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ORGANIC-BASED NUTRIENT SOLUTIONS FOR SUSTAINABLE VEGETABLE PRODUCTION IN A ZERO -RUNOFF SOILLESS GROWING SYSTEM

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Department of Integrative Agriculture

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This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Science in Horticulture

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Cover: Dutch Bucket hydroponic system integrated with zero-runoff auto-pot technology.

(Photo: By Maitha Salem Almheiri)

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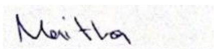
Declaration of Original Work

I, Maitha Salem Almheiri, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Organic-Based Nutrient Solutions for Sustainable Vegetable Production in A Zero-Runoff Soilless Growing System*", hereby, solemnly declare that this is the original research work done by me under the supervision of Dr. Zienab Ahmed, in the College of Agriculture and Veterinary Medicine at UAEU. This work has not previously formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

Student's Signature: 

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Abstract

As the adoption of soilless production systems escalates to meet the rising demand for safe and healthy fresh produce, the growing environmental awareness and consumer’s preference for sustainable production systems are stimulating the reduction of synthetic inputs. A greenhouse study using an auto-pot zero-runoff hydroponic system and lettuce (*Lactuca sativa* L.) as a model vegetable crop was conducted to evaluate the potential of substituting synthetic fertilizer Nutrient Solutions (NS) with organic-based NS. The use of organic NS resulted in lettuce plants with fewer leaves and a smaller leaf area, plant height, stem diameter, and fresh biomass compared to those grown with inorganic fertilizer. Among the organic NS used, NS B from fish farm waste (159.8 g) and E from plant sources (157.9 g) ensured crop yield performance slightly lower than the inorganic fertilizer NS (175.1 g), but higher than the other humic acid based-organic NS C and D. In organic lettuce, the amounts of chlorophyll and carotene were higher compared to regular lettuce. Chlorophyll levels were 0.81 and 0.93 mg/g, while carotene levels were 0.23 and 0.26 mg/g in organic lettuce. In regular lettuce, the levels were lower, with chlorophyll at 0.95 mg/g and carotene at 0.17 mg/g. Furthermore, plants grown organically in NS C and D had greater phenolic levels (3.36 and 3.22 g/100 g, respectively) as compared to those nourished with inorganic fertilizer (2.28 g/100 g). All organically grown lettuce plants had lower levels of Ca, K, and Mg, and higher P compared to the control. Moreover, all organic NS resulted in lower leaf nitrate levels (ranging from 3.2 to 8.7 mg/kg) compared to the inorganic NS (259.8 mg/kg) based on dry weight. Our findings suggest that organic liquid fertilizers may enable the sustainable production of safe, nutritious, and healthy vegetable crops. However, further study is required to improve and overcome the limitations of such systems.

Keywords: Organic fertilizer, animal source, plant source, organic hydroponic, lettuce.

Title and Abstract (in Arabic)

المغذيات العضوية: طريقة مستدامة لإنتاج الخضروات في نظام الزراعة المائية بدون تربة

الملخص

مع تصاعد اعتماد أنظمة الإنتاج بدون تربة لتلبية الطلب المتزايد على المنتجات الطازجة الآمنة والصحية، فإن الوعي البيئي المتزايد وتفضيل المستهلك لأنظمة الإنتاج المستدامة يحفز على تقليل المدخلات الاصطناعية فى انظمة الزراعة. لذلك تم إجراء دراسة داخل البيوت المحمية باستخدام نظام الزراعة المائية المغلقة لزراعة نباتات الخس (*Lactuca sativa* L.) كنموذج ممثل للخضروات لتقييم إمكانية استبدال محاليل مغذيات الأسمدة الكيميائية بمحاليل من مصادر عضوية مختلفة. أظهرت النتائج ان استخدام المحاليل العضوية ادت إلى انتاج نباتات خس بأوراق أقل ومساحة ورقية أصغر الى حد ما مقارنة بتلك المزروعة باستخدام الأسمدة غير العضوية. من بين الأسمدة العضوية المستخدمة،المحلول B من مخلفات المزارع السمكية (159.8 جم) والمحلول E من المصادر النباتية (157.9 جم) حيث اعطت نتائج أقل قليلاً من الأسمدة غير العضوية (175.1 جم)، ولكنها أعلى من غيرها من الأسمدة العضوية من مصادر اخرى مثل حمض الهيوميكمحلول C ومحلول D، ومع ذلك كانت مستويات الكلوروفيل الكلي (0.81 و 0.93 ملغم / جم على التوالي) والكاروتين (0.23 و 0.26 ملغم / جم، على التوالي) أعلى في الخس المزروع عضويًا مقارنة بالكنترول (المحلول المغذى الكيميائي (0.95 0.17 ملغم / جم). علاوة على ذلك، فإن النباتات المزروعة عضويًا في المحلول C وD لديها مستويات عاللية من المركبات الفينولية (3.36 و3.22 جم/100 جم، على التوالي) مقارنة بتلك التي تتغذى على الأسمدة غير العضوية (2.28 جم/100 جم). تحتوي جميع نباتات الخس المزروعة عضويًا على مستويات أقل من الكالسيوم والبوتاسيوم والمغنيسيوم، وأعلى من الفسفور مقارنةً بالكنترول. علاوة على ذلك، أدت جميع المحاليل العضوية إلى انخفاض مستويات النترات فى الأوراق حيث كانت تتراوح من 3.2 إلى 8.7 ملجم / كجم مقارنة بالـ المحاليل المغذية الغير عضوية (259.8 ملجم / كجم). تشير النتائج التي توصلت إليها الدراسة الحالية إلى أن الأسمدة السائلة العضوية قد تمكن من الإنتاج المستدام لمحاصيل الخضروات بطريقة امنة وتكون هذه النباتات مغذية وصحية اكثر. ومع ذلك، هناك حاجة إلى المزيد من الدراسة للتحسين والتغلب على التحديات التى واجهت هذة الانظمة لانتاج الخضروات بطريقة مثلى ومستدامة.

مفاهيم البحث الرئيسية: سماد عضوي، مصدر حيواني، مصدر نباتي الزراعة المائية العضوية، خس.

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Dedication

To my beloved parents and family

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List of Abbreviations

ABTS	3-Ethylbenzothiazoline-6-Sulfonic Acid
ANOVA	Analysis of Variance
C	Carbon
Ca	Calcium
CHP	Combined Heat and Power
Cu	Copper
DAP	Days After Planting
DPPH	1,1-Diphenyl-2-Picrylhydrazyl
DW	Dry Weight
EC	Electrical Conductivity
FDFO	Fertilizer Drawn Forward Osmosis
FW	Fresh Weight
GAE	Gallic Acid Equivalents
IC	Ion Chromatography Instrument
LED	Light Emitting Diode
LSD	Least Significant Differences
NO_3	Nitrate
NH_4	Ammonium Phosphate
NFT	Nutrient Film Technique
NS	Nutrient Solutions
pH	Potential of Hydrogen
VFS	Vertical Farming Systems
UAE	United Arab Emirates
US	United States

Chapter 1: Introduction

1.1 Overview

Climate change, limited arable land, and water scarcity are among the primary challenges constraining current conventional agriculture systems (Pomoni et al., 2023). Agricultural land in many countries has been converted for residential and industrial use, while arid regions have hindered agricultural production in others. In numerous countries, available agricultural land has been repurposed for residential and industrial developments, whereas arid regions have impeded agricultural production in others (Kurowska et al., 2020; Sambo et al., 2019). Concurrently, the demand for high-quality fresh food is increasing with the growing global population. Consequently, scalable, and geographically adaptable alternative agricultural systems are necessary to preserve food security without compromising environmental sustainability (Pomoni et al., 2023).

Soilless growing systems allow the cultivation of plants without soil. These systems use limited water and nutrient resources efficiently, and thus represent one of the most promising solutions for producing high-quality crops in arid regions and areas with limited availability of fertile agricultural land (Di Gioia et al., 2018; Putra & Yuliando, 2015). These systems employ various substrates, including organic and inorganic growing media (Gruda, 2019; Poudel et al., 2023), as well as water culture systems with Nutrient Solutions (NS) prepared from water-soluble fertilizers. As a reliable technology, soilless systems enable the consistent production of a variety of nutritious crops on both large and small scales in the presence of limiting environmental conditions (Dubey & Nain, 2020; Singh et al., 2019). They have the potential to improve the availability of local fresh produce (Michel-Villarreal et al., 2020) and enhance global food and nutrition security amid climate change (Banerjee et al., 2022; Di Gioia et al., 2021).

Although soilless production systems are highly efficient, they typically depend on synthetic chemical fertilizers. With increasing environmental awareness and concerns about the potential human health risks associated with excessive chemical fertilizer use consumer demand for organic production and consumption is increasing (Bergstrand, 2022; Di Gioia & Rosskopf, 2021; Moncada et al., 2021). In recent years, there has been significant debate over whether hydroponic farming qualifies as a certified organic farming method in the United States (U.S.) (Dorais & Cull, 2017), or whether it falls outside the scope of the EU's organic production directive, except for products intended to be sold as potted plants (Schmidt, 2019). Employing organic fertilizers can serve as a nutrient-recycling mechanism while reducing the reliance on synthetic mineral fertilizers, particularly in closed-loop hydroponic systems, thereby enhancing sustainability compared to conventional hydroponics.

The continuous demand for organic products has spurred increasing interest in developing organic soilless cultivation systems, or bioponic systems, which employ solely organic fertilizer sources (Bergstrand, 2022; Di Gioia & Rosskopf, 2021; Dorais & Cull, 2017; Moncada et al., 2021; Schmidt, 2019; L. Wang et al., 2019). Previous studies have shown that incorporating organic materials into the substrate or using them as liquid fertilizers enhances the efficiency of hydroponic systems. This results in leafy vegetables and fruit of better quality, characterized by higher levels of antioxidant compounds and lower nitrate levels (Ahmed, Alnuaimi, et al., 2021; Ahmed, Askri, et al., 2021; Bergstrand et al., 2020). Furthermore, macroalgae can serve as biodegradable bio stimulants, which may help replenish potassium minerals to some extent in hydroponic systems (Souza et al., 2019). Recent research has also highlighted a limitation: the nutrient content in organic hydroponics (Ahmed, Alnuaimi, et al., 2021).

