, autotrophic, and heterotrophic removal of ammonia–nitrogen in aquaculture systems. *Aquaculture*, 257(1-4), 346-358. https://doi.org/ 10.1016/ j.aquaculture. 2006.03.019

Ebeling, J., G. Jensen, T. Losordo, M. Masser, J. McMullen, L. Pfeiffer, J. Rakocy, and M. Sette. (1995). Model Aquaculture recirculation system (MARS). *Engineering and operations manual. Department of Agricultural Education and Studies. Iowa State University. USA.*

Eckhard TU, Mas Marques A and Buckhout TJ (2001) Two iron regulated cation transporters from tomato complement metal uptake-deficient yeast mutants. *Plant Mol. Biol*., 45: 437-448

Eding, E. H., Kamstra, A., Verreth, J. A. J., Huisman, E. A., & Klapwijk, A. (2006). Design and operation of nitrifying trickling filters in recirculating aquaculture: a review. Aquacultural Engineering, 34(3), 234-260. https://doi.org/ 10.1016/ j.aquaeng. 2005. 09.007

Effendi, H., AmalrullahUtomo, B., Maruto Darmawangsa, G., & Aprianti Hanafiah, D. (2015). Wastewater treatment of freshwater crayfish (*Cherax quadricarinatus*) culture with lettuce (*Lactuca sativa*). *Int J Appl Environ Sci*, 10(1):409–420

Effendi, H., Utomo, B. A., & Pratiwi, N. T. (2020). Ammonia and orthophosphate removal of tilapia cultivation wastewater with Vetiveria zizanioides. *Journal of King Saud University-Science*, 32(1), 207-212. https://doi.org/10.1016/j.jksus. 2018.04.018

Effendi, H., Wahyuningsih, S. and Wardiatno, Y. (2017). The use of nile tilapia (*Oreochromis niloticus*) cultivation wastewater for the production of romaine lettuce (*Lactuca sativa* L. var. longifolia) in water recirculation system. *Applied Water Science*, *7*(6), pp.3055-3063. https://doi.org/10.1007/s13201-016-0418-z

Elia, E., Popa, D. C., & Nicolae, C. G. (2014). Startup stages of a low-tech aquaponic system. *Scientific Papers: Series D, Animal Science-The International Session of Scientific Communications of the Faculty of Animal Science*, *57*.

El-Sayed, A.-F.M. Tilapia Culture; CABI Publishing: Oxfordshire, UK, 2006.

El-Shafai, S. A., El-Gohary, F. A., Nasr, F. A., van der Steen, N. P., & Gijzen, H. J. (2004). Chronic ammonia toxicity to duckweed-fed tilapia (Oreochromis niloticus). *Aquaculture*, 232(1-4), 117-127. https://doi.org/10.1016/S0044-8486(03)00516-7

El-Sherif, M. S., & El-Feky, A. M. I. (2009). Performance of Nile tilapia (Oreochromis niloticus) fingerlings. II. Influence of different water temperatures. *International Journal of Agriculture and Biology*, 11(3), 301-305.

Emerson, K., Russo, R.C., Lund, R.E. and Thurston, R.V.(1975). Aqueous ammonia equilibrium calculations: effect of pH and temperature. *Journal of the Fisheries Board of Canada*, 32(12), pp.2379-2383.

Emparanza, E. J. (2009). Problems affecting nitrification in commercial RAS with fixed-bed biofilters for salmonids in Chile. *Aquacultural engineering*, *41*(2), 91-96. https://doi.org/10.1016/j.aquaeng.2009.06.010

Endut, A., Jusoh, A., Ali, N., Nik, W. W., & Hassan, A. (2010). A study on the optimal hydraulic loading rate and plant ratios in recirculation aquaponic system. *Bioresource technology*, 101(5), 1511-1517. https://doi.org/ 10.1016/ j.biortech. 2009.09.040

Endut, A., Lananan, F., Abdul Hamid, S. H., Jusoh, A., & Wan Nik, W. N. (2016). Balancing of nutrient uptake by water spinach (Ipomoea aquatica) and mustard green (Brassica juncea) with nutrient production by African catfish (Clarias gariepinus) in scaling aquaponic recirculation system. *Desalination and Water Treatment*, 57(60), 29531-29540. https://doi.org/10.1080/19443994.2016.1184593

Eskew, D. L., Welch, R. M., & Norvell, W. A. (1984). Nickel in higher plants: further evidence for an essential role. *Plant Physiology*, 76(3), 691-693.

Espinosa Moya, E. A., Angel Sahagún, C. A., Mendoza Carrillo, J. M., Albertos Alpuche, P. J., Álvarez- González, C. A., & Martínez- Yáñez, R.(2016). Herbaceous plants as part of biological filter for aquaponics system. *Aquaculture Research*, 47(6), 1716-1726. https://doi.org/10.1111/are.12626

Estim, A., Saufie, S., & Mustafa, S (2019). Water quality remediation using aquaponics sub-systems as biological and mechanical filters in aquaculture. *Journal of Water Process Engineering*, 30, 100566. https://doi.org/10.1016/j.jwpe.2018.02.001

Evans, D.H., Claiborne, J.B., 2006. The Physiology of Fishes. Third edition, CRC Press, Taylor & Francis Group. 602 pp.

Evans, J. R. (1983). Nitrogen and photosynthesis in the flag leaf of wheat (Triticum aestivum L.). *Plant Physiol.* 72, 297–302. https://doi.org/10.1104/pp.72.2.297

Evans, J. R. (1989). Photosynthesis and nitrogen relationships in leaves of C3 plants. *Oecologia,* 78, 9–19. https://doi.org/10.1007/BF00377192

Fabiano, C., Tezotto, T., Favarin, J. L., Polacco, J. C., & Mazzafera, P. (2015). Essentiality of nickel in plants: a role in plant stresses. *Frontiers in plant science*, *6*, 754. https://doi.org/10.3389/fpls.2015.00754

Fallovo, C., Rouphael, Y., Rea, E., Battistelli, A., & Colla, G (2009). Nutrient solution concentration and growing season affect yield and quality of Lactuca sativa L. var. acephala in floating raft culture. *Journal of the Science of Food and Agriculture*, 89(10), 1682-1689. https://doi.org/10.1002/jsfa.3641

Fernández-Cabanás, V. M., Pérez-Urrestarazu, L., Juárez, A., Kaufman, N. T., & Gross, J. A. (2020). Comparative Analysis of Horizontal and Vertical Decoupled Aquaponic Systems for Basil Production and Effect of Light Supplementation by LED. Agronomy, 10(9), 1414

Fernandez, M. C., & Rubio, G. (2015). Root morphological traits related to phosphorus-uptake efficiency of soybean, sunflower, and maize. *Journal of Plant Nutrition and Soil Science*, 178(5), 807-815. https://doi.org/10.1002/jpln.201500155

Fernàndez, V., Ebert, G. and Winkelmann, G. (2005). The use of microbial siderophores for foliar iron application studies. *Plant and soil*, 272(1-2), 245-252. https://doi.org/10. 1007/s11104-004-5212-2.

Food and Agriculture Organization of the United Nations (FAO). (2017). The State of Food Security and Nutrition in the World 2017: *Building Resilience for Peace and Food Security*. FAO.

Gad, N., El-Sherif, M. H., & El-Gereedly, N. H. M. (2007). Influence of nickel on some physiological aspects of tomato plants. *Australian Journal of Basic and Applied Sciences*, *1*(3), 286-293.

Gajewska E, Wielanek M, Bergier K, Skłodowska M. (2009) Nickel-induced depression of nitrogen assimilation in wheat roots. *Acta Physiol Plant* 31:1291–1300

Gajewska, E., & Skłodowska, M. (2009). Nickel-induced changes in nitrogen metabolism in wheat shoots. *Journal of Plant Physiology*, 166(10), 1034-1044.

Gajewska, E., Skłodowska, M., Słaba, M., & Mazur, J. (2006). Effect of nickel on antioxidative enzyme activities, proline and chlorophyll contents in wheat shoots. *Biologia Plantarum*, 50(4), 653-659.

Gallegos-Cedillo, V. M., Urrestarazu, M., & Álvaro, J. E. (2016). Influence of salinity on transport of Nitrates and Potassium by means of the xylem sap content between roots and shoots in young tomato plants. *Journal of soil science and plant nutrition*, *16*(4), 991-998.

Garcia, L. L., Haag, H. P., & Diehl Neto, W. (1982). Mineral nutrition of vegetable crops: XXXVIII. Symptoms of macronutrient deficiencies in two varieties of lettuce (*Lactuca sativa* L.): Brasil 48 and Clause's Aurelia. *Anais da Escola Superior de Agricultura Luiz de Queiroz*, 39(1), 349-372. https://doi.org/10.1590/S0071-12761982000100023.

Geisenhoff, L.O., Jordan, R.A., Santos, R.C., Oliveira, F.C.D. and Gomes, E.P. (2016). Effect of different substrates in aquaponic lettuce production associated with intensive tilapia farming with water recirculation systems. *Engenharia Agrícola*, 36(2),291-299. https://doi.org/10.1590/1809-4430-Eng.Agric.v36n2p291-299/2016.

Gerardi, M. H. (2003). Nitrification and denitrification in the activated sludge process. John Wiley & Sons.

Gerendás, J., Polacco, J. C., Freyermuth, S. K., & Sattelmacher, B. (1999). Significance of nickel for plant growth and metabolism. *Journal of Plant Nutrition and Soil Science*, 162(3), 241-256.

Gerenda´s, J. Sattelmacher, B. (1999). Influence of Ni supply on growth and nitrogen metabolism of Brassica napusL.grown with NH_4NO_3or urea as N source. *Ann Bot*, 83:65–71

Gerendas, J. and Sattelmacher, B. (1997b). Significance of N source (urea vs. NH4N03) and Ni supply for growth, urease activity and nitrogen metabolism of zucchini (*Cueurbita pepo convar. giromontiina*). *Plant Soil*, 196: 217–222.