Identifying reliable organic fertilizer sources that can provide all the required nutrients throughout the crop growth cycle is critical. The choice of organic fertilizer can significantly impact crop yield and quality (Cometti et al., 2013; Williams & Nelson, 2016). For instance, Brassica rapa L. var. chinensis plants grown hydroponically with a diluted liquid biodigestates organic solution exhibited a 47% reduction in yield (fresh weight) compared to those fertilized with an inorganic solution (Albadwawi et al., 2022). The availability of specific nutrients can be impeded by the pH and EC of the NS, as well as by a lack of microorganisms essential for the mineralization of organic matter and the release of essential nutrients in soluble inorganic forms that plants can absorb (Di Gioia & Rosskopf, 2021; Miyazawa et al., 2006; L. Wang et al., 2019). This complexity makes bioponic growing systems more challenging than conventional soilless growing systems.

Lettuce (*Lactuca sativa* L.) a highly popular leafy vegetable, thrives in soilless systems and is increasingly valued by consumers for its rich nutritional profile (Williams & Nelson, 2016). It is particularly well-suited to hydroponic cultivation, and easily adapted to this method. As a model vegetable crop, lettuce features shallow roots and a relatively short growing season, with high productivity in cyclical cultivation compared to soil-based methods (Cometti et al., 2013).

Given the increasing demand for organic vegetable products, there is a growing interest in the agriculture industry to develop more efficient bioponic systems that employ organic-based fertilizer sources (Miyazawa et al., 2006). Therefore, the primary objective of this study was to assess the efficacy of liquid organic fertilizers derived from various organic residues such as fish farm waste, plant waste, and humic-based materials, on the growth, yield, and quality of lettuce plants in a zero-runoff auto-pot soilless system, compared to a conventional NS prepared with inorganic fertilizers.

1.2 Statement of the Problem

Traditional farming can have several disadvantages. For example, weeding, diseases, and loss of fertile land after harvest are a few drawbacks of traditional farming. These disadvantages can be overcome with a soilless farming method known as hydroponics that uses only water and nutrients without any use of the soil. The traditional hydroponics system uses the same water in a circulatory motion with only one water tank. This method of utilizing a restricted water supply contributes to a reduction in overall water usage by approximately 60% when compared to traditional farming practices. This limited water usage approach reduces overall water consumption by roughly 60% when compared to traditional farming methods (Gartmann et al., 2023; Szekely & Jijakli, 2022). This circulatory motion of water and nutrients form a nutrient film which is one of the most famous hydroponic setups is Nutrient Film Technique (NFT) (Bharti et al., 2019).

Traditional hydroponic system has its own limitations such as it cannot log or fetch live sensing parameters (Rajaseger et al., 2023). These limitations can be addressed through the integration of IoT-based monitoring and control systems in hydroponic cultivation, allowing for efficient logging and fetching of live sensing parameters

(Gashgari et al., 2018; Rajaseger et al., 2023). Hydroponics stands out as a premier solution for cultivating plants on limited land, offering unparalleled efficiency and productivity (Gashgari et al., 2018; Rajaseger et al., 2023). This innovative technique enables farmers to optimize space utilization by requiring minimal land while providing a controlled environment for plant growth (Gashgari et al., 2018; Rajaseger et al., 2023). The integration of microprocessors for nutrient control in hydroponic systems ensures precise nutrient delivery, enhancing plant health and overall productivity (Gashgari et al., 2018). These systems can be tailored to support vertical or horizontal farming based on user preferences, showcasing their versatility and adaptability to diverse agricultural needs. Despite the initial installation costs, which can be recovered within 6 to 10 months post-planting, hydroponics proves to be a cost-effective and sustainable method for soilless farming (Rajaseger et al., 2023). Furthermore, the germination of seeds without soil underscores the potential for complete soilless farming, making hydroponics an ideal alternative for maximizing plant growth in constrained spaces (Gashgari et al., 2018; Rajaseger et al., 2023).

In recent years, there has been a growing body of research focusing on the utilization of organic fertilizers in hydroponics as an alternative to chemical fertilizers (Gashgari et al., 2018; Rajaseger et al., 2023; Tikasz, 2019). While chemical fertilizers are commonly used in hydroponic systems, concerns have been raised regarding the potential risks associated with high concentrations of these fertilizers, leading to the accumulation of toxic chemicals in vegetables (Phibunwatthanawong & Riddech, 2019; Rajaseger et al., 2023; Tikasz, 2019). Notably, the accumulation of nitrates, such as NH_{4+} and NO_{3-}, from chemical fertilizers poses risks to both consumer health and plant growth. Nitrates are essential nutrients for plant growth and are part of the natural nitrogen cycle; however, prolonged use of chemical fertilizers can lead to excessive nitrate accumulation in vegetable leaves, particularly in crops like lettuce. This accumulation can have detrimental effects on both human health and plant development (Gashgari et al., 2018; Phibunwatthanawong & Riddech, 2019; Rajaseger et al., 2023; Tikasz, 2019).

Given these concerns, the use of liquid organic fertilizers has emerged as an attractive solution for hydroponic cultivation, offering a safer and more sustainable alternative to chemical fertilizers (Ahmed, Askri, et al., 2021; Crozier et al., 1997; Phibunwatthanawong & Riddech, 2019; Tikasz, 2019). Organic fertilizers, being generally insoluble in water, release nutrients slowly as they are broken down into soluble forms by microorganisms (Bergstrand, 2022; Gartmann et al., 2023; Phibunwatthanawong & Riddech, 2019). The abundance of essential macro and micronutrients in liquid organic fertilizers makes them a popular choice for hydroponic plant cultivation, providing a nutrient-rich environment that supports healthy plant growth and higher yields. Additionally, many farmers have shown interest in using organic fertilizers for vegetable transplant production, highlighting the shift towards more environmentally friendly and sustainable practices in hydroponics (Bergstrand, 2022; Gartmann et al., 2023; Phibunwatthanawong & Riddech, 2019; Zandvakili et al., 2019).

1.3 Research Objectives

The main objective of the study was to establish a sustainable hydroponic system for producing safe and healthy vegetables locally in the UAE. The systematic approach for attaining this objective involves the following steps:

- Assess the efficacy of liquid organic fertilizers derived from various organic residues such as fish farm waste, plant waste, and humic-based materials in hydroponic systems.
- Explore the growth, yield, and quality of lettuce plants in a zero-runoff auto-pot soilless system, utilizing organic Nutrient Solutions (NS) compared to a conventional NS prepared with inorganic fertilizers.
- Investigate the plant behavior, phytochemicals' composition, and antioxidant capacity of lettuce in response to organic nutrient solutions.

1.4 Relevant Literature

1.4.1 Hydroponics as a Sustainable Solution in Arid Region

Hydroponics emerges as a compelling solution to the sustainability challenges faced by conventional soil-based agriculture, particularly in arid regions hindered by limited arable land and harsh climate conditions. Intensive cultivation in other regions has led to soil exhaustion and reduced fertility, necessitating alternative approaches (Das et al., 2021; Sahoo et al., 2023). Hydroponics, a soilless farming method, offers precise control over soil properties through artificial mediums and high-tech greenhouse structures with automatic climate control (Gaikwad et al., 2022; Gaikwad & Maitra, 2020; Savvas & Gruda, 2018). It enables year-round cultivation of various crops, significantly improving resource efficiency while reducing water usage and the need for pesticides. Furthermore, hydroponic systems can be customized to suit different environments, making them ideal for urban areas and regions with limited arable land.

Aquaponics, a fusion of hydroponics and aquaculture, further enhances sustainability by closing nutrient cycles and minimizing water consumption (Goddek et al., 2015; Hart et al., 2013). Complementing these systems with forward osmosis technologies like Fertilizer Drawn Forward Osmosis (FDFO) presents promising opportunities for achieving significant water and energy savings in agricultural practices. FDFO utilizes highly concentrated fertilizer solutions as draw solutions, which can be seamlessly integrated with hydroponics, presenting promising opportunities for achieving significant water and energy savings in agricultural practices (Bassiouny et al., 2022; Mohammadifakhr et al., 2020). This aligns with the broader theme of using innovative approaches like FDFO to enhance the sustainability and efficiency of hydroponic systems in addressing water scarcity, increasing crop yields, and advancing agriculture (Bassiouny et al., 2022).

Hydroponics not only conserves resources but also often leads to higher crop yields compared to traditional soil-based agriculture (Hochmuth & Hochmuth, 2001). The controlled environment allows for optimal growth conditions, resulting in more productive plants. Sustainability in hydroponics involves not only water and energy savings but also efficient nutrient utilization, reducing the environmental impact (Touliatos et al., 2016).

Moreover, hydroponics is resilient to climate change, providing a stable food supply in the face of unpredictable weather patterns. It promotes community involvement in agriculture, reduces the carbon footprint associated with long-distance food transportation, and addresses water quality issues (Sahoo et al., 2023). As water scarcity continues to affect a significant portion of the global population, hydroponics stands out as a water-efficient, climate-resilient, and sustainable method for increasing food production while minimizing environmental impacts (Manos & Xydis, 2019; Sardare & Admane, 2019).

1.4.2 The Role of Organic-Based Resources

Hydroponics is recognized for its environmental advantages, including reduced water usage and pesticide application. However, the quest for even greater eco-friendliness and nutritional excellence has led to the exploration of bioponics, a branch of hydroponics that incorporates organic-based resources, such as nutrient solutions and substrates (Szekely & Jijakli, 2022). Incorporating organic-based resources can further enhance the eco-friendliness of hydroponics. This innovation not only enhances the sustainability of hydroponic systems but also influences the nutritional content and overall quality of produce (Gartmann et al., 2023; Szekely & Jijakli, 2022; Vanacore & Cirillo, 2023). Furthermore, there's ongoing research into how organic-based nutrients and substrates can potentially influence sensory attributes, making sensory evaluations an integral part of these investigations. Sensory evaluations offer insights into potential differences between hydroponically and soil-grown plants, where organic-based resources may play a role (Matthew et al., 2011; Nassar et al., 2015). In essence, utilizing organic-based resources in hydroponics holds promise for environmental sustainability, improved nutrition, and potentially enhanced sensory qualities in hydroponically grown produce.

Selecting the right organic materials is a critical consideration because using materials that lack essential nutrients can actually limit plant growth, even if the overall method is highly efficient (Szekely & Jijakli, 2022). To overcome this limitation, it is recommended to explore options like utilizing the solid portion of digestate and adding specific components that can address any nutrient deficiencies that may arise during the cultivation process. Additionally, maintaining the right pH levels is essential for promoting optimal plant growth, and this can be easily managed by employing automatic devices that help ensure a suitable environment for healthy plants to thrive (Velazquez-

Gonzalez et al., 2022). Many studies have explored the use of aerobic degradation for bioponics using different organic materials like solid food waste, goat manure, and chicken manure (Shaji et al., 2021; Silva et al., 2019; Szekely & Jijakli, 2022). Proper processing through aerobic mineralization proved effective in producing nutrient-rich solutions and achieving quality plant growth. This mineralization process parallels aquaponics principles, where fish effluents are mineralized by microorganisms to provide nutrients for plant growth (Szekely & Jijakli, 2022). In some cases, chicken manure was directly used in hydroponic systems during plant cultivation with the aid of a biofilter, successfully producing lettuces and kale. The "tea" method, involving water extracts of compost or animal manure, has also been explored. Compost teas, which contain microorganisms from compost, have been used as nutrient solutions in hydroponics, showing various effects on plant growth and soil health (Charoenpakdee, 2014; El-Shinawy et al., 1999; Szekely & Jijakli, 2022; Tikasz, 2019). However, their nutrient content and quality depend on the primary organic material used. Stable materials with high mineral content and a substantial proportion of NO_{3-} nitrogen are preferred to avoid issues like phytotoxicity and unbalanced nutrient composition (Goldan et al., 2023; Szekely & Jijakli, 2022). These methods hold promise for sustainable hydroponics by improving nutrient availability, plant growth, and reducing reliance on chemical fertilizers.

1.4.3 From Hydroponics to Low Height Vertical Farming

Vertical farming as a component of urban agriculture is the practice of producing food in vertically stacked layers, vertically inclined surfaces and/or integrated into other structures. Vertical farming is not a new idea. In 1915, Bailey coined the term “vertical farming” (Bailey, 1915). Since then, architects and scientists, especially towards the end of the twentieth century, have repeatedly looked into the idea of producing food in urban environments because of constant human population growth and the pressures exerted on resources for food production. Denmark was the first country to attempt to implement the concept of agricultural integration in a built environment in a house in the 1950s; they tried to grow watercress (*Nasturtium officinale* W.T.Aiton) on a large scale. Today a more evolved urban agriculture, where the product is grown in a totally controlled urban environment, in closed vertical structures, is attracting more attention in several countries. In the past two decades, scientists in the United States, Europe and several Asian countries have been conducting research and development to bring this concept into reality (The Vertical Farm: Feeding the World in the 21st Century | WorldCat.Org, 2010). Several countries, such as South Korea, Japan, China, Singapore, Italy, Holland, United Kingdom, Jordan, Saudi Arabia, United Arab Emirates and Canada, are moving ahead in the development of vertical farming projects. Vertical farming technology has been seen as a solution to the problems of limited land area suitable for agriculture, as well as a more rational use of water resources, thus providing better opportunities for a sustainable food supply in both developed and developing countries (Besthorn, 2013). Because of advances in hydroponic and aeroponic technology, lighting through LEDs and energy provided using solar cells, it is now possible to have agriculture in cities and possibly even in individual households to create centers of production and consumption integrated with urban and suburban communities. One can grow crops inside multi-story city buildings, using very little land to produce food that would not need to be shipped far to the end consumer (Hsieh et al., 2018).

The large-scale implementation of vertical farming involves stacking growth rooms, such as glasshouses and controlled environment rooms, on top of each other to construct food-producing high-rise buildings (Despommier, 2011). The same concept can be applied at a smaller scale through Vertical Farming Systems (VFS). These growth systems expand crop production into the vertical dimension to produce a higher yield using less floor area (Hochmuth & Hochmuth, 2001, p. 200; Resh, 2022). Examples of VFS include the use of vertical columns (Touliatos et al., 2016), vertically suspended grow bags (Neocleous et al., 2010), conveyor-driven stacked growth systems (Mahdavi et al., 2012), A-frame designs (Hayden, 2006), and plant factory approaches (Kato et al., 2010). Although these studies have quantified crop production, there have been few direct comparisons with horizontal systems of similar cropping density and little information is available on whether vertical column systems present a viable alternative to horizontal crop production systems.

1.4.4 Technical Challenges and Considerations in Aquaponics and Hydroponics Systems

Aquaponics and hydroponics represent innovative approaches to sustainable food production, sharing several common technical challenges and considerations (Diver, 2006; Goddek et al., 2015). These systems require a multidisciplinary approach, drawing upon fields such as engineering, biology, and computer science. Their inherent complexity demands specialized expertise, particularly in commercial applications, necessitating a deep understanding of economics and marketing. Maintaining pH stability is of paramount importance due to the diverse pH requirements among the organisms involved, underscoring the need for achieving a delicate equilibrium (Goddek et al., 2015). Moreover, the responsible management of finite resources like phosphorus becomes a concern, prompting the exploration of recovery and reuse strategies (Goddek et al., 2015; López-Arredondo & Herrera-Estrella, 2013; Schneider et al., 2005; Seawright et al., 1998). Pest and disease management pose intricate challenges, given the complex microflora present in these systems (Goddek et al., 2015; Lennard & Leonard, 2004; Pantanella et al., 2012; Savidov, 2004).

In addressing these issues, some solutions involve the separation of aquaculture and hydroponic components into decoupled systems. These shared considerations underscore the intricate nature of aquaponics and hydroponics, emphasizing the necessity for innovative solutions to ensure their sustainable success (Ekoungoulou & Mikouendanandi, 2020; Monsees et al., 2017; Palm et al., 2024). Within the realm of hydroponics, specific technical challenges come to the forefront. Firstly, there is a pressing need to enhance nutrient solubilization and recovery, essential for optimizing nutrient input utilization and minimizing the demand for additional minerals. Notably, the recycling of phosphorus stands out as a priority in this regard. Secondly, effective pest management strategies must be adapted to address the unique challenges posed by pests in aquaponic environments. Thirdly, the significant reduction of water consumption by limiting the frequency of water exchange emerges as a crucial goal for water conservation (Goddek et al., 2015; Sverdrup et al., 1981; Sverdrup & Ragnarsdottir, 2011).

Furthermore, exploring alternative energy sources, such as harnessing Combined Heat and Power (CHP) waste heat or geothermal energy, holds the potential to reduce energy costs and minimize the environmental footprint, particularly in regions with varying climatic conditions. Lastly, the maintenance of the optimal pH level remains a vital consideration, necessitating innovative methods like fluidized lime-bed reactors to ensure the overall health of the system (Goddek et al., 2015).

These technical challenges demand comprehensive attention and resolution to establish controlled and standardized aquaponic and hydroponic systems that are both environmentally sustainable and economically viable. The competitiveness of aquaponics and hydroponics as methods of food production depends on technological advancements, local market conditions, and various climatic and geographic factors, all of which require careful assessment and adaptation to thrive in the evolving landscape of sustainable agriculture (Goddek et al., 2015, 2019; T, 2016; Yep & Zheng, 2019).

1.4.5 Leveraging Hydroponics for Food Security

The United Arab Emirates (UAE) faces significant challenges in ensuring food security due to its increasing population and reliance on food imports (Saif Al Qaydi, 2016). Traditional agriculture in this arid region is limited restricted by limited arable land, harsh climate conditions, and the encroachment of urbanization. To address these pressing concerns and safeguard food security without compromising environmental sustainability, the UAE is exploring innovative solutions, with hydroponic agriculture emerging as a promising and efficient strategy.

Hydroponic systems, characterized by soil-less cultivation, offer numerous advantages in the context of the UAE's unique agricultural landscape. They have the potential to revolutionize food production by dramatically reducing water wastage, often exceeding the efficiency of traditional farming methods by up to 90% (UAE Government, 2023; Malek, 2012; Saif Al Qaydi, 2016). Moreover, hydroponics eliminates the need for harmful chemicals like pesticides and insecticides, ensuring the production of healthy and safe food. These systems are adaptable to varying climates and crop types, making them ideal for regions with extreme temperatures (Van Delden et al., 2021; Velazquez-Gonzalez et al., 2022).

One of the critical benefits of hydroponics is its ability to overcome the challenge of limited arable land (Gaikwad et al., 2022; Mir et al., 2022). In areas where agricultural land is gradually being converted into residential zones, hydroponics requires less space, offering a sustainable solution to produce food locally. By reducing reliance on food imports, hydroponic farming contributes significantly to food security.

Furthermore, hydroponics aligns with the UAE government's focus on scientific principles regarding nutritional intake and food quality (UAE Government, 2023; Saif Al Qaydi, 2016). It offers precise control over nutrient levels, ensuring that crops are rich in essential nutrients. This approach not only enhances food security but also promotes a healthier population.

In addition to hydroponics, the integration of bioponics further enhances resource use efficiency and sustainability while reducing the environmental impact. Bioponics maximizes nutrient recycling, minimizes water consumption, and allows for year-round crop production. This innovative approach fosters community engagement and diversifies available food sources, contributing to long-term food security (Gartmann et al., 2023; Szekely & Jijakli, 2022; Vanacore & Cirillo, 2023).

The economic viability of hydroponics, its potential for increased crop yields, and the growing interest from governments worldwide underscore its role in addressing food security challenges. It is increasingly accepted as a global solution in the quest for sustainable and secure food production (Bassiouny et al., 2022; Folorunso et al., 2023; Goddek et al., 2015; Mir et al., 2022).

In conclusion, the United Arab Emirates (UAE) is actively exploring urban agriculture and vertical urban farming, utilizing advanced technology and controlled environments to enhance the food production in urban areas. This approach aims to conserve water resources and maintain product quality by embracing contemporary agricultural practices like hydroponics and other modern farming technologies.