Gerendas, J. and Sattelmacher, B. (1997a). Significance of Ni supply for growth, urease activity and the concentrations of urea, amino acids and mineral nutrients of urea-grown plants. Plant Soil, 190: 153–162. https://doi.org/10.1023/A:1004260730027

Gerendás, J., Zhu, Z., & Sattelmacher, B. (1998). Influence of N and Ni supply on nitrogen metabolism and urease activity in rice (*Oryza sativa* L.). *Journal of Experimental Botany*, *49*(326), 1545-1554. https://doi.org/10.1093/jxb/49.326.1545

Gichana, Z., Meulenbroek, P., Ogello, E., Drexler, S., Zollitsch, W., Liti, D., Akoll, P. and Waidbacher, H. (2019). Growth and Nutrient Removal Efficiency of Sweet Wormwood (*Artemisia annua*) in a Recirculating Aquaculture System for Nile Tilapia (*Oreochromis niloticus*). *Water*, 11(5), 923.

Gislerød, H.R. and Kempton, R.J. (1983). The oxygen content of flowing nutrient solutions used for cucumber and tomato culture. *Scientia Horticulturae*, 20(1), 23-33. https://doi.org/10.1016/0304-4238(83)90108-5

Gjesteland, I. (2013). Study of water quality of recirculated water in aquaponic systems. Study of speciation of selected metals and characterization of the properties of natural organic matter.(Mastergrad), Norges Teknologiske og Naturvitenskapelige Universitet, NTNU, Trondheim.

Goddek, S., & Keesman, K. J. (2020). Improving nutrient and water use efficiencies in multi-loop aquaponics systems. *Aquaculture International*, 1-10. https://doi.org/ 10.1007/ s10499-020-00600-6

Goddek, S., & Vermeulen, T. (2018). Comparison of Lactuca sativa growth performance in conventional and RAS-based hydroponic systems. *Aquaculture International*, 26(6), 1377-1386. https://doi.org/10.1007/s10499-018-0293-8

Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K. V., Jijakli, H., & Thorarinsdottir, R. (2015). Challenges of sustainable and commercial aquaponics. *Sustainability*, 7(4), 4199-4224. https://doi.org/10.3390/su7044199

Goddek, S., Espinal, C. A., Delaide, B., Jijakli, M. H., Schmautz, Z., Wuertz, S., & Keesman, K. J. (2016). Navigating towards decoupled aquaponic systems: A system dynamics design approach. *Water*, 8(7), 303. https://doi.org/10.3390/W8070303

Godsey, C.B., Schmidt, J.P., Schlegel, A.J., Taylor, R.K., Thompson, C.R. and Gehl, R.J. (2003). Correcting iron deficiency in corn with seed row–applied iron sulfate. *Agronomy Journal*, 95(1), pp.160-166. https://doi.org/ 10.2134/agronj 2003.1600

Goto, E., Both, A.J., Albright, L.D., Langhans, R.W. and Leed, A.R. (1996). Dffect of dissolved oxygen concentration on lettuce growth in floating hydroponics. *Acta Hortic*. 440, 205-210.https://doi.org/10.17660/ActaHortic.1996.440.36

Goyal, S. S., & Huffaker, R. C. (1984). Nitrogen toxicity in plants. Nitrogen in crop production, 97-118. https://doi.org/10.2134/1990.nitrogenincropproduction.c6

Graber, A., & Junge, R. (2009). Aquaponic Systems: Nutrient recycling from fish wastewater by vegetable production. *Desalination*, 246(1-3), 147-156. https://doi.org/10.1016/ j.desal. 2008.03.048

Gunes, A., Post, W. N., Kirkby, E. A., & Aktas, M. (1994). Influence of partial replacement of nitrate by amino acid nitrogen or urea in the nutrient medium on nitrate accumulation in NFT grown winter lettuce. *Journal of plant nutrition*, *17*(11), 1929-1938. https://doi.org/10.1080/01904169409364855

Gutierrez-Wing, M. T., & Malone, R. F. (2006). Biological filters in aquaculture: trends and research directions for freshwater and marine applications. *Aquacultural Engineering*, *34*(3), 163-171. https://doi.org/ 10.1016/j.aquaeng.2005.08.003

Hänsch, R., & Mendel, R. R. (2009). Physiological functions of mineral micronutrients (cu, Zn, Mn, Fe, Ni, Mo, B, cl). *Current opinion in plant biology*, *12*(3), 259-266. https://doi.org/ 10.1016/j.pbi.2009.05.006

Hargreaves, J.A. and Tucker, C.S (2004). Managing ammonia in fish ponds (Vol. 4603). Stoneville, MS: Southern Regional Aquaculture Center.

Harmon, T. S (2009). Methods for reducing stressors and maintaining water quality associated with live fish transport in tanks: a review of the basics. *Reviews in Aquaculture*, 1(1), 58-66. https://doi.org/ 10.1111/j.1753-5131.2008.01003.x

Hassan, M. U., Chattha, M. U., Khan, I., Chattha, M. B., Aamer, M., Nawaz, M., ... & Khan, T. A. (2019). Nickel toxicity in plants: reasons, toxic effects, tolerance mechanisms, and remediation possibilities—a review. *Environmental Science and Pollution Research*, 26(13), 12673-12688.https://doi.org/10.1007/s11356-019-04892-x

He, J., See, X.E., Qin, L. and Choong, T.W. (2016). Effects of Root-Zone Temperature on Photosynthesis, Productivity and Nutritional Quality of Aeroponically Grown Salad Rocket (Eruca sativa) Vegetable. *American Journal of Plant Sciences*, 7, 1993-2005. http://dx.doi.org/ 10.4236/ajps.2016.714181

He, J., Tan, L. P., & Lee, S. K. (2009). Root-zone temperature effects on photosynthesis, 14 C-photoassimilate partitioning and growth of temperate lettuce (Lactuca sativa cv.'Panama') in the tropics. *Photosynthetica*, 47(1), 95-103. https://doi.org/10.1007 /s11099-009-0015-6

Hermans, C., Hammond, J. P., White, P. J., & Verbruggen, N (2006). How do plants respond to nutrient shortage by biomass allocation?. *Trends in plant science*, 11(12), 610-617. https://doi.org/ 10.1016/j.tplants.2006.10.007

Holmes, S. C., Wells, D. E., Pickens, J. M., & Kemble, J. M. (2019). Selection of Heat Tolerant Lettuce (Lactuca sativa L.) Cultivars Grown in Deep Water Culture and Their Marketability. *Horticulturae*, 5(3), 50. https://doi.org/ 10.3390/horticulturae5030050

Horchani, F., Hajri, R., & Aschi- Smiti, S. (2010). Effect of ammonium or nitrate nutrition on photosynthesis, growth, and nitrogen assimilation in tomato plants. *Journal of Plant Nutrition and Soil Science*, 173(4), 610-617.

Hossein Khoshgoftarmanesh, A., & Bahmanziari, H. (2012). Stimulating and toxicity effects of nickel on growth, yield, and fruit quality of cucumber supplied with different nitrogen sources. *Journal of Plant Nutrition and Soil Science*, 175(3), 474-481.

Hosseini, H., & Khoshgoftarmanesh, A. H. (2013). The effect of foliar application of nickel in the mineral form and urea-Ni complex on fresh weight and nitrogen metabolism of lettuce. *Scientia Horticulturae*, 164, 178-182. https://doi.org/ 10.1016/ j.scienta. 2013.09.030

Hu, Z., Lee, J. W., Chandran, K., Kim, S., Brotto, A. C., & Khanal, S. K. (2015). Effect of plant species on nitrogen recovery in aquaponics. *Bioresource technology*, *188*, 92-98. https://doi.org/ 10.1016/j.biortech.2015.01.013

Hung, H.C., Joshipura, K.J., Jiang, R., Hu, F.B., Hunter, D., Smith-Warner, S.A., Colditz, G.A., Rosner, B., Spiegelman, D. and Willett, W.C. (2004). Fruit and vegetable intake and risk of major chronic disease. *Journal of the National Cancer Institute*, 96(21), 1577-1584. https://doi.org/ 10.1093/jnci/djh296

Hunt R (1982) Plant growth curves: the functional approach to plant growth analysis. Edward Arnold, London

Ikeda, H., & Osawa, T. (1984). Lettuce growth as influenced by N source and temperature of the nutrient solution. In 6. International Congress on Soilless Culture, Lunteren (Netherlands), 29 Apr-5 May 1984. ISOSC.

Jetten, M.S., Strous, M., Van de Pas-Schoonen, K.T., Schalk, J., van Dongen, U.G., van de Graaf, A.A., Logemann, S., Muyzer, G., van Loosdrecht, M.C. and Kuenen, J.G. (1998). The anaerobic oxidation of ammonium. *FEMS Microbiology reviews*, 22(5), 421-437.

Jian-yu, X., Xiang-wen, M., Ying, L., & Shao-rong, C. (2005). Behavioral response of tilapia (Oreochromis niloticus) to acute ammonia stress monitored by computer vision. *Journal of Zhejiang university science B*, 6(8), 812-816. https:// doi.org/ 10. 1007/BF02842442

Jimoh, W.A., Kamarudin, M.S., Sulaiman, M.A. and Dauda, A.B.(2019). Assessment of prebiotic potentials in selected leaf meals of high dietary fibre on growth performance, body composition, nutrient utilization and amylase activities of a tropical commercial carp fingerlings. *Aquaculture Research*, 50(11), 3401-3411. https://doi.org/ 10.1111/are.14298

Johnson, G.E., Buzby, K.M., Semmens, K.J., Holaskova, I. and Waterland, N.L (2017). Evaluation of lettuce between spring water, hydroponic, and flow-through aquaponic systems. *International Journal of Vegetable Science*, 23(5), 456-470. https://doi.org/ 10.1080/19315260.2017.1319888

Jones, J. B.(2005). Hydroponics: a practical guide for the soilless grower. CRC Press

Jordan, R. A., Ribeiro, E. F., Oliveira, F. C. D., Geisenhoff, L. O., & Martins, E. A (2018b). Yield of lettuce grown in hydroponic and aquaponic systems using different substrates. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 22(8), 525-529. https://doi.org/ 10.1590/1807-1929/agriambi.v22n8p525-529

Jordan, R.A., Geisenhoff, L.O., Oliveira, F.C.D., Santos, R.C. and Martins, E.A. (2018a). Yield of lettuce grown in aquaponic system using different substrates. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 22(1), 27-31. https://doi.org/ 10.1590/1807-1929/agriambi.v22n1p27-31

Junge, R., König, B., Villarroel, M., Komives, T., Jijakli, M.H. (2017). Strategic Points in Aquaponics. *Water*, *9*(3), 182; https://doi.org/10.3390/w9030182

Kabata-Pendias, A. and Pendias, H. (2001) Trace Elements in Soils and Plants; CRC Press: Washington, D.C.