Chapter 2: Methods

2.1 Growth Conditions, Treatments, and Experimental Design

This study was conducted in a polycarbonate greenhouse situated at the Al Foah Experimental Farm, United Arab Emirates University, located in Al Ain, UAE (55.7146° E, 24.2191°N), spanning from October to February 2022. Greenhouse temperatures were maintained between 19.2°C and 26.4°C, with the relative humidity ranging from between 40-60%. Plants received natural sunlight, experiencing day lengths of 10 h: 40 min: 40 s to 11 h: 50 min: 20 s ±1 h: 20 min:0 s throughout the experimental period.

In this experiment, we utilized a Dutch Bucket hydroponic system integrated with zero-runoff auto-pot technology (Figure 1). This system operates via a gravity-based mechanism that regulates water flow using a valve. This valve automatically opens when the tray beneath the pot is empty eliminating the need for electricity, pumps, water pressure, or timers. Each unit of the system comprised multiple components: a 100 L tank for NS, pots with a 40 cm depth and 25 L capacity filled with perlite media (Gulf Perlite LLC, UAE), and a network of pipes/micropipes connected to a valve and float at the base of eight pots.

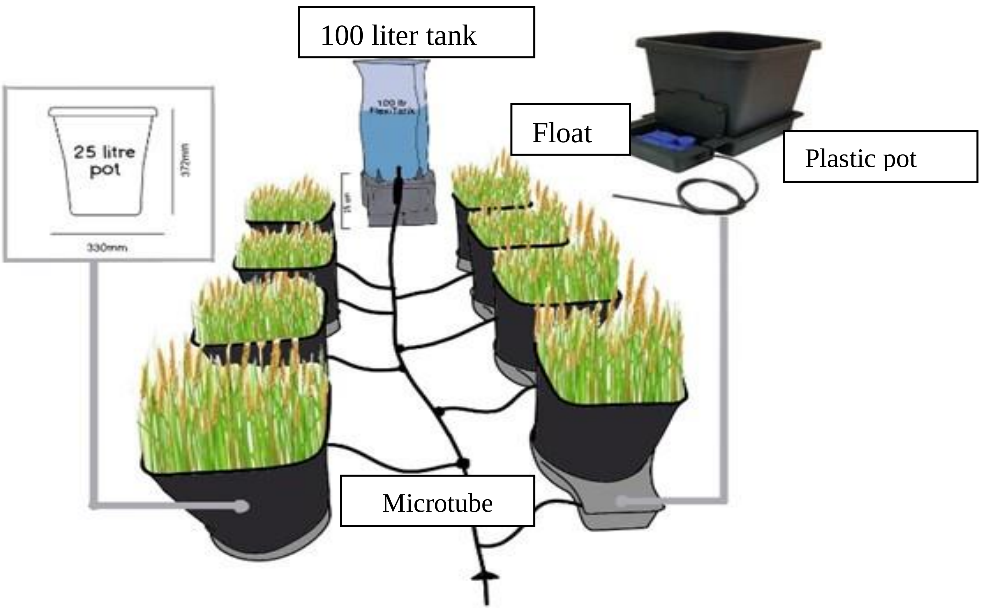

Figure 1: Example of soilless system with zero-runoff auto-pot technology.

To prepare the organic nutrient solutions, we used four commercial liquid organic fertilizers produced locally by Emirates Biofertilizers Factory (Al Ain, UAE) as follows:

- Nutrient Solution (A): Chemical nutrient solution (Control).
- Nutrient Solution (B): agro-fish (8-2-2), 2% Ca, 30% organic matter, and 50% protein.
- Nutrient Solution (C): nutrihumate (15-10-9), 12% humic acid, and 35% organic matter.
- Nutrient Solution (D): rods-fert (28-14-14), 7% humic acid, 1% Ca, and 2% S plus trace elements.
- Nutrient solution (E): Bio-green (0.3-2-6), 4% alginic acid, 1% amino acid, and 200 ppm cytokinin and GA plus trace elements.

All nutrient solutions were prepared with a fixed EC of 2.0 mS/cm and were checked and corrected every 2 d (Williams & Nelson, 2016). The pH of the NS was adjusted to between 5.5 and 5.8) and was checked and readjusted three times per week by adding NaOH or HCl. The tanks were refilled with NS as necessary to maintain the flow.

The ‘Parris Island cos’ cultivar of lettuce (*Lactuca sativa* L.) (USA) was used as the model vegetable crop. Lettuce seedlings were produced in a peat-based growing medium in small plastic pots housed in the same greenhouse. Ten days’ post-germination, seedlings measuring 5 cm in length and sprouting three to four true leaves were relocated to an auto-pot soilless system. Prior to transplantation into the perlite media, roots of the lettuce seedlings were gently rinsed to remove the peat-based medium. Each pot, within the soilless system, received two seedlings. These were fertigated with either the control hydroponic chemical solution (A) or one of the four organic fertilizer-based NS (B, C, D, and E). The study utilized eight pots, totaling 16 plants (replicates) for each treatment within the soilless system.

2.2 Plant Growth and Physiology Assessments

The investigation spanned 60 Days After Planting (DAP) in the soilless system. Leaf number and plant height measurement were taken at 0, 15, 30, 45, and 60 DAP. Mid-season (30 DAP) and at harvest (60 DAP), stomatal density, leaf area, chlorophyll, and carotene content were measured using fresh leaf samples. At harvest, we measured the fresh weight of the plant shoots and roots, and the dry mass of the leaves and roots after drying in an oven at 70°C for 48 h. The dry leaf tissue was finely ground and then analyzed for mineral content (N, P, K, Ca, Mg, Cu, Mn, and Fe), nitrate and ammonium levels, and antioxidant compounds and activity. Detailed explanations of all methods are described below:

2.2.1 The Leaf Area

Samples of three fully developed leaves were randomly collected from each treatment, and their leaf length (mm), width (mm), and area (cm^2) were measured using a leaf area meter (LICOR Photo Electric Area Meter, Model LI-3100, Lincoln, NE, USA) (Wellburn, 1994).

2.2.2 Stomata Density

To prepare an epidermal impression, transparent nail polish was applied to the area on the lower surface of three leaves, specifically between the second-order veins. Once the nail polish dried, Sellotape was used to remove the dry layer containing the leaf impression, which was then fixed to a slide. The number of stomata was counted at five randomly selected disc positions within the intercostal regions of each leaf using light microscopy. Stomatal images were observed at 40x magnification, covering an area of 0.65 mm^2 (Viacava et al., 2015).

2.2.2 Chlorophyll and Carotene Determination

Chlorophyll *a* and *b*, total chlorophyll, and carotene were extracted from 0.5 g of fresh leaves using a mortar and pestle with 50 mL of 80% methanol. The mixture was filtered, and the resulting supernatant was used to quantify chlorophyll a and b at absorbances of 663 and 645 nm using a Hitachi U-2001 UV/Vis Spectrometer (OK, USA). The carotenoid content was determined by measuring the absorbance of the supernatant at 470 nm (Crozier et al., 1997). The following formulas were applied to calculate the total chlorophyll and carotene contents:

Chlorophyll *a* (mg/mL) = 12.7 A663 - 2.69 A645

Chlorophyll *b* (mg/mL) = 22.9 A645 - 4.68 A663

Carotene (mg/mL) = (1000*A470)-1.82 Cha-85.02Chb)/198

The results were reported in milligrams per gram (mg/g) of Fresh Weight (FW), and the combined amounts of chlorophyll *a* and *b* were used to estimate the total chlorophyll content.

2.3 Antioxidant Compounds Content and the Antioxidant Activity

The chemicals 1,1-Diphenyl-2-Picrylhydrazyl (DPPH), 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), Folin-Ciocalteu's phenol reagent, catechin, quercetin, and sodium carbonate were purchased from Sigma Chemical Co. (St. Louis, MO, USA). All chemicals, solvents, and reagents used were of analytical grade.

Polyphenols were extracted from oven-dried leaf samples following the method of Viacava et al. 2015, with minor modifications. The resulting extract was used to determine the total phenolic and flavonoid contents. Folin-Ciocalteu's reagent was used to determine the total phenolic content. The sample extract (100 µL) was added, then 2 mL of 6% NaOH was added, and the mixture was allowed to stand for 2 min. Subsequently, 50 µL of Folin-Ciocalteu's reagent was added, and the mixture was incubated for 45 min in the dark at room temperature (22 ± 1°C). Absorbance at 650 nm was measured with a UV-vis spectrophotometer (Shimadzu, Kyoto, Japan). The total phenolic compound content was calculated and expressed in grams of Gallic Acid Equivalents (GAE) per 100 g of Dry Weight (DW), using a gallic acid standard curve (Kaur et al., 2023).

Total flavonoids were quantified following the method of Crozier et al., 1997, which involves the use of 5% $NaNO_2$ and 10% $AlCl_3$, followed by the addition of 1M NaOH. Absorbance was measured at 510 nm using a UV-1601 visible spectrophotometer (Thermo Scientific, Waltham, MA, USA). The total flavonoid content was calculated from a standard curve and expressed in grams of catechin equivalents (CE) per 100 g (DW) (Al Dahnani & Ahmed et al., 2022).

The antioxidant activities were evaluated using DPPH and ABTS radical scavenging assays as described by Chrysargyris et al., 2016, and Al Dahnani & Singh et al., (2022). For the DPPH assay, a stock solution of DPPH (50 mg/100 mL) was prepared in absolute methanol. A working solution was then made by diluting a 500 µL aliquot of the stock solution with 4.5 mL of absolute methanol. Then a 500 µL aliquot of the sample was added to the DPPH working solution and kept in the dark for 45 min at room temperature. Subsequently, the absorbance of each sample was measured at 517 nm using a UV-vis spectrophotometer. A working solution without the sample served as the control. For the ABTS assay, stock solutions of ABTS (7 mM) and potassium persulfate (2.6 mM) were prepared separately. The ABTS working solution was created by mixing equal volumes of these stock solutions and allowing them to react in the dark for 12 h. Prior to the assay, this solution was diluted with 80% methanol to achieve an absorbance of approximately 0.710 at 732 nm. The assay was conducted by combining 3 mL of the diluted ABTS solution with 30 µL of the sample, allowing the mixture to stand react in the dark at room temperature for 6 min before measuring the absorbance at 732 nm using a UV-vis spectrophotometer. A diluted ABTS solution without the sample served as the control. The percentage of DPPH and ABTS scavenging was calculated using the following equation:

$$\text{Scavanging (\%)} = \frac{\text{Absorbance of control} - \text{Absorbance of sample}}{\text{Absorbance of control}} \times 100$$

2.4 Analysis of Mineral Content in Nutrient Solutions and Plant Tissues

Three replicates of ground, dried lettuce leaves were digested using HNO_3 and H_2O_2 at a 1:5 (v/v) ratio in a microwave at 200ºC for 60 min. Concentrations of macro and micro elements (K, P, Ca, Mg, S, Mn, Na, Fe, and Zn) in the prepared leaf material and NS samples were measured using inductively coupled plasma-optical emission spectrometry (ICP-OES Agilent Technologies) following the method described by Hseu (Wellburn, 1994). Results were expressed in milligrams per gram (mg/g) or micrograms per gram (μg/g) (DW). Standard reference solutions were purchased from Accu Standard, USA, and a linear regression coefficient (R^2) of 0.9972 was achieved for 1000 mg/L of each metal. Each sample was measured in triplicate.