Karimanzira, D., Keesman, K. J., Kloas, W., Baganz, D., & Rauschenbach, T. (2016). Dynamic modeling of the INAPRO aquaponic system. *Aquacultural Engineering*, 75, 29-45. https://doi.org/ 10.1016/j.aquaeng.2016.10.004

Kasozi, N., Tandlich, R., Fick, M., Kaiser, H., & Wilhelmi, B. (2019). Iron supplementation and management in aquaponic systems: A review. *Aquaculture Reports*, 15, 100221. https://doi.org/ 10.1016/j.aqrep.2019.100221

Keen, G.A.; Prosser, J.I. Interrelationship between pH and surface growth of Nitrobacter. (1987). *Soil Biol. Biochem*. 19, 665–672

Kevresan, S., Petrovic, N., Popovic, M., & Kandrac, J. (2001). Nitrogen and protein metabolism in young pea plants as affected by different concentrations of nickel, cadmium, lead, and molybdenum. *Journal of plant nutrition*, 24(10), 1633-1644.

Khan, N. K., and Y. Watanabe. (1999). Effect of different concentrations of urea with or without Ni addition on spinach (Spinacia oleracea L.) growth under hydroponic culture. *Soil Science and Plant Nutrition*, 45: 569–575

Khan, N. K., Watanabe, M., & Watanabe, Y. (2000). Effect of partial urea application on nutrient absorption by hydroponically grown *spinach (Spinacia oleracea L.). Soil science and plant nutrition*, 46(1), 199-208.

Khiari, Z., Kaluthota, S., & Savidov, N. (2019). Aerobic bioconversion of aquaculture solid waste into liquid fertilizer: Effects of bioprocess parameters on kinetics of nitrogen mineralization. Aquaculture, 500, 492-499. https:// doi.org/ 10.1016/ j.aquaculture. 2018.10.059

Khoshgoftarmanesh, A. H., Hosseini, F., & Afyuni, M. (2011). Nickel supplementation effect on the growth, urease activity and urea and nitrate concentrations in lettuce supplied with different nitrogen sources. *Scientia Horticulturae*, *130*(2), 381-385. https://doi.org/ 10.1016/ j.scienta. 2011.07.009

Kim, M. J., Moon, Y., Tou, J. C., Mou, B., & Waterland, N. L. (2016). Nutritional value, bioactive compounds and health benefits of lettuce (*Lactuca sativa* L.). *Journal of Food Composition and Analysis*, 49, 19-34. https://doi.org/10.1016/j.jfca. 2016.03.004

Kleiber T. 2014. Effect of manganese nutrition on content of nutrient and yield of lettuce (Lactuca sativa L.) in hydroponic. *Ecol Chem Eng S*., 21(3): 529-537. DOI: 10.2478/eces-2014-0039

Kloas, W., Groß, R., Baganz, D., Graupner, J., Monsees, H., Schmidt, U., Staaks, G., Suhl, J., Tschirner, M., Wittstock, B. and Wuertz, S. (2015). A new concept for aquaponic systems to improve sustainability, increase productivity, and reduce environmental impacts. *Aquaculture Environment Interactions*, 7(2), 179–192. https://doi.org/ 10.3354/aei00146

Knaus, U., & Palm, H. W (2017). Effects of the fish species choice on vegetables in aquaponics under spring-summer conditions in northern Germany (Mecklenburg Western Pomerania). *Aquaculture*, 473,62–73. https://doi.org/ 10.1016/ j. aquaculture.2017.01.020

Komives, T., & Junge, R. (2018). Importance of nickel as a nutrient in aquaponic systems-some theoretical considerations. Ecocycles, 4(2), 1-3.

Kosegarten, H., & Koyro, H. W (2001). Apoplastic accumulation of iron in the epidermis of maize (Zea mays) roots grown in calcareous soil. Physiologia plantarum, 113(4), 515-522. https://doi.org/ 10.1034/j.1399-3054.2001.1130410.x

Kotsiras, A., Olympios, C. M., Drosopoulos, J., & Passam, H. C. (2002). Effects of nitrogen form and concentration on the distribution of ions within cucumber fruits. *Scientia Horticulturae*, 95(3), 175-183.

Kowalchuk, G. A., & Stephen, J. R. (2001). Ammonia-oxidizing bacteria: a model for molecular microbial ecology. *Annual Reviews in Microbiology*, 55(1), 485-529.

Kozik, E., Tyksinski, W., & Bosiacki, M. (2011). A comparison of the efficiency of organic and mineral iron compounds in the greenhouse cultivation of lettuce. *Journal of Elementology*, 16(1).

Krogmeier, M. J., McCarty, G. W., Shogren, D. R., & Bremner, J. M. (1991). Effect of nickel deficiency in soybeans on the phytotoxicity of foliar-applied urea. *Plant and Soil*, *135*(2), 283-286. https://doi.org/ 10.1007/BF00010917

Krüner, G., & Rosenthal, H. (1983). Efficiency of nitrification in trickling filters using different substrates. *Aquacultural Engineering*, 2(1), 49-67. https://doi.org/ 10.1016/0144-8609(83)90005-5

Kuhn, D. D., Drahos, D. D., Marsh, L., & Flick Jr, G. J. (2010). Evaluation of nitrifying bacteria product to improve nitrification efficacy in recirculating aquaculture systems. *Aquacultural Engineering*, *43*(2), 78-82. https://doi.org/ 10.1016/ j.aquaeng. 2010.07.001

Larbi, A., Abadía, A., Abadía, J., & Morales, F. (2006). Down co-regulation of light absorption, photochemistry, and carboxylation in Fe-deficient plants growing in different environments. *Photosynthesis Research*, *89*(2-3), 113-126. https://doi.org/ 10.1007/s11120-006-9089-1

Lei, S., & Li, D. (2000). Effect of temperature on energy budget of Taiwanese red tilapia hybrid (*Oreochromis niloticus* x *O. mossambicus*). Ying yong sheng tai xue bao= *The journal of applied ecology*, 11(4), 618.

Lekang, O. I. (2007). Aquaculture engineering. Oxford: Blackwell Publishing Ltd

Lemarie, G., Dosdat, A., Covès, D., Dutto, G., Gasset, E., & Person-Le Ruyet, J. (2004). Effect of chronic ammonia exposure on growth of European seabass (Dicentrarchus labrax) juveniles. *Aquaculture*, *229*(1-4), 479-491. https://doi.org/ 10.1016/S0044-8486(03)00392-2

Lennard, W.A., Leonard, B.V.(2006). A Comparison of Three Different Hydroponic Sub-systems (gravel bed, floating and nutrient film technique) in an Aquaponic

Test System. *Aquaculture International*, 14(6), 539–550. https://doi.org/10.1007/s10499-006-9053-2.

Li, M., Cao, H., Hong, Y., & Gu, J. D. (2011). Spatial distribution and abundances of ammonia-oxidizing archaea (AOA) and ammonia-oxidizing bacteria (AOB) in mangrove sediments. *Applied microbiology and biotechnology*, 89(4), 1243-1254.

Li, M., Wang, X., Qi, C., Li, E., Du, Z., Qin, J. G., & Chen, L (2018). Metabolic response of Nile tilapia (*Oreochromis niloticus*) to acute and chronic hypoxia stress. *Aquaculture*, 495, 187-195. https://doi.org/ 10.1016/j.aquaculture.2018.05.031

Li, R. R., Zhu, Y. L., Takagaki, M., Yamori, W., and Yang, L. F. (2015). Effects of root zone temperature on the growth and mineral elements content of hydroponically grow lettuce. *Acta Agric. Shanghai* 31, 48–52.

Li, Y., He, N., Hou, J., Xu, L., Liu, C., Zhang, J., Wang, Q., Zhang, X. and Wu, X. (2018). Factors influencing leaf chlorophyll content in natural forests at the biome scale. *Frontiers in Ecology and Evolution*, *6*, 64.

Liang, J. Y., & Chien, Y. H (2013). Effects of feeding frequency and photoperiod on water quality and crop production in a tilapia–water spinach raft aquaponics system. *International Biodeterioration & Biodegradation*, 85, 693-700. https://doi.org/ 10.1016/j.ibiod.2013.03.029

Licamele J (2009) Biomass production and nutrient dynamics in an aquaponics system. PhD thesis. Department of Agriculture and biosystems engineering, University of Arizona

Lichtenthaler, H. K. (1987). Chlorophylls and carotenoids: pigments of photosynthetic biomembranes. In Methods in enzymology (Vol. 148, pp. 350-382). Academic Press.

Liu, G., Ye, Z., Liu, D., Zhao, J., Sivaramasamy, E., Deng, Y. and Zhu, S.(2018). Influence of stocking density on growth, digestive enzyme activities, immune responses, antioxidant of *Oreochromis niloticus* fingerlings in biofloc systems. *Fish & shellfish immunology*, 81, 416-422. https://doi.org/ 10.1016/j.fsi.2018.07.047

Long, L., Zhang, H., Ni, Q., Liu, H., Wu, F. and Wang, X. (2019). Effects of stocking density on growth, stress, and immune responses of juvenile Chinese sturgeon (*Acipenser sinensis*) in a recirculating aquaculture system. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology*, 219, 25-34. https://doi.org/ 10.1016/j.cbpc.2019.02.002

López-Millán, A. F., Morales, F., Andaluz, S., Gogorcena, Y., Abadıa, A., De Las Rivas, J., & Abadıa, J. (2000). Responses of sugar beet roots to iron deficiency. Changes in carbon assimilation and oxygen use. *Plant Physiology*, 124(2), 885-898.

Losordo, T.M., Masser, M.P. and Rakocy, J. (1998). Recirculating aquaculture tank production systems. Overview of Critical Considerations. SRAC Publication, 451.