The Kjeldahl method was used to determine the total nitrogen (N) content, which was calculated as a percentage of DW (Bradstreet, 2013). Nitrate-N (mg/kg) and ammonium-N (%) were quantified in dried and milled lettuce leaves at the national laboratories of the Ministry of Climate Change and Environment, Sharjah, UAE (ISO 17025:2017, UKAS), as described by Cataldi et al. (2003).

An Ion Chromatography Instrument IC (Thermo Scientific, Dionex ICS-2100) was used to measure nitrate-N, and a Buchi KjelMaster K-375 was used to measure ammonium-N. A 12.5 mg sample of dried and milled leaves was weighed, and 5 mM hydrochloric acid was used as the extraction solvent. After centrifuging at 3000 rpm for 10 min, the solution was filtered through 0.22-μm nylon filters to remove particulates before injection into the IC.

2.5 Statistical Analysis

The research experiment was designed as a completely randomized block. Statistical analysis of the collected data was conducted using one-way ANOVA with SAS software (SAS Institute Inc., 2000, Cary, NC., USA). The means of growth, yield, and quality indices for the control group and four organically nourished plants were statistically compared using the Least Significant Differences (LSD) test at $p \leq 0.05$. The experiment was conducted twice, and all analyses were performed in triplicate.

Chapter 3: Results and Discussions

3.1 Elemental Composition of Nutrient Solutions and Lettuce Leaves

The elemental composition of nutrient solutions and lettuce leaves is presented in Tables: 1 and 2. The elemental content of the NS varied significantly ($p \leq 0.05$) (Table 1), with NS D and C exhibiting similar N content with 3.50 and 3.59 mg/g, respectively. These levels of N were higher than those in the control (1.74 mg/g) and other organic NS. Although the NS B solution had a lower N level compared to the other organic NS, its N concentration was not significantly different from that of the control (Table 1). Similarly, the source of fertilizer significantly affected the elemental composition of the leaves at harvest (Table 2). Except for plants nourished with NS B (18.5 mg/g), the N content in leaves of organically produced plants was higher ($p \leq 0.05$) than in the control (26.7 mg/g) (Table 2). Plants grown with NS D and C had the highest N levels, while those supplied with NS B had the lowest. These results align with the N content in the different NS (Table 1). The reduced N concentration in plants grown with NS B may result from the poor availability and slow release of inorganic N from organic NS compared to the inorganic ones. Previous reports suggest that organic fertilizers may not sufficiently support plant growth, as their N content is primarily in the organic form not available for the plant, and thus less beneficial for plant growth and development. In contrast to inorganic fertilizers, which release nutrients immediately, organic fertilizers require mineralization of organic matter to make essential minerals, such as nitrogen, phosphorus, potassium, magnesium, and other nutrients, readily available to crops (Bergstrand et al., 2020).

The NS exhibited significantly different levels of Ca, K, and Mg contents ($p \leq 0.05$). Organic NS C and D contained lower levels ($p \leq 0.05$) of K, Ca, and Mg than the control (Table 1). Similarly, all organically grown lettuce plants had lower levels of K, Ca, and Mg than the control ($p \leq 0.05$) (Table 2). Additionally, organically grown lettuce from NS C, D, and E had K levels comparable to the control. These results indicate that organic fertilizer feed reduced the Ca, K, and Mg contents in leaf tissues. In contrast, the P content was higher in organic fertilizers (ranging from 95-210 mg/g) compared with the inorganic control (26 mg/g) (Table 1), but this did not consistently translate into significant differences in P levels in the leaf tissues of plants grown in the organic versus inorganic solutions (Table 2). Notably, not all organic fertilizers resulted in the highest P levels in lettuce leaves; for example, the P levels in plants grown in NS B were not significantly different from the control. This is consistent with the results of (Zandvakili et al., 2019), who reported high P levels in lettuce grown with organic NS. Conversely, the Ca content in leaves of organically nourished plants (4.5-6.8 mg/g) was significantly lower than that in the control plants (11.9 mg/g) (Table 2). However, a previous study found no significant difference in Ca levels between organically and inorganically grown lettuce (Zandvakili et al., 2019). In this study, the organic NS had lower Mg content (2.7-5 mg/g) ($p \leq 0.05$) than the control (9.2 mg/g) (Table 1). Accordingly, Mg levels in organically grown plants were significantly lower than that in the control plants (Table 2). Organic fertilizers had higher Mn levels (90-122 µg/g) than the inorganic fertilizers (66 µg/g) (Table 1). Plants grown in the control solution had higher Mn content than those grown in NS B and E (Table 2), despite the latter having higher initial Mn levels. Lettuce plants grown with NS C and D accumulated higher levels of Mn (0.268 and 0.262 µg/g, respectively) compared to those supplied with NS B (0.031 µg/g) (Table 2). These results could be due to various factors affecting Mn absorption and accumulation, such as the level of organic matter (Alejandro et al., 2020). An earlier study (Warman & Havard, 1998) also reported significant Mn levels in Brassica oleracea var. capitata L. grown in organically fertilized medium. This investigation further revealed that Zn, Cu, Na, S, and Al levels varied significantly between plants fertigated with different fertilizer solutions. Plants grown with NS C, D, and E had lower levels of Zn and Cu in their leaves than NS B and the control (Table 2), despite having higher initial Zn and Cu levels (except for Zn in NS E, which was slightly lower than the control). This could be due to the lower availability, weaker release, and slower absorption of organic nutrients compared to inorganic NS. Organic nutrients from animal and plant remnants must be transformed by bacteria in the substrate into forms usable by plants (Burnett et al., 2016; Treadwell et al., 2007). Additionally, factors such as the type of organic nutrition supply (e.g., particle size and composition), porosity, substrate moisture, and temperature, impact the rate of microbial-mediated mineralization (Burnett et al., 2016). Results also revealed that all organically grown plants had higher Na levels than the control.

Furthermore, higher accumulations of Fe were observed in organically grown plants (2.5-10 µg/g) compared to the control (0.43 µg/g) (Table 2). The NS B and E treatments accumulated higher levels of Fe than the control and other treatments. Plants grown in NS B had the highest Fe content, despite NS B having the lowest Fe levels among the tested solutions. These findings suggest that nutrient imbalances in organic feeding solutions, due to NS composition, significantly impacted the elemental content of plant leaves at harvest.

Table 1: Macro and micromineral content of different Nutrient Solutions (ns) used in a zero- runoff auto-pot soilless system.

	Macro elements (mg/g)					
Nutrient solution	N	Ca	K	Mg	P	S
A	2.09 ± 0.15^{bc}	80.0 ± 1.91^{a}	57.4 ± 2.45^{ab}	9.02 ± 1.11^{a}	26.1 ± 1.34^{d}	1.35 ± 0.13^{a}
B	1.74 ± 0.12^{c}	34.3 ± 2.76^{b}	65.6 ± 3.31^{a}	5.03 ± 0.61^{b}	95.9 ± 5.72^{c}	1.02 ± 0.05^{b}
C	3.50 ± 0.14^{a}	20.0 ± 1.95^{d}	17.0 ± 0.89^{c}	2.75 ± 0.25^{d}	196.2 ± 6.44^{b}	1.27 ± 0.12^{ab}
D	3.59 ± 0.11^{a}	19.7 ± 1.54^{d}	16.9 ± 1.05^{c}	3.61 ± 0.47^{c}	210.1 ± 7.13^{a}	1.18 ± 0.09^{b}
E	2.42 ± 0.07^{b}	25.7 ± 2.73^{c}	61.7 ± 3.34^{ab}	3.19 ± 0.81^{c}	190.1 ± 5.96^{b}	1.39 ± 0.15^{a}
	Micro elements (µg/g)					
	Fe	Mn	Zn	Cu	Na	Al
A	69.48 ± 3.16^{e}	66.02 ± 2.65^{c}	14.49 ± 0.82^{b}	$7.41\pm 0.71b^{c}$	8.96 ± 0.61^{b}	0.13 ± 0.03^{d}
B	55.98 ± 4.30^{d}	92.53 ± 7.42^{b}	15.35 ± 1.25^{b}	6.82 ± 0.35^{c}	10.32 ± 0.72^{a}	2.61 ± 0.11^{c}
C	137.9 ± 9.80^{b}	122.31 ± 5.51^{a}	18.09 ± 0.94^{a}	11.93 ± 0.79^{a}	8.52 ± 0.95^{b}	5.24 ± 0.85^{a}
D	174.22 ± 12.34^{a}	90.29 ± 6.30^{b}	18.37 ± 1.41^{a}	12.50 ± 1.05^{a}	8.61 ± 0.65^{b}	4.62 ± 0.76^{a}
E	76.78 ± 5.74^{c}	117.00 ± 7.76^{a}	13.21 ± 0.91^{b}	8.05 ± 0.83^{b}	10.59 ± 0.73^{a}	3.21 ± 0.40^{b}

Mean±SE. Different lowercase letters indicate significant differences at $p \leq 0.05$ as determined by the LSD test. A=Chemical nutrient solution (control), B= Agro-fish liquid organic fertilizer, C= Nutrihumate liquid organic fertilizer, D= Rods-fert liquid organic fertilizer, E= Bio-green liquid organic fertilizer.