Losordo, T.M., Masser, M.P. and Rakocy, J. (1999). Recirculating Aquaculture Tank Production Systems. A Review of Component Options. SRAC Publication, 453

Love, D. C., Fry, J. P., Li, X., Hill, E. S., Genello, L., Semmens, K., & Thompson, R. E. (2015a). Commercial aquaponics production and profitability: Findings from an international survey. *Aquaculture*, 435, 67-74. https://doi.org/ 10.1016/j. aquaculture. 2014.09.023

Love, D. C., Uhl, M. S., & Genello, L. (2015b). Energy and water use of a small-scale raft aquaponics system in Baltimore, Maryland, United States. *Aquacultural engineering*, 68, 19-27. https://doi.org/ 10.1016/j.aquaeng.2015.07.003

Luo, J., Lian, Z., & Yan, X. (1993). Urea transformation and the adaptability of three leafy vegetables to urea as a source of nitrogen in hydroponic culture. *Journal of plant nutrition*, *16*(5), 797-812. https://doi.org/ 10.1080/01904169309364575

Ma, N., Yuan, J., Li, M., Li, J., Zhang, L., Liu, L., ... & Zhang, C. (2014). Ideotype population exploration: growth, photosynthesis, and yield components at different planting densities in winter oilseed rape (Brassica napus L.). *PloS one*, *9*(12), e114232.

Maboko, M.M. (2013). Effect of plant density and harvesting frequency on yield components of hydroponically grown mustard spinach (*Brassica juncea*). *Acta Hortic*. 1007, 515-521. https://doi.org/ 10.17660/ActaHortic.2013.1007.59

Maboko, M. M., & Du Plooy, C. P. (2013). Effect of plant spacing and harvesting frequency on the yield of Swiss chard cultivars (Beta vulgaris L.) in a closed hydroponic system. *African journal of agricultural research*, 8(10), 936-942.

Maboko, M.M. and Du Plooy, C.P. (2012). Effect of plant density and harvesting method on yield components of hydroponically grown amaranth. *Acta Hortic*. 947, 415-42. https://doi.org/ 10.17660/ActaHortic.2012.947.54

Maboko, M.M. and Du Plooy, C.P. (2009). Effect of plant spacing on growth and yield of lettuce (*Lactuca sativa* L.) in a soilless production system. *S. Afr. J. Plant Soil* 26:199- 201. https://doi.org/ 10.1080/02571862.2009.10639954

Madar, Á.K., Rubóczki, T. and Hájos, M.T (2019). Lettuce production in aquaponic and hydroponic systems. Acta Universitatis Sapientiae, *Agriculture and Environment*, 11(1),51-59. https://doi.org/ 10.2478/ausae-2019-0005

Mahfouz, M. E., Hegazi, M. M., El-Magd, M. A., & Kasem, E. A. (2015). Metabolic and molecular responses in Nile tilapia, Oreochromis niloticus during short and prolonged hypoxia. *Marine and Freshwater Behaviour and Physiology*, 48(5), 319-340. https://doi.org/ 10.1080/10236244.2015.1055915

Mahlangu, R. I. S., Maboko, M. M., Sivakumar, D., Soundy, P., & Jifon, J. (2016). Lettuce (Lactuca sativa L.) growth, yield and quality response to nitrogen fertilization in a non-circulating hydroponic system. *Journal of Plant Nutrition*, 39(12), 1766-1775.

Makhadmeh, I.M., Al-Tawaha, A., Edaroyati, P., Al-Karaki, G., Tawaha, A.R.A. and Hassan, S.A. (2017). Effects of different growth media and planting densities on growth of lettuce grown in a closed soilless system. *Research on Crops*, *18*(2), pp.294-298. https://doi.org/ 10.5958/2348-7542.2017.00050.X

Malone, R. F., & Pfeiffer, T. J. (2006). Rating fixed film nitrifying biofilters used in recirculating aquaculture systems. *Aquacultural engineering*, *34*(3), 389-402. https://doi.org/ 10.1016/j.aquaeng.2005.08.007

Marschner, H. 1995. Mineral Nutrition of Higher Plants. 2nd Edition, Academic Press, London.

Marschner, H. (2012). Mineral nutrition of higher plants. 3rd Editions.

Marschner, H., Kirkby, E.A. and Cakmak, I., 1996. Effect of mineral nutritional status on shoot—root partitioning of photoassimilates and cycling of mineral nutrients. *Journal of experimental botany*, pp.1255-1263. https://doi.org/10.1093/jxb/47 Special_Issue .1255

Masser, M. P., Rakocy, J., & Losordo, T. M. (1999). Recirculating aquaculture tank production systems. *Management of recirculating systems. SRAC Publication*, *452*.

Masson, J., Tremblay, N., & Gosselin, A. (1991). Nitrogen fertilization and HPS supplementary lighting influence vegetable transplant production. I. Transplant growth. *Journal of the American Society for Horticultural Science*, 116(4), 594-598.

Matraszek, R. (2008). Nitrate reductase activity of two leafy vegetables as affected by nickel and different nitrogen forms. *Acta Physiologiae Plantarum*, 30(3), 361.

Matthews, K. R., & Berg, N. H. (1997). Rainbow trout responses to water temperature and dissolved oxygen stress in two southern California stream pools. *Journal of Fish Biolog*y, 50(1), 50-67. https://doi.org/ 10.1111/j.1095-8649.1997.tb01339.x

Maucieri, C., Nicoletto, C., Junge, R., Schmautz, Z., Sambo, P., & Borin, M., (2017b). Hydroponic systems and water management in aquaponics: A review. Italian Journal of Agronomy, 13(1), 1-11. https://doi.org/ 10.4081/ija.2017.1012

Maucieri, C., Nicoletto, C., Schmautz, Z., Sambo, P., Komives, T., Borin, M., & Junge, R. (2017a). Vegetable intercropping in a small-scale aquaponic system. *Agronomy*, 7(4), 63. https://doi.org/ 10.3390/agronomy7040063

Maucieri, C., Nicoletto, C., Zanin, G., Birolo, M., Trocino, A., Sambo, P., Borin, M. and Xiccato, G. (2019). Effect of stocking density of fish on water quality and growth performance of European Carp and leafy vegetables in a low-tech aquaponic system. *PLoS ONE* 14(5): e0217561. https://doi.org/ 10.1371/journal.pone.0217561

Meister, R., Rajani, M.S., Ruzicka, D. and Schachtman, D.P. (2014). Challenges of modifying root traits in crops for agriculture. Trends in Plant Science, 19(12),779-788. https://doi.org/ 10.1016/j.desal.2008.03.048

Mekonnen, M. M., & Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences*, 15, 1577-1600. https://doi.org/ 10.5194/hess-15-1577-2011

Molas, J. (2002). Changes of chloroplast ultrastructure and total chlorophyll concentration in cabbage leaves caused by excess of organic Ni (II) complexes. *Environmental and Experimental Botany*, *47*(2), 115-126.

Moniruzzaman, M. (2006). Effects of plant spacing and mulching on yield and profitability of lettuce (Lactuca sativa L.). *Journal of Agriculture & Rural Development*, 4(1), 107-111. https://doi.org/10.3329/jard.v4i1.776

Monsees, H., Kloas, W. and Wuertz, S. (2017). Decoupled systems on trial: Eliminating bottlenecks to improve aquaponic processes. *PloS One*, *12*(9), p.e0183056. https://doi.org/10.1371/journal.pone.0183056

Monsees, H., Suhl, J., Paul, M., Kloas, W., Dannehl, D. and Würtz, S. (2019). Lettuce (*Lactuca sativa,* variety Salanova) production in decoupled aquaponic systems: Same yield and similar quality as in conventional hydroponic systems but drastically reduced greenhouse gas emissions by saving inorganic fertilizer. *PLoS ONE* 14(6): e0218368. https://doi.org/ 10.1371/journal.pone.0218368

Morard, P. and Silvestre, J. (1996). Plant injury due to oxygen deficiency in the root environment of soilless culture: a review. Plant and soil, 184(2), 243-254. https://doi.org/ 10.1007/BF00010453

Morard, P., Lacoste, L. and Silvestre, J. (2000). Effect of oxygen deficiency on uptake of water and mineral nutrients by tomato plants in soilless culture. *Journal of Plant Nutrition*, *23*(8), 1063-1078. https://doi.org/ 10.1080/01904160009382082

Moya, C., Oyanedel, E., Verdugo, G., Flores, M. F., Urrestarazu, M., & Álvaro, J. E. (2017). Increased electrical conductivity in nutrient solution management enhances dietary and organoleptic qualities in soilless culture tomato. *HortScience, 52*(6), 868-872.

Naegel, L. C. (1977). Combined production of fish and plants in recirculating water. *Aquaculture*, 10 (1), 17-24. https://doi.org/ 10.1016/0044-8486(77)90029-1

Nelson, R. L., & Pade, J. S. (2008). Aquaponic food production: growing fish and vegetables for food and profit.

Neocleous, D., & Savvas, D. (2017). Simulating NaCl accumulation in a closed hydroponic crop of zucchini: Impact on macronutrient uptake, growth, yield, and photosynthesis. *Journal of Plant Nutrition and Soil Science*, 180(3), 283-293. https://doi.org/10.1002/jpln.201600338

Ng, W. K., & Romano, N. (2013). A review of the nutrition and feeding management of farmed tilapia throughout the culture cycle. *Reviews in Aquaculture*, *5*(4), 220-254. https://doi.org/10.1111/raq.12014

Nicoulaud, B. A., & Bloom, A. J. (1998). Nickel supplements improve growth when foliar urea is the sole nitrogen source for tomato. *Journal of the American Society for Horticultural Science*, 123(4), 556-559.

Novoa, R., and R. S. Loomis. (1981). Nitrogen and plant production.Plant and Soil58: 781–783

Nozzi, V., Graber, A., Schmautz, Z., Mathis, A., & Junge, R (2018). Nutrient management in aquaponics: comparison of three approaches for cultivating lettuce, mint and mushroom herb. *Agronomy*, *8*(3), 27. https://doi.org/ 10.3390/agronomy8030027

Ogah, S. I., Kamarudin, M. S., Nurul Amin, S. M., & Puteri Edaroyati, M. W (2020). Biological filtration properties of selected herbs in an aquaponic system. *Aquaculture Research*, 51(5), 1771-1779.

Olowolaju, E. D., Okunlola, G. O., & Ayeotan, O. J. (2020). Growth, yield and uptake of some nutrients by tomato as affected by iron concentration. *International Journal of Vegetable Science*, 1-10. https://doi.org/ 10.1080/19315260 .2020.1805668

Oyugi, D. O., Cucherousset, J., Baker, D. J., & Britton, J. R. (2012). Effects of temperature on the foraging and growth rate of juvenile common carp, Cyprinus carpio. *Journal of Thermal Biology*, *37*(1), 89-94. https://doi.org/ 10.1016/j.jtherbio.2011.11.005

Padilla, F. M., Gallardo, M., Peña-Fleitas, M. T., de Souza, R., & Thompson, R. B. (2018). Proximal optical sensors for nitrogen management of vegetable crops: A review. *Sensors*, 18, 2083.

Padilla, F.M., de Souza, R., Peña-Fleitas, M.T. (2019). Influence of time of day on measurement with chlorophyll meters and canopy reflectance sensors of different crop N status. *Precision Agric* 20, 1087–1106. https://doi.org/ 10.1007/s11119-019-09641-1

Panda, G. C., Das, S. K., Bandopadhyay, T. S., & Guha, A. K. (2007). Adsorption of nickel on husk of Lathyrus sativus: behavior and binding mechanism. *Colloids and Surfaces B: Biointerfaces*, 57(2), 135-142. https://doi.org/10.1016/j.colsurfb. 2007.01.022

Pantanella, E., Cardarelli, M., Colla, G., Rea, E. and Marcucci, A. (2010), August. Aquaponics vs. hydroponics: production and quality of lettuce crop. In XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010): International Symposium on 927 (887-893).

Panuvatvanich, A., Koottatep, T., & Kone, D. (2009). Influence of sand layer depth and percolate impounding regime on nitrogen transformation in vertical-flow constructed wetlands treating faecal sludge. *Water Research*, *43*(10), 2623-2630. https://doi.org/ 10.1016/j.watres.2009.03.029

Parker, R. 2002. Aquaculture science. Delmar, New York, 621 pp

Pattillo, D.A.,2017. An overview of aquaponic systems: hydroponic components. NRAC Tech. Bull. Ser., 19,1-10.

Paulus, D., Paulus, E., Nava, G. A., & Moura, C. A. (2012). Growth, water consumption and mineral composition of lettuce in hydroponic system with saline water. *Revista Ceres*, 59(1), 110-117. https://doi.org/ 10.1590/S0034-737X2012000100016

Pei, S., Dong, S., Wang, F., Tian, X. and Gao, Q. (2012). Effects of density on variation in individual growth and differentiation in endocrine response of Japanese sea cucumber (*Apostichopus japonicus Selenka*). *Aquaculture*, *356*, 398-403. https://doi.org/ 10.1016/j.aquaculture.2012.04.032

Pérez-Urrestarazu, L., Lobillo-Eguíbar, J., Fernández-Cañero, R., & Fernández-Cabanás, V. M., 2019. Suitability and optimization of FAO's small-scale aquaponics systems for joint production of lettuce (Lactuca sativa) and fish (Carassius auratus). *Aquacultural Engineering*, *85*, 129-137. https://doi.org/ 10.1016/j.aquaeng.2019.04.001

Person-Le Ruyet, J., Buchet, V., Vincent, B., Le Delliou, H. and Quemener, L. (2006). Effects of temperature on the growth of pollack (*Pollachius pollachius*) juveniles. *Aquaculture*, 251(2-4), pp.340-345. https://doi.org/ 10.1016/j .aquaculture. 2005. 06.029

Pestana, M., de Varennes, A., Abadía, J., & Faria, E. A. (2005). Differential tolerance to iron deficiency of citrus rootstocks grown in nutrient solution. *Scientia Horticulturae*, 104(1), 25-36. https://doi.org/10.1016/j.scienta.2004.07.007Get

Phippen, B., Horvath, C., Nordin, R., & Nagpal, N. (2008). Ambient water quality guidelines for iron: overview. *Ministry of Environment Province of British Columbia*.

Pinho, S.M., Molinari, D., de Mello, G.L., Fitzsimmons, K.M. and Emerenciano, M.G.C. (2017). Effluent from a biofloc technology (BFT) tilapia culture on the aquaponics production of different lettuce varieties. *Ecological Engineering*, 103, 146-153. https://doi.org/ 10.1016/j.ecoleng.2017.03.009

Prinsloo, J. F., Roets, W., Theron, J., Hoffman, L. C., & Schoonbee, H. J. (1999). Changes in some water quality conditions in recycling water using three types of biofiltration systems during the production of the sharptooth catfish Clarias gariepinus(Burchell). Part I: Relative efficiency in the breakdown of nitrogenous wastes by the different biofiltration units. *Water S. A.*, *25*(2), 239-252.

Qiang, J., Bao, J.W., He, J., Tao, Y.F., Habte‐ Tsion, H.M. and Xu, P. (2017). Growth, biochemical, fatty acid composition, and mRNA levels of hepatic enzymes in genetically improved farmed tilapia (GIFT, *Oreochromis niloticus*) (Linnaeus, 1758) at different stocking densities. Journal of Applied Ichthyology, 33(4),757-766. https://doi.org/ 10.1111/jai.13330

Rabhi, M., Barhoumi, Z., Ksouri, R., Abdelly, C., & Gharsalli, M. (2007). Interactive effects of salinity and iron deficiency in Medicago ciliaris. Comptes Rendus Biologies, 330(11), 779-788.

Radzki, W., Mañero, F. G., Algar, E., García, J. L., García-Villaraco, A., & Solano, B. R. (2013). Bacterial siderophores efficiently provide iron to iron-starved tomato plants in hydroponics culture. Antonie Van Leeuwenhoek, 104(3), 321-330. https://doi.org/ 10.1007/s10482-013-9954-9

Rakocy, J (2007). Ten Guidelines for Aquaponic Systems. Aquaponics Journal, 46, 14–17. Retrieved from http://santarosa.ifas.ufl.edu/wp-content/uploads/ 2013/06/ Aquaponics-Journal-10-Guidelines.pdf.

Rakocy, J. E. (1989). 'Tank Culture of Tilapia', Southern Regional Aquaculture Center, pp. 1–4. Available at: https://cals.arizona.edu/azaqua/extension/ Classroom/ pdffiles/ 282fs.pdf

Rakocy, J. E., & Hargreaves, J. A. (1993). Nutrient accumulation in a recirculating aquaculture system integrated with hydroponic vegetable production (Vol. 3495).

Rakocy, J., Shultz, R.C., Bailey, D.S., Thoman, E.S. (2004). Aquaponic production of tilapia and basil: comparing a batch and staggered cropping system. *Acta Horticulturae*. (ISHS) 648:63-69. https://doi.org/ 10.17660/ ActaHortic.2004.648.8

Rakocy, J.E. (2012). Aquaponics: integrating fish and plant culture. *Aquaculture production systems*, 1, pp.344-386. https://doi.org/ 10.1002/9781118250105.ch14

Rakocy, J.E., Masser, M.P., Losordo, T.M (2006). Recirculating aquaculture tank production systems: aquaponics—integrating fish and plant culture. *SRAC publication*, *454*, 1-16.

Randall, S. R., Sherman, D. M., Ragnarsdottir, K. V., & Collins, C. R. (1999). The mechanism of cadmium surface complexation on iron oxyhydroxide minerals. *Geochimica et Cosmochimica Acta*, 63(19-20), 2971-2987. https://doi.org/ 10.1016/S0016-7037(99)00263-X

Raviv, M., Krasnovsky, A., Medina, S., & Reuveni, R. (1998). Assessment of various control strategies for recirculation of greenhouse effluents under semi-arid conditions. *The Journal of Horticultural Science and Biotechnology*, 73(4), 485-491.

Resh, H. M. (2001). Hydroponic Food Production. Woodbridge Press Publishing Company. Santa Barbra, CA 93012.

Resh, H.M (2012). Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower. Boca Raton, Florida: CRC Press. Retrieved from http://howardresh.com/dr-howard-resh-hydroponic-services/hydroponic-lettuce-production-i/

Resh, H.M (2013). Hydroponic food production: a definitive guidebook for the advanced home gardener and the commercial hydroponic grower. CRC Press.

Riche, M. and Garling, D., (2003). Feeding tilapia in intensive recirculating systems.

Robinson, M. V., Alvariño, J. R., & Duran, J. M. (2011). Aquaponics: integrating fish feeding rates and ion waste production for strawberry hydroponics. *Spanish journal of agricultural research*, (2), 537-545. https://doi.org/ 10.5424/sjar/20110902-181-10

Rombolà, A. D., Brüggemann, W., Tagliavini, M., Marangoni, B., & Moog, P. R. (2000). Iron source affects iron reduction and re- greening of kiwifruit (Actinidia deliciosa) leaves. *Journal of Plant Nutrition*, *23*(11-12), 1751-1765. https://doi.org/10.1080/01904160009382139

Roosta, H. R., & Hamidpour, M (2011). Effects of foliar application of some macro- and micro-nutrients on tomato plants in aquaponic and hydroponic systems. *Scientia Horticulturae*, *129*(3), 396–402. https://doi.org/ 10.1016/j.scienta.2011.04.006

Roosta, H. R., & Hamidpour, M. (2013). Mineral nutrient content of tomato plants in aquaponic and hydroponic systems: Effect of foliar application of some macro- and micro-nutrients. *Journal of plant nutrition*, 36(13), 2070-2083. https://doi.org/ 10.1080/01904167.2013.821707

Roosta, H. R., & Mohsenian, Y. (2012). Effects of foliar spray of different Fe sources on pepper (Capsicum annum L.) plants in aquaponic system. *Scientia Horticulturae,* 146, 182-191. https://doi.org/ 10.1016/j.scienta.2012.08.018

Roosta, H. R., & Mohsenian, Y. (2015). Alleviation of alkalinity-induced Fe deficiency in eggplant (Solanum melongena L.) by foliar application of different Fe sources in recirculating system. Journal of plant nutrition, 38(11), 1768-1786. https://doi.org/ 10.1080/01904167.2015.1061542

Roosta, H. R., Jalali, M., & Ali Vakili Shahrbabaki, S. M. (2015). Effect of nano Fe-chelate, Fe-EDDHA and $FeSO_4$ on vegetative growth, physiological parameters and some nutrient elements concentrations of four varieties of lettuce (*Lactuca* *sativa* L.) in NFT system. *Journal of plant nutrition*, *38*(14), 2176-2184. https://doi.org/ 10.1080/01904167.2015.1043378

Ross, L.G. (2000). Environmental physiology and energetics. In *Tilapias: Biology and Exploitation*; McAndrew, B.J., Ed.; Springer Netherlands: Dordrecht, The Netherlands,89–128

Rouphael, Y., & Colla, G. (2005). Growth, yield, fruit quality and nutrient uptake of hydroponically cultivated zucchini squash as affected by irrigation systems and growing seasons. *Scientia Horticulturae*, *105*(2), 177-195. https://doi.org/ 10.1016/ j.scienta.2005.01.025

Rout, G. R., & Sahoo, S. (2015). Role of iron in plant growth and metabolism. *Reviews in Agricultural Science*, 3, 1-24.