Table 2: Macro and micromineral content of lettuce (cultivar 'parris island cos') leaves grown in different ns in a zero-runoff auto-pot soilless system.

			Macro elements (mg/g)			
Nutrient solution	N	Ca	K	Mg	P	S
A	26.7± 1.3b[c]	11.90 ± 0.57[a]	19.85 ± 1.23[a]	2.88 ± 0.30[a]	4.33 ± 0.15[c]	1.43 ± 0.05[a]
B	18.5± 0.97[c]	6.87 ± 0.31[b]	10.49 ± 0.47[b]	1.55 ± 0.04[c]	4.65 ± 0.25[c]	1.09 ± 0.07[c]
C	73.0± 1.59[a]	6.31 ± 0.36[b]	5.85 ± 0.67[c]	1.88 ± 0.04[b]	8.33 ± 0.25[a]	1.23 ± 0.04[b]
D	85.4± 2.87[a]	6.31 ± 0.65[b]	6.38 ± 0.23[c]	2.01 ± 0.12[b]	8.68 ± 0.19[a]	1.18 ± 0.07[bc]
E	32.2± 1.13[b]	4.58 ± 0.22[c]	6.64 ± 0.54[c]	1.43 ± 0.06[c]	6.71 ± 0.46[b]	1.39 ± 0.10[a]
			Micro elements (µg/g)			
	Fe	Mn	Zn	Cu	Na	Al
A	0.43± 0.03[d]	0.155± 0.05[b]	0.143± 0.01[b]	0.261± 0.02[a]	42.5± 2.73[c]	22.6± 3.73[c]
B	1.30± 0.89[a]	0.031± 0.00[c]	0.330± 0.02[a]	0.105± 0.03[a]	90.3± 6.18[a]	20.4± 1.55[c]
C	2.93± 0.31[c]	0.268± 0.05[a]	0.095± 0.03[c]	0.011± 0.00[c]	51.8± 2.83[b]	30.3± 2.03[a]
D	2.53± 0.12[c]	0.262± 0.03[a]	0.134± 0.01[b]	0.025± 0.01[c]	57.4± 4.79[b]	25.0± 1.85[b]
E	4.58± 0.75[b]	0.052± 0.01[c]	0.119± 0.01[c]	0.056± 0.01[c]	89.9± 7.33[a]	28.0± 2.93a[b]

Mean±SE. Different lowercase letters indicate significant differences at $p \leq 0.05$ as determined by the LSD test.A=Chemical nutrient solution (control), B= Agro-fish liquid organic fertilizer, C= Nutrihumate liquid organic fertilizer, D= Rods-fert liquid organic fertilizer, E= Bio-green liquid organic fertilizer.

3.2 Effects on Plant Growth Components

The fertilizer source applied significantly affected the plant growth components of lettuce (Table 3 and Figure 2). At 15 DAP, the fertilizer source had a significant impact on plant height but did not affect the number of leaves or their size and area; however, by 30 DAP, a significant effect was observed. At 30 and 60 DAP, plants grown with organic NS exhibited lower plant heights and leaf numbers ($p \leq 0.05$) compared to those grown with inorganic fertilizer; yet at 45 DAP, NS B did not differ significantly from the control in terms of plant height (Figure 2). Among the organic NS, plants fertigated with NS B (fish source) and E (plant source) did not consistently show greater height or a higher leaf count at 30, 45, and 60 DAP compared to other organic NS (Figure 2). In contrast, NS C (nutrihumate) yielded the lowest plant growth performance. This trend was also observed for leaf area, height, and width (Table 3). These results suggest that organic fertilizer-based NS likely provided fewer nutrients than inorganic fertilizer-based NS. According to Atkin & Nichols (2004) and Ahmed, Askri, et al. (2021) organically derived NS can be used to produce lettuce plants using the NFT, albeit with slower growth than with standard inorganic NS. Similar findings were reported for hydroponically grown strawberries (Ahmed, Askri, et al., 2021). Moncada et al. (2021)

found that reducing the mineral NS content in favor of organic NS adversely affected the growth of soilless basil plants, including the stem diameter, leaf number, and area.

Unlike water-soluble inorganic fertilizers, organic liquid fertilizers derived from animal and plant waste sources are not readily available to plants. They often require mineralization and transformation into plant-available forms by microorganisms that may be present in the substrate (Bergstrand, 2022; Bi et al., 2010). The rate of microbial-mediated mineralization varies significantly and is influenced by various parameters, including the nature of the organic nutrient supply, substrate temperature, moisture, and porosity (Bergstrand, 2022; Gaskell & Smith, 2007). A major drawback of using organic fertilizers is that the nutrient release rate may not meet the plant's nutrient requirements. To ensure adequate nutrient uptake by plants, continuous adjustment of the soilless system and growing media may be necessary to enhance the microbial activity and achieve an optimal decomposition rate of the organic fertilizer source (Burnett et al., 2016; Treadwell et al., 2007).

Table 3: Effect of ns in a zero-runoff auto-pot soilless system on the morphological characteristics of lettuce leaves 30 and 60 DAP.

Solution code	Area (cm^2)	Length (cm)	Width (cm)	Stomata density /mm^2 disc
			30 days	
A	53.80±4.11^a	11.34±1.13^a	6.79±0.94^a	20.0±1.76^c
B	34.14±2.43^b	9.27±1.21^b	6.07±0.66^b	27.4±1.38^b
C	27.12±3.51^c	7.50±0.87^c	4.57±0.89^c	32.3±2.11^b
D	26.67±2.13^c	7.04±1.31^c	4.64±1.01^c	35.0±1.74^a
E	30.15±1.72^b	9.26±0.84^b	5.48±0.71^{bc}	28.4±3.21^b
			60 days	
A	73.99±5.10^a	15.91±1.33^a	8.29±1.01^a	29.0±1.16^b
B	65.18±3.22^a	15.04±1.26^a	7.15±0.88^b	31.1±1.45^b
C	49.55±1.81^c	12.90±0.98 ^{b}	6.50±1.02^c	35.9±2.14^{ab}
D	46.63±3.19^c	12.24±1.43^b	6.52±1.11^c	38.4±2.15^a
E	58.23±2.25^b	14.28±1.12^b	7.20±0.64^b	31.2±1.78^b

Mean±SE. Different lowercase letters indicate significant differences at $p \leq 0.05$ as determined by the LSD test.A=Chemical nutrient solution (control), B= Agro-fish liquid organic fertilizer, C= Nutrihumate liquid organic fertilizer, D= Rods-fert liquid organic fertilizer, E= Bio-green liquid organic fertilizer.

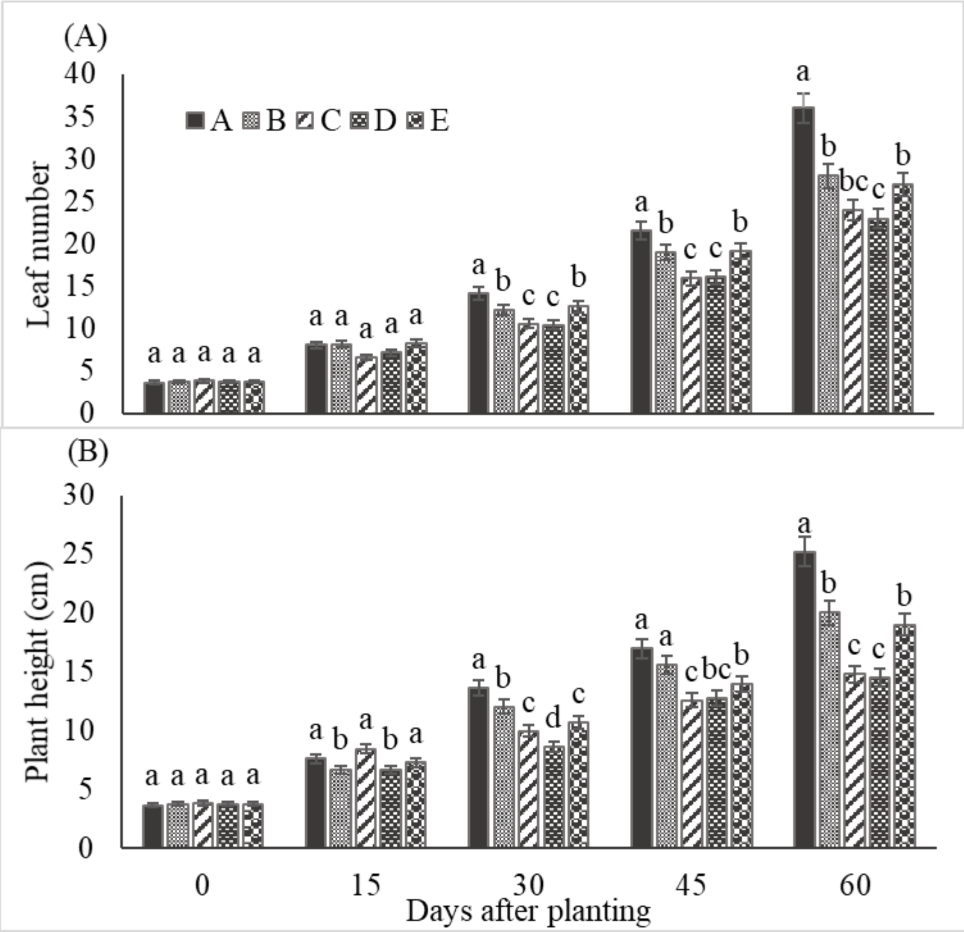

Figure 2: Effect of Nutrient Solutions (NS) in a zero-runoff auto-pot soilless system on the leaf number (a) and plant height (b) of lettuce (cultivar 'parris island cos').

3.3 Stomatal Density

The source of NS significantly affected leaf stomatal density (Table 3). at 30 DAP, plants nourished with organic NS exhibited higher stomatal density (27-38/mm2) than those fertilized inorganically (20-29/mm^2 ($p<0.05$)) (Table 3). Specifically, at 30 DAP, plants treated with NS D solution (35 mm2) had a higher leaf stomatal density than those receiving other organic NS. A similar trend was observed at the time of harvest, with only plants grown in NS D showing higher stomatal density compared to the control (A), and plants fertigated with NS B and E (Table 3). These findings indicate that the fertilizer source markedly influenced plant physiology, resulting in variations in leaf stomatal density. Such differences may be associated with differences in nutrient availability and relative stress effects. Stomata are critical in modulating plant water use and carbon uptake (Bergstrand et al., 2020; Bertolino et al., 2019), which significantly affects photosynthesis and plant growth (Mattiello et al., 2015; Sakoda et al., 2020).

Moncada et al., 2021 recently reported that soilless-grown basil plants fertilized with organic liquid fertilizer exhibited substantially lower stomatal conductance than those that received chemical fertilizers. The number, distribution, size, form, and mobility of stomata are species-specific traits that can change in response to environmental factors such as nutritional deprivation (Souza et al., 2019). Our results indicated that the stomatal density of soilless-grown lettuce leaves was influenced by the type of fertilizer. However, further research is required to fully understand how stomatal density affects lettuce growth and biomass production in soilless systems under nutrient scarcity and higher chlorophyll contents.

3.4 Chlorophyll and Carotene Contents

Our results revealed significant variations in chlorophyll and carotene contents between plants nourished with different fertilizer sources (Table 4). Generally, at 30 DAP, the total chlorophyll content was higher ($p \leq 0.05$) in organically fertigated lettuce compared to the control, except for plants fertigated with NS C, which had a total chlorophyll content similar to the control (Table 4). Chlorophyll A and B levels were higher in plants fertigated with NS B and E than in the control plants. Conversely, the carotenoid content was consistently higher in all plants fertigated with organic fertilizer-based NS compared to the control (Table 4). At 60 DAP, the plants fertigated with NS B and C had lower total chlorophyll content than those fertigated with inorganic fertilizer, while the carotenoid content remained higher in organically fertilized plants compared to the control only when using NS C and E. These findings are consistent with the N content of NS (Table 1) and the N uptake by the plants. The amount of chlorophyll and carotenoids in a plant is generally proportional to its photosynthetic capacity, which is related to the N content of their leaves (Gamon & Surfus, 1999).

Table 4: Effect of ns in a zero-runoff auto-pot soilless system on the chlorophyll and carotene contents in lettuce leaves 30 and 60 DAP.

Solution code	**Total Ch (mg/g)**	**Ch *a* (mg/g)**	**Ch *b* (mg/g)**	**Carotene (mg/g)**
		30 days after planting		
A	0.95±0.11^{b}	0.69±0.13^{b}	0.26±0.01^{b}	0.17±0.01^{b}
B	1.14±0.12^{a}	0.74±0.17^{a}	0.40±0.02^{a}	0.24±0.00^{a}
C	0.96±0.14^{ab}	0.66±0.05^{b}	0.30±0.00^{b}	0.25±0.02^{a}
D	1.03±0.06^{a}	0.74±0.08^{a}	0.28±0.01^{b}	0.28±0.03^{a}
E	1.16±0.14^{a}	0.78±0.04^{a}	0.38±0.04^{a}	0.25±0.03^{a}
		60 days after planting		
A	0.87±0.06^{a}	0.53±0.05^{a}	0.33±0.02^{ab}	0.18±0.00^{b}
B	0.74±0.16^{b}	0.47±0.03^{b}	0.27±0.01^{b}	0.22±0.03^{ab}
C	0.81±0.16^{b}	0.50±0.06^{ab}	0.30±0.02^{b}	0.26±0.06^{a}
D	0.93±0.08^{a}	0.54±0.03^{a}	0.38±0.02^{a}	0.23±0.03^{ab}
E	0.89±0.07^{a}	0.57±0.03^{a}	0.31±0.01^{b}	0.27±0.02^{a}

Mean±SE. Different lowercase letters indicate significant differences at $p \leq 0.05$ as determined by the LSD test.A=Chemical nutrient solution (control), B= Agro-fish liquid organic fertilizer, C= Nutrihumate liquid organic fertilizer, D= Rods-fert liquid organic fertilizer, E= Bio-green liquid organic fertilizer.

Since N is required for chlorophyll synthesis, lower N levels in the NS may result in a reduced chlorophyll content, thereby diminishing photosynthesis and ultimately crop yield (Rambo et al., 2010). However, in the present study, lettuce fertigated with organic fertilizer exhibited a slightly higher chlorophyll content at 30 DAP compared to those grown with inorganic fertilizer; however, this did not correspond to increased plant growth (Figure 2 and Table 3). A similar result was reported by Phibunwatthanawong and Riddech (Phibunwatthanawong & Riddech, 2019), who suggested that plant growth and yield are influenced by numerous variables, and factors other than chlorophyll content may have affected plant growth and crop yield.

3.5 Plant Fresh and Dry Weights

The NS source significantly influenced lettuce stem diameter, root FW and DW, and total plant FW at harvest ($p \leq 0.05$) (Table 5). Lettuce fertigated with organic NS exhibited lower root FW and DW and total plant FW than those in the control group ($p \leq 0.05$). Among the organic solutions, NS B and E resulted in higher root FW and DW and total plant FW compared to plants fertigated with NS C and D (Table 5). The reduced fresh biomass in organically fertigated plants may be attributed to the differing mineral availability between the two nutrient sources. These findings are consistent with the composition of the tested NS (Table 1), and suggest that the diminished leaf area, stem diameter, and root FW and DW in plants receiving these NS were likely due to a lower availability of macronutrients such as Ca, K, and Mg in the solution (Table 1). Despite higher N and chlorophyll content (Tables 1 and 4), organically grown plants accumulated less biomass than inorganically grown plants (Table 5). This finding indicates that factors other than N availability constrained lettuce plant growth (Fallovo et al., 2009) and that a balanced nutrient composition is essential for many metabolic activities in lettuce plants. Miyazawa et al. (2006) observed that butterhead lettuce shoot FW and DW were smaller in plants grown with organic NS compared to those grown with inorganic NS. (Ahmed, Alnuaimi, et al., 2021) also found that lettuce fertilized organically accumulated less biomass than those fertilized with inorganic fertilizer. Similarly, the use of liquid organic fertilizer negatively affected several basil plant traits, including their DW and FW (Moncada et al., 2021). Previous research has demonstrated how the composition of NS in soilless systems influences various plant growth parameters, such as leaf number, leaf area, crop quality, and marketable yield (Di Gioia et al., 2017; Sapkota et al., 2019). Moreover, there may be a disparity between nutrient availability and plant nutrient requirements to limit production in organically fertilized plants compared to those fertilized with water-soluble inorganic NS fertilizers. Our study highlights the impact of fertilizer sources on plant biomass and lettuce yield within a hydroponic system.

Table 5: Effect of ns of in a zero-runoff auto-pot soilless system on the stem diameter, fresh weight, and root fresh and dry weight of lettuce plants at harvest.

Solution Code	Stem diameter (mm)	Shoot FW (g)	Shoot DW (g)	Root FW (g)	Root DW (g)
A	16.8±2.06[a]	175.1±4.28[a]	7.63±0.41[a]	45.44±2.57[a]	8.59±0.72[a]
B	12.1±1.34[b]	159.8±3.70[b]	7.24±0.37[ab]	41.55±3.16[b]	8.17±0.43[a]
C	12.2±1.22[b]	143.6±1.06[c]	6.48±0.19[c]	34.61±2.67[c]	5.69±0.86[b]
D	13.1±1.31[b]	140.2±2.03[c]	6.35±0.26[c]	34.96±2.81[c]	6.79±0.98b
E	12.3±0.96[b]	157.9±1.11[b]	7.10±0.22[b]	39.88±1.64[b]	7.52b±0.46[a]

Mean±SE. Different lowercase letters indicate significant differences at $p \leq 0.05$ as determined by the LSD test.A=Chemical nutrient solution (control), B= Agro-fish liquid organic fertilizer, C= Nutrihumate liquid organic fertilizer, D= Rods-fert liquid organic fertilizer, E= Bio-green liquid organic fertilizer.

3.6 The Nitrate and Ammonium Content of Lettuce Leaves

Lettuce is a leafy vegetable that tends to accumulate high levels of nitrates, and since daily nitrate intake affects human health (Di Gioia et al., 2013, 2017), its concentration at harvest is an important quality characteristic. Nitrate accumulation occurs when plant nitrate intake surpasses metabolic requirements. Our results showed that the nutrition solution formula significantly influenced the nitrate levels in plant leaves (Figure 3). Lettuce plants fertilized with organic NS exhibited significantly lower nitrate levels ($p \leq 0.05$), ranging from < 3.2 to 8.7 mg/kg DW, compared to the control group at 259.8 mg/ kg DW. The use of organic solutions substantially reduced nitrate content in organically grown plants to below the EU's maximum permissible limits (European Commission, 2011) for lettuce (5000 mg/kg FW). Basil plants receiving 100% inorganic mineral NS had significant nitrate levels in their leaves; however, these levels decreased by 88% when the mineral component was reduced to 75% in favor of organic fertilizer in NS (Moncada et al., 2021). Typically, nitrate accumulation in the petioles and leaves of organic cultivation systems is lower than that in inorganic systems because the N content in organic fertilizers is primarily in the NH_4-N form, not NO_3-N, which likely accounts for the reduced NO_3-N levels in the lettuce (Miyazawa et al., 2006). Lettuce is a major source of dietary nitrate for humans (Du et al., 2007). Previous studies have shown a strong correlation between nitrate levels in leafy greens and N application, suggesting that N supply is the main factor driving nitrate accumulation in vegetable crops (Z & Li, 2004).

Regarding ammonium accumulation in leaves, significant variations were observed among the different plants. The highest NH_4-N accumulation occurred with NS B and E (164.23 and 174.30 mg/kg, respectively), while the lowest occurred with NS C and D (127.2 and 121.5 mg/kg, respectively) (Figure 3). Although excessive NH_4-N quantities can influence plant growth (Zandvakili et al., 2019), in this investigation, no detrimental impacts were observed as its concentration was insufficient to affect growth. Therefore, ammonium accumulation may result from the N metabolism in lettuce leaves.