Roy, R.N., Finck, A., Blair, G.J., Tandon. H.L.S. (2006) Plant nutrients and basics of plant nutrition. In: Plant nutrition for food security: a guide for integrated nutrient management. FAO Fertilizer and Plant Nutrition Bulletin, United Nations, 16: 25–42.

Ru, D., Liu, J., Hu, Z., Zou, Y., Jiang, L., Cheng, X., & Lv, Z. (2017). Improvement of aquaponic performance through micro-and macro-nutrient addition. *Environmental Science and Pollution Research*, *24*(19), 16328-16335. https://doi.org/ 10.1007/ s11356-017-9273-1

Rubio, M. I., Escrig, I., Martinez-Cortina, C., Lopez-Benet, F. J., & Sanz, A. (1994). Cadmium and nickel accumulation in rice plants. Effects on mineral nutrition and possible interactions of abscisic and gibberellic acids. *Plant growth regulation*, 14(2), 151-157. https://doi.org/10.1007/BF00025217

Ruiz, G., Jeison, D., & Chamy, R. (2003). Nitrification with high nitrite accumulation for the treatment of wastewater with high ammonia concentration. *Water research*, *37*(6), 1371-1377. https://doi.org/ 10.1016/S0043-1354(02)00475-X

Sadeghi, S., Rahnavard, A., & Ashrafi, Z. Y. (2009). The effect of plant-density and sowing-date on yield of basil (Ocimum basilicum L.) In Iran. *Journal of Agricultural Technology*, 5(2), 413-422.

Sakamoto, M. and Suzuki, T. (2015). Effect of Root-Zone Temperature on Growth and Quality of Hydroponically Grown Red Leaf Lettuce (*Lactuca sativa* L. cv. Red Wave). *American Journal of Plant Sciences*, 6, 2350-2360. https://doi.org/ 10.4236/ ajps.2015.614238.

Sala, F.C. and da Costa, C.P. (2012). Retrospective and trends of Brazilian lettuce crop. Horticultura Brasileira, 30(2), pp.187-194. http://dx.doi.org/ 10.1590/S0102-05362012000200002

Sallenave, R. (2016). Important water quality parameters in aquaponics systems. NM State University, Cooperative Extension Service, College of Agricultural, Consumer and Environmental Sciences. https://aces.nmsu.edu/pubs/_ circulars/CR680.pdf

Samaranayake P., Peiris B.D., Dssanayake S. (2012): Effect of excessive ferrous (Fe^{2+}) on growth and iron content in rice (Oryza sativa). *International Journal of Agriculture and Biology*, 14: 296–298.

Sambo, P., Nicoletto, C., Giro, A., Pii, Y., Valentinuzzi, F., Mimmo, T., ... & Terzano, R. (2019). Hydroponic Solutions for Soilless Production Systems: Issues and Opportunities in a Smart Agriculture Perspective. *Frontiers in Plant Science*, *10*, 923-923.

Samborski, S. M., Tremblay, N., and Fallon, E. (2009). Strategies to make use of plant sensors-based diagnostic information for nitrogen recommendations. *Agronomy Journal.* 101, 800–816. https://doi.org/ 10.2134/agronj2008.0162Rx

Sánchez-Guerrero, M. C., Lorenzo, P., Medrano, E., Baille, A., & Castilla, N. (2009). Effects of EC-based irrigation scheduling and CO2 enrichment on water use efficiency of a greenhouse cucumber crop. *Agricultural Water Management*, 96(3), 429-436.

Santamaria, P. (2006). Nitrate in vegetables: toxicity, content, intake and EC regulation. *Journal of the Science of Food and Agriculture*, 86(1), pp.10-17. https://doi.org/10.1002/jsfa.2351

Sarooshi, R. A., & Cresswell, G. C. (1994). Effects of hydroponic solution composition, electrical conductivity and plant spacing on yield and quality of strawberries. *Australian Journal of Experimental Agriculture*, 34(4), 529-535. https://doi.org/ 10.1071/EA9940529

Savidov, N.A., Hutchings, E. and Rakocy, J.E. (2007). Fish and plant production in a recirculating aquaponic system a new approach to sustainable agriculture in Canada. *Acta Hortic.* (Wagening.), 742,209-222. https://doi.org/10.17660/ ActaHortic. 2007. 742.28

Savvas, D., Mantzos, N., Barouchas, P. E., Tsirogiannis, I. L., Olympios, C., & Passam, H. C. (2007). Modelling salt accumulation by a bean crop grown in a closed hydroponic system in relation to water uptake. *Scientia horticulturae*, 111(4), 311-318.

Savvas, D., Pappa, V. A., Kotsiras, A., & Gizas, G. (2005). NaCl accumulation in a cucumber crop grown in a completely closed hydroponic system as influenced by NaCl concentration in irrigation water. *European Journal of Horticultural Science*, 70(5), 217.

Schepers, J. S., Blackmer, T. M., Wilhelm, W. W., & Resende, M. (1996). Transmittance and reflectance measurements of cornleaves from plants with different nitrogen and water supply. *Journal of plant physiology*, 148(5), 523-529. https://doi.org/ 10.1016/ S0176-1617(96)80071-X

Schmautz, Z., Graber, A., Jaenicke, S., Goesmann, A., Junge, R. and Smits, T.H. (2017). Microbial diversity in different compartments of an aquaponics system. *Archives of microbiology*, 199(4), 613-620.https://doi.org/10.1007/s00203-016-1334-1

Schmautz, Z., Graber, A., Mathis, A., Griessler Bulc, T., & Junge, R. (2015). Tomato production in aquaponic system: mass balance and nutrient recycling. *Aquaculture Europe*, 15.

Schmautz, Z., Loeu, F., Liebisch, F., Graber, A., Mathis, A., Griessler Bulc, T. and Junge, R. (2016). Tomato productivity and quality in aquaponics: Comparison of three hydroponic methods. *Water*, *8*(11),533. https://doi.org/10.3390/w8110533

Seawright, D.E., Stickney, R. R., & Walker, R. B (1998). Nutrient dynamics in integrated aquaculture–hydroponics systems. *Aquaculture*, 160(3–4), 215–237. https://doi.org/ 10.1016/S0044-8486(97)00168-3

Seregin, I., & Kozhevnikova, A. D. (2006). Physiological role of nickel and its toxic effects on higher plants. *Russian Journal of Plant Physiology*, *53*(2), 257-277.

Shaban, N. T., Tzvetkova, N., Cherkez, R., & Parvanova, P. (2016). Evaluation of response of lettuce (Lactuca sativa L.) to temperature and light stress. *Acta Agrobotanica*, 69(2). https://doi.org/ 10.5586/aa.1664

Shan, H., & Obbard, J. (2001). Ammonia removal from prawn aquaculture water using immobilized nitrifying bacteria. *Applied microbiology and biotechnology*, *57*(5-6), 791-798.

Shaw B.P, Sahu S.K, Mishra R.K. (2004). Heavy metal induced oxidative damage in terrestrial plants. In: Prasad MNV (ed)Heavy metal stress in plants: from biomolecules to ecosystems.Narosa Publishing House, New Delhi, India, pp 84–126

Shohreh, V., and Leila, M. (2015). Effect of some processing methods on nitrate changes in different vegetables. *Food Measure*, 9, 241-247. https://doi.org/ 10.1007/s11694-015-9229-4.

Silva, L., Escalante, E., Valdés-Lozano, D., Hernández, M. and Gasca-Leyva, E. (2017). Evaluation of a semi-intensive aquaponics system, with and without bacterial biofilter in a tropical location. *Sustainability*, 9(4), 592. https://doi.org/ 10.3390/ su9040592

Simeonidou, M., Paschos, I., Gouva, E., Kolygas, M. and Perdikaris, C. (2012). Performance of a small-scale modular aquaponic system. *Aquaculture, Aquarium, Conservation & Legislation*, 5(4), 182-188.

Singh, S., Ebeling, J., & Wheaton, F. (1999). Water quality trials in four recirculating aquacultural system configurations. *Aquacultural engineering*, *20*(2), 75-84. https://doi.org/ 10.1016/S0144-8609(99)00003-5

Somerville, C., Cohen, M., Pantanella, E., Stankus, A., Lovatelli, A. (2014). Small-scale aquaponic food production. Integrated fish and plant farming. FAO Fisheries and Aquaculture Technical Paper No. 589. FAO, Rome (262 pp).

Sonneveld, C., Baas, R., Nijssen, H. M. C., & De Hoog, J. (1999). Salt tolerance of flower crops grown in soilless culture. *Journal of Plant Nutrition*, *22*(6), 1033-1048. https://doi.org/10.1080/01904169909365692

Sonneveld, C. (1982). Items for application of macro-elements in soilless cultures. *Acta Hortic*. 126, 187-196.https://doi.org/10.17660/ActaHortic.1982.126.23

Sorphea, S., Lundh, T., Preston, T.R. and Borin, K. (2010). Effect of stocking densities and feed supplements on the growth performance of tilapia (Oreochromis spp.) raised in ponds and in the paddy field. *Livestock Research for Rural Development*, *22*(11).

Spiller, S. and Terry, N (1980). Limiting factors in photosynthesis: II. Iron stress diminishes photochemical capacity by reducing the number of photosynthetic units. *Plant Physiology*, 65(1), pp.121-125. https://doi.org/ 10.1104/pp.65.1.121

Sreejariya, P., Raynaud, T., Dabbadie, L. and Yakupitiyage, A. (2016). Effect of water recirculation duration and shading on lettuce (Lactuca sativa) growth and leaf nitrate content in a commercial aquaponic system. *Turkish Journal of Fisheries and Aquatic Sciences*, 16 (2): 311-319. http://dx.doi.org/ 10.4194/1303-2712-v16_2_11

Sreekanth, T. V. M., Nagajyothi, P. C., Lee, K. D., & Prasad, T. N. V. K. V. (2013). Occurrence, physiological responses and toxicity of nickel in plants. *International Journal of Environmental Science and Technology*, *10*(5), 1129-1140.

Stagnari, F., Galieni, A., & Pisante, M. (2015). Shading and nitrogen management affect quality, safety and yield of greenhouse-grown leaf lettuce. *Scientia Horticulturae*, 192, 70-79.

Stewart, N. T., Boardman, G. D., & Helfrich, L. A. (2006). Characterization of nutrient leaching rates from settled rainbow trout (Oncorhynchus mykiss) sludge. *Aquacultural engineering*, *35*(2), 191-198.

Su, M. H., Azwar, E., Ya, Y., Sonne, C., Yek, P. N. Y., Liew, R. K., ... & Lam, S. S. (2020). Simultaneous removal of toxic ammonia and lettuce cultivation in aquaponic system using microwave pyrolysis biochar. *Journal of Hazardous Materials*, 122610.

Suhl, J., Dannehl, D., Baganz, D., Schmidt, U., & Kloas, W. (2018a). An innovative suction filter device reduces nitrogen loss in double recirculating aquaponic systems. *Aquacultural Engineering*, *82*, 63-72. https://doi.org/10.1016/j. aquaeng.2018. 06. 008.

Suhl, J., Dannehl, D., Kloas, W., Baganz, D., Jobs, S., Scheibe, G. and Schmidt, U. (2016). Advanced aquaponics: Evaluation of intensive tomato production in aquaponics vs. conventional hydroponics. *Agricultural Water Management*, 178,.335-344. https://doi.org/ 10.1016/j.agwat.2016.10.013

Suhl, J., Dannehl, D., Zechmeister, L., Baganz, D., Kloas, W., Lehmann, B., Scheibe, G. and Schmidt, U. (2018b). Prospects and challenges of double recirculating aquaponic systems (DRAPS) for intensive plant production. *Acta horticulturae*. 1227, 449-456. https://doi.org/ 10.17660/ActaHortic.2018.1227.56.

Summerfelt, S. T., Zühlke, A., Kolarevic, J., Reiten, B. K. M., Selset, R., Gutierrez, X., & Terjesen, B. F. (2015). Effects of alkalinity on ammonia removal, carbon dioxide stripping, and system pH in semi-commercial scale water recirculating aquaculture systems operated with moving bed bioreactors. *Aquacultural Engineering*, 65, 46- 54. https://doi.org/ 10.1016/ j.aquaeng. 2014.11.002

Summerfelt, S.T. and Sharrer, M.J. (2004). Design implication of carbon dioxide production within biofilters contained in recirculating salmonid culture systems. *Aquacultural Engineering*, *32*(1), 171-182. https://doi.org/ 10.1016/j.aquaeng.2004.03.006

Sveier, H., Raae, A.J. and Lied, E.(2000). Growth and protein turnover in Atlantic salmon (Salmo salar L.); the effect of dietary protein level and protein particle size. *Aquaculture*, 185(1-2), pp.101-120. https://doi.org/ 10.1016/S0044-8486(99)00344-0

Tabatabaei, S. J. (2009). Supplements of nickel affect yield, quality, and nitrogen metabolism when urea or nitrate is the sole nitrogen source for cucumber. *Journal of plant nutrition*, *32*(5), 713-724.https://doi.org/ 10.1080/01904160902787834

Tan, L.P., He, J. and Lee, S.K. (2002). Effects of root-zone temperature on the root development and nutrient uptake of Lactuca sativa L."Panama" grown in an aeroponic system in the tropics. *Journal of Plant Nutrition*, 25(2), 297-314.

Tan, X. W., Ikeda, H., & Oda, M. (2000a). Effects of nickel concentration in the nutrient solution on the nitrogen assimilation and growth of tomato seedlings in hydroponic culture supplied with urea or nitrate as the sole nitrogen source. *Scientia Horticulturae*, *84*(3-4), 265-273. https://doi.org/ 10.1016/S0304-4238(99)00107-7

Tan, X. W., Ikeda, H., & Oda, M. (2000b). The absorption, translocation, and assimilation of urea, nitrate or ammonium in tomato plants at different plant growth stages in hydroponic culture. *Scientia Horticulturae*, *84*(3-4), 275-283. https://doi.org/ 10.1016/ 0304-4238(99)00108-9

Tei, F., Scaife, A., & Aikman, D. P. (1996). Growth of lettuce, onion, and red beet. 1. Growth analysis, light interception, and radiation use efficiency. *Annals of Botany*, 78(5), 633-643. https://doi.org/ 10.1006/anbo.1996.0171

Temp. G.A. (1991). Nickel in plants and its toxicity: Ustoichivost'k tyazhelym metallam dikorastushchikh vidov (Resistance of wild species to heavy metals). In: Alekseeva-Popova NV (ed). Lenuprizdat, Leningrad. pp. 139–146

Thomas, P. and M. Michael. (1999). Tilapia Life History and Biology. Southern Regional Aquaculture Center, Stone Ville, Ms. Publication No. 283

Thorarensen, H., & Farrell, A. P. (2011). The biological requirements for post-smolt Atlantic salmon in closed-containment systems. *Aquaculture*, 312(1-4), 1-14. https://doi.org/10.1016/j.aquaculture.2010.11.043

Timmons, M. B., Ebeling, J. M., & Center, N. R. A. (2007). Recirculating aquaculture: Cayuga Aqua Ventures.

Timmons, M.B., and Ebeling, J, M (2013). Recirculating Aquaculture (3rd ed.). Reading, United Kingdom: Ithaca Publishing Company. Retrieved from https://www.amazon.in/Recirculating-Aquaculture-3rd-Michael-Timmons/dp/0971264651

Timmons, M.B., Ebeling, J.M., Wheaton, F.W., Summerfelt, S.T., Vinci, B.J. (2002). Recirculating Aquaculture Systems, second ed. Cayuga Aqua Ventures, Northeastern Regional Aquaculture Center Publication 01-002

Trang, N. T. D., & Brix, H. (2012). Use of planted biofilters in integrated recirculating aquaculture- hydroponics systems in the Mekong Delta, Vietnam. *Aquaculture Research*, 45(3), 460-469. https://doi.org/ 10.1111/j.1365-2109.2012.03247.

Tremblay, N., Wang, Z., & Cerovic, Z. G. (2012). Sensing crop nitrogen status with fluorescence indicators. A review. *Agronomy for Sustainable Development*, 32, 451–464.

Terry, N. (1980). Limiting factors in photosynthesis: I. Use of iron stress to control photochemical capacity in vivo. Plant Physiology, 65(1), 114-120.

Tyksiński, W., & Komosa, A. (2008). After effect of iron chelates on the yielding and iron content in greenhouse lettuce. *Acta Scientiarum Polonorum. Hortorum Cultus (Poland)*, 7(2), 3-10.

Tryggvason, Á. Þ. (2016). A Systematic View on a Recirculating Aquaculture System: Causality Relation Between Variables (Doctoral dissertation, University of Iceland).

Tyson, R. V., Simonne, E. H., Davis, M., Lamb, E. M., White, J. M., & Treadwell, D. D. (2007). Effect of nutrient solution, nitrate-nitrogen concentration, and pH on nitrification rate in perlite medium. *Journal of plant nutrition*, *30*(6), 901-913. https://doi.org/ 10.1080/15226510701375101

Tyson, R.V., Treadwell, D.D. and Simonne, E.H. (2011). Opportunities and challenges to sustainability in aquaponic systems. *HortTechnology*, 21(1),6-13. https://doi.org/ 10.21273/ HORTTECH.21.1.6

UN (United Nations). (2014) The United Nations World Water Development Report 3 water in a changing world, Book 1. UNESCO Publishing/Earthscan, Paris

Vadas, T. M., Zhang, X., Curran, A. M., & Ahner, B. A. (2007). Fate of DTPA, EDTA, and EDDS in hydroponic media and effects on plant mineral nutrition. *Journal of plant nutrition*, 30(8), 1229-1246. https://doi.org/ 10.1080/01904160701555119

Van der Werf, A., Enserink, C. T., Smit, A. L., & Booij, R. (1996). Components of relative growth rate and nitrogen productivity of Brussels sprouts and leeks grown at two widely differing light intensities. *NJAS wageningen journal of life sciences*, 44(1), 21-29. https://doi.org/ 10.18174/njas.v44i1.555

Van Rijn, J. (2013). Waste treatment in recirculating aquaculture systems. *Aquacultural Engineering*, 53, 49-56. https://doi.org/10.1016/j.aquaeng.2012.11.010

Valenzano, V., Parente, A., Serio, F., & Santamaria, P. (2008). Effect of growing system and cultivar on yield and water-use efficiency of greenhouse-grown tomato. *The Journal of Horticultural Science and Biotechnology*, 83(1), 71-75.

Villarroel, M., Alvariño, J. M. R., & Duran, J. M. (2011). Aquaponics: integrating fish feeding rates and ion waste production for strawberry hydroponics. *Spanish Journal of Agricultural Research*, 9(2), 537-545.

Velichkova, K., Sirakov, I., Stoyanova, S. and Staykov, Y. (2019). Cultivation of lettuce (Lactuca sativa L.) and rainbow trout (Oncorhynchus mykiss W.) in the aquaponic recirculation system. *Journal of Central European Agriculture*, *20*(3),.967-973. https://doi.org/ 10.5513/JCEA01/20.3.2223

Vempati, R.K. and Loeppert, R.H. (1988). Chemistry and mineralogy of Fe- containing oxides and layer silicates in relation to plant available iron. *Journal of plant nutrition*, 11(6-11), pp.1557-1574. https://doi.org/ 10.1080/01904168809363910

Vigani, G. (2012). Discovering the role of mitochondria in the iron deficiency-induced metabolic responses of plants. *Journal of plant physiology*, 169(1), 1-11. https://doi.org/ 10.1016/j.jplph.2011.09.008

Wahyuningsih, S., Effendi, H. and Wardiatno, Y. (2015). Nitrogen removal of aquaculture wastewater in aquaponic recirculation system. *Aquaculture, Aquarium, Conservation & Legislation*, 8(4),491-499.

Wang, C. Y., Chang, C. Y., Chien, Y. H., & Lai, H. T. (2016). The performance of coupling membrane filtration in recirculating aquaponic system for tilapia culture. *International Biodeterioration & Biodegradation*, 107, 21-30. https://doi.org/ 10. 1016/j.ibiod.2015.10.016

Wang, M., & Lu, M. (2016). Tilapia polyculture: a global review. *Aquaculture research*, *47*(8), 2363-2374.

White, P. J. (2012). Ion uptake mechanisms of individual cells and roots: short-distance transport. In Marschner's mineral nutrition of higher plants (pp. 7-47). Academic Press

Windsor G, Adams P (1987). Diagnosis of mineral disorders in plants. Glasshouse Crops, Vol 3. Her Majesty's Stationery Office, London, UK

Witte, C.P., 2011. Urea metabolism in plants. *Plant Science*, *180*(3), pp.431-438. https://doi.org/ 10.1016/j.plantsci.2010.11.010

Wojciechowska, E., Golcz, A., Kozik, E., & Mieloszyk, E. (2019). Effect of differentiated iron nutrition on the content of macronutrients in leaves of lettuce (Lactuca sativa L. var. capitata L.) cultivated in peat substrate. *Journal of Elementology*, 24(1). https://doi.org/ 10.5601/jelem.2018.23.1.1623

Wongkiew, S., Hu, Z., Chandran, K., Lee, J.W. and Khanal,S.K. ((2017a). Nitrogen transformations in aquaponic systems: A review. *Aquacultural Engineering*, 76, 9-19. https://doi.org/ 10.1016/j.aquaeng.2017.01.004

Wongkiew, S., Popp, B.N., Kim, H.J. and Khanal, S.K. (2017b). Fate of nitrogen in floating-raft aquaponic systems using natural abundance nitrogen isotopic compositions. *International Biodeterioration & Biodegradation*, 125, pp.24-32. https://doi.org/ 10.1016/j.ibiod.2017.08.006

World Bank, World Development Indicators. (2020). Water In Agriculture. https://www.worldbank.org/en/topic/water-in-agriculture#1. https://population.un.org/ wpp/ Publications/Files/WPP2019_Highlights.pdf

Wortman, S. E. (2015). Crop physiological response to nutrient solution electrical conductivity and pH in an ebb-and-flow hydroponic system. *Scientia Horticulturae*, 194, 34-42. https://doi.org/ 10.1016/j.scienta.2015.07.045

Xia, B., Ren, Y., Wang, J., Sun, Y. and Zhang, Z (2017). Effects of feeding frequency and density on growth, energy budget and physiological performance of sea cucumber Apostichopus japonicus (Selenka). *Aquaculture*, *466*, 26-32. https://doi.org/ 10.1016/j.aquaculture.2016.09.039

Xu, J., Liu, Y., Cui, S., & Miao, X. (2006). Behavioral responses of tilapia (Oreochromis niloticus) to acute fluctuations in dissolved oxygen levels as monitored by computer vision. *Aquacultural Engineering*, 35(3), 207-217.

Xue, W. T., I. Hideo, and O. Masyuki. (2000). Effects of Ni concentration in the nutrient solution on the N assimilation and growth of tomato seedlings in hydroponic culture supplied with urea or nitrate as the sole N source. Scietia Horticulturae 84: 265–273.

Yan, Q., Duan, Z., Mao, J., Li, X. and Dong, F. (2012). Effects of root-zone temperature and N, P, and K supplies on nutrient uptake of cucumber (Cucumis sativus L.) seedlings in hydroponics. *Soil science and plant nutrition*, 58(6), pp.707-717.

Yang, T., & Kim, H. J. (2020). Characterizing Nutrient Composition and Concentration in Tomato-, Basil-, and Lettuce-Based Aquaponic and Hydroponic Systems. *Water*, 12(5), 1259. https://doi.org/10.3390/w12051259

Yavuzcan Yildiz, H., Robaina, L., Pirhonen, J., Mente, E., Domínguez, D. and Parisi, G. (2017). Fish welfare in aquaponic systems: its relation to water quality with an emphasis on feed and faeces—a review. *Water*, 9(1), p.13. https://doi.org/ 10.3390/w9010013

Yep, B., & Zheng, Y. (2019). Aquaponic trends and challenges–A review. *Journal of Cleaner Production*, 228, 1586-1599. https://doi.org/10.1016/ j.jclepro.2019.04.290

Yruela, I. (2013). Transition metals in plant photosynthesis. *Metallomics*, 5(9), 1090-1109.

Yusuf, M., Fariduddin, Q., Hayat, S., & Ahmad, A. (2011). Nickel: an overview of uptake, essentiality and toxicity in plants. *Bulletin of Environmental Contamination and Toxicology*, 86(1), 1-17. https://doi.org/10.1007/s00128-010-0171-1

Zaharieva, T. B., Gogorcena, Y., & Abadıa, J. (2004). Dynamics of metabolic responses to iron deficiency in sugar beet roots. *Plant Science*, 166(4), 1045-1050.

Zaki, M.A., Alabssawy, A.N., Nour, A.E.A.M., El Basuini, M.F., Dawood, M.A., Alkahtani, S. and Abdel-Daim, M.M (2020). The impact of stocking density and dietary carbon sources on the growth, oxidative status and stress markers of Nile tilapia (Oreochromis niloticus) reared under biofloc conditions. *Aquaculture Reports*, 16, p.100282. https://doi.org/ 10.1016/j.aqrep.2020.100282

Zekki, H., Gauthier, L., & Gosselin, A. (1996). Growth, productivity, and mineral composition of hydroponically cultivated greenhouse tomatoes, with or without nutrient solution recycling. *Journal of the American Society for Horticultural Science*, 121(6), 1082-1088.

Zhao, Z., Dong, S. and Xu, Q (2018). Respiratory response of grass carp Ctenopharyngodon idellus to dissolved oxygen changes at three acclimation temperatures. *Fish physiology and biochemistry*, 44(1), pp.63-71. https://doi.org/ 10.1007/s10695-017-0413-9

Zhu, Z., Gerendas, J., & Sattelmacher, B. (1997). Effects of replacing of nitrate with urea or chloride on the growth and nitrate accumulation in pak-choi in the hydroponics. In Plant nutrition for sustainable food production and environment (pp. 963-964). Springer, Dordrecht.

Zocchi, G., De Nisi, P., Dell'Orto, M., Espen, L., & Gallina, P. M. (2007). Iron deficiency differently affects metabolic responses in soybean roots. *Journal of experimental botany*, 58(5), 993-1000. https://doi.org/10.1093/jxb/erl259

Zou, Y., Hu, Z., Zhang, J., Xie, H., Guimbaud, C., & Fang, Y. (2016). Effects of pH on nitrogen transformations in media-based aquaponics. *Bioresource Technology*, *210*, 81–87. https://doi.org/ 10.1016/j.biortech.2015.12.079

Zuo Y., Zhang F. (2011): Soil and crop management strategies to prevent iron deficiency in crops. *Plant and Soil*, 339: 83–95.

BIODATA OF STUDENT

Abdel Razzaq Mohammad Saeed Altawaha was born on 10th August 1984 in Irbid, Hashemite Kingdom of Jordan. He received the bachelor's degree in plant production from Jordan University of Science and Technology, Faculty of Agriculture, Department of Plant Production, Irbid, Jordan, in 2007. Also, he earned his Master of Science in Plant Production\ Horticulture from the Faculty of Agriculture from the Jordan University of Science and Technology, Irbid, Jordan, in 2012. He works as research assistants after MSc focused on Hydroponics production forage crops, medicinal and aromatic herb plants (thyme, sage, mint), vegetables like a cherry tomato, pepper, cucumber in Jordan University of Science and Technology. He is currently a PhD student in the Universiti Putra Malaysia (UPM), Selangor, Malaysia. His research focused on the Decoupled Recirculation Aquaponics System in a small-scale for lettuce production.

LIST OF PUBLICATIONS

Edaroyati, M. P., Aishah, H. S., & Al-Tawaha, A. M. (2017). Requirements for inserting intercropping in aquaponics system for sustainability in agricultural production system. Agronomy Research, 15(5), 2048-2067 (Published).

Al Tawaha, A. R., Megat Wahab, P. E., binti Jaafar, H., Kee Zuan, A. T., Hassan, M. Z. (2020). Effects of Fish Stocking Density on Water Quality, Growth Performance of Tilapia (*Oreochromis niloticus*) and Yield of Butterhead Lettuce (*Lactuca sativa*) Grown in Decoupled Recirculation Aquaponic Systems. Journal of Ecological Engineering, 2021; 22(1):8–19. https://doi.org/10.12911/22998993/128692 (Published).

Abdel Razzaq Al Tawaha, Puteri Edaroyati Megat Wahab, Hawa binti Jaafar, Ali Tan Kee Zuan, Mohd Zafri Hassan, Abdel Rahman M. Al-Tawaha. (2021). Yield and nutrients leaf content of butterhead lettuce (Lactuca sativa) in response to fish nutrient solution in a small scale of aquaponic systems. Ecological Engineering & Environmental Technology (Accepted).

UNIVERSITI PUTRA MALAYSIA

STATUS CONFIRMATION FOR THESIS / PROJECT REPORT AND COPYRIGHT

ACADEMIC SESSION : First Semester 2021/2022

TITLE OF THESIS / PROJECT REPORT :

INCREASED BIOMASS PRODUCTION OF LETTUCE (*Lactuca sativa* L.) THROUGH NUTRIENT MANAGEMENT IN A RED HYBRID TILAPIA (*Oreochromis spp.*) BASED ON DECOUPLED RECIRCULATION AQUAPONICS SYSTEM

NAME OF STUDENT: ABDEL RAZZAQ MOHAMMAD SAEED ALTAWAHA

I acknowledge that the copyright and other intellectual property in the thesis/project report belonged to Universiti Putra Malaysia and I agree to allow this thesis/project report to be placed at the library under the following terms:

1. This thesis/project report is the property of Universiti Putra Malaysia.
2. The library of Universiti Putra Malaysia has the right to make copies for educational purposes only.
3. The library of Universiti Putra Malaysia is allowed to make copies of this thesis for academic exchange.

I declare that this thesis is classified as :

*Please tick (V)

☐	**CONFIDENTIAL**	(Contain confidential information under Official Secret Act 1972).
☐	**RESTRICTED**	(Contains restricted information as specified by the organization/institution where research was done).
☐	**OPEN ACCESS**	I agree that my thesis/project report to be published as hard copy or online open access.

This thesis is submitted for :

☐	**PATENT**	Embargo from_____________ until _____________ (date) (date)

Approved by:

(Signature of Student) New IC No/ Passport No.:	(Signature of Chairman of Supervisory Committee) Name:
Date :	Date :

[Note : If the thesis is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization/institution with period and reasons for confidentially or restricted.]