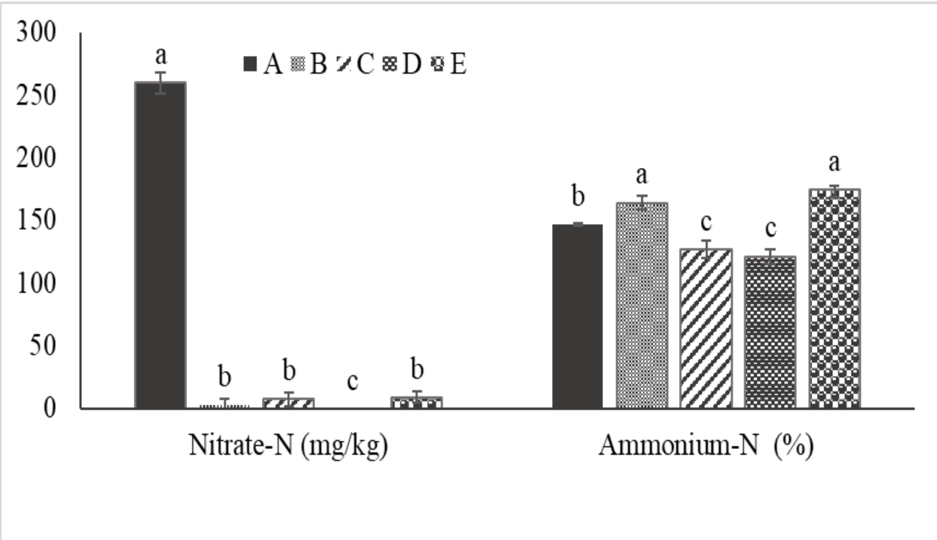

Figure 3: Effect of NS composition on leaf nitrate and ammonium content of lettuce (cultivar 'parris island cos') grown in a zero-runoff auto-pot soilless system.

3.7 Total Phenolic, Flavonoid, and Antioxidant Activity

Organically grown lettuce exhibited a higher total phenolic content than the control (Figure 4A). Lettuce treated with the NS E and C demonstrated significantly greater total phenolic content (3.36 and 3.22 g/100 g DW, respectively) ($p \leq 0.05$) compared to the control (2.28 g/100 g DW) and other NS treatments (Figure 4A). Conversely, NS D solution yielded the highest total flavonoid content (2.68 g/100g DW), while NS B produced the lowest (1.00g/100 g DW) compared with the control and other NS (Figure 4B). The synthesis of phenolic compounds is primarily regulated by two enzymes of the shikimic acid pathway: tyrosine ammonium lyase and phenylalanine ammonium lyase (Viacava et al., 2018; Vogt, 2010). These findings suggest that the source of NS significantly affects the phenolic and flavonoid contents of lettuce leaves.

The results of the antioxidant activity obtained from the DPPH scavenging assay were higher in plants produced from NS C and D than in those treated with inorganic fertilizer (Figure 4C). Plants from the NS E treatment exhibited slightly lower antioxidant activity (53.01%) (Figure 4C). The ABTS radical scavenging percentage displayed a similar trend (Figure 4D). Increased levels of chlorophyll, carotenoids, phenolics, and flavonoids influenced the antioxidant activity in the plant, consistent with previous reports (Nicolle et al., 2004; Schmidt, 2019). Therefore, the higher levels of phenolics, flavonoids, and total chlorophyll detected in lettuce plants grown with the organic solution may be the cause of the increased antioxidant activity observed in these plants (Table 4 and Figure 4A and B). The increased level of antioxidant activity is crucial as it enhances the nutritional value of the lettuce. Thus, despite lower production, the application of organic fertilizers may improve human nutrition.

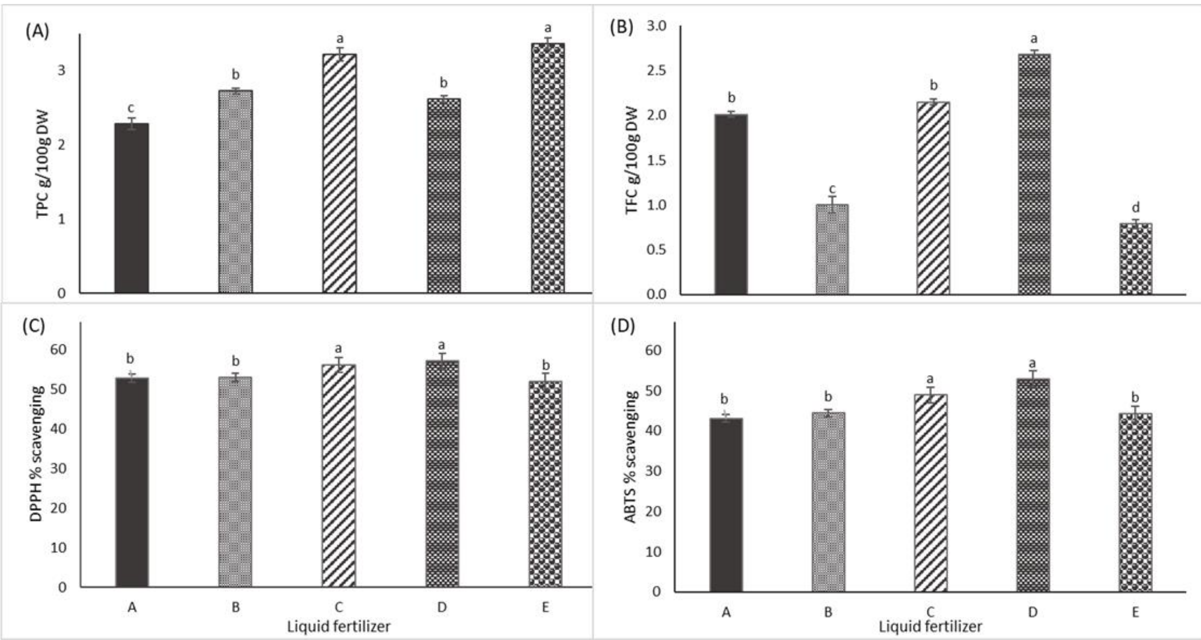

Figure 4: Effect of ns on total phenolics content (a), total flavonoid content (b), and antioxidant activity (c and d) of lettuce (cultivar ‘parris island cos’) leaves grown in a zero-runoff auto-pot soilless system using organic and inorganic liquid fertilizers.

Chapter 4: Conclusion

The aim of this study was to evaluate the effectiveness of liquid organic fertilizers derived from various organic residues such as fish farm waste, plant waste, and humic-based materials, on the growth, yield, and quality of lettuce plants within a zero-runoff auto-pot soilless system, in comparison to a conventional NS prepared with inorganic fertilizers. The present findings indicate that the performance of organic liquid NS varies greatly depending on the fertilizer source. All organic NS produced lettuce plants with lower yields compared to those grown with inorganic solutions. Nutrient solutions B (agro-fish) and E (bio-green) performed better than NS C (Nutri humate) and D (rods-fert). Interestingly, organic NS produced lower nitrate levels and higher total chlorophyll, carotene, phenolics, and flavonoid levels in organically grown lettuce, suggesting a higher antioxidant capacity and nutrition value for human consumption. Lettuce plants grown in organic NS exhibited significantly lower levels of Ca, K, and Mg but higher P levels in the lettuce leaves. This suggests that, while organic agriculture is more sustainable, organic products are increasingly recognized for their environmental and human health benefits. However, the use of organic NS in hydroponic systems presents challenges too. It is critical to modify the components used in hydroponic systems to accommodate organic fertilizers, considering factors that affect the robust plant nutrient availability. It is recommended that organic fertilizers be carefully selected, and that biofertilizers (microorganisms) be added to augment the readily availability of nutrients. Additionally, information on the NS mineral composition and nutrient availability should be provided and their water-soluble composition should be considered. By addressing these factors, a balanced organic NS specifically designed for hydroponic systems can be developed to optimize sustainable production. Further research is required to improve the efficacy of such systems and to understand their significance for food security, nutrition, and overall crop sustainability.

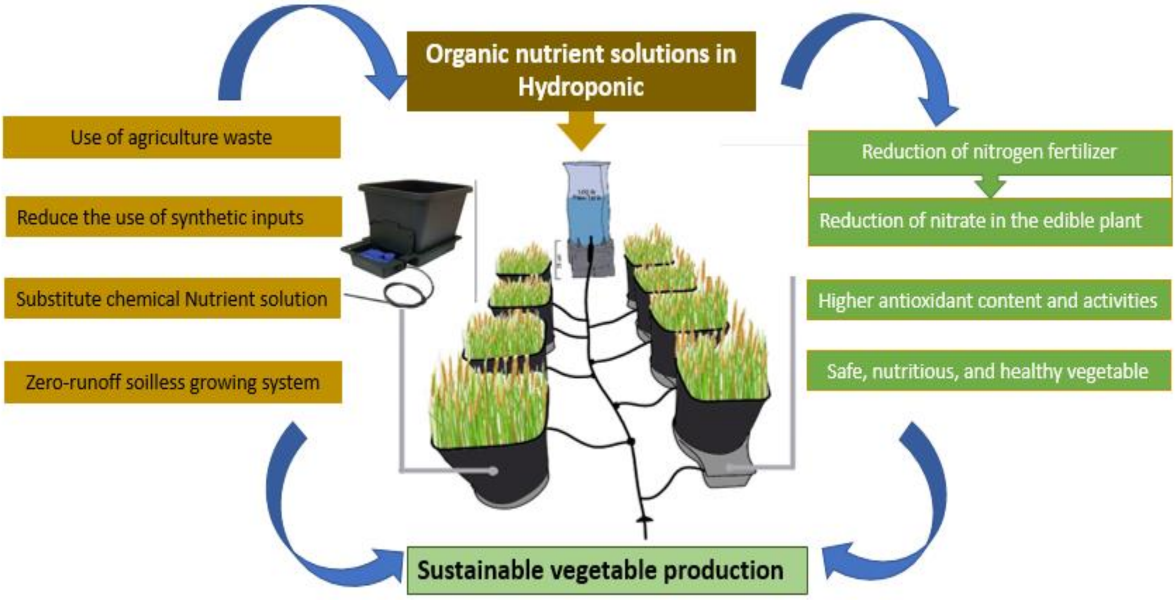

Figure 5: Graphical abstract of the sustainable vegetable production in a zero-runoff soilless growing system using organic-based nutrient solutions.

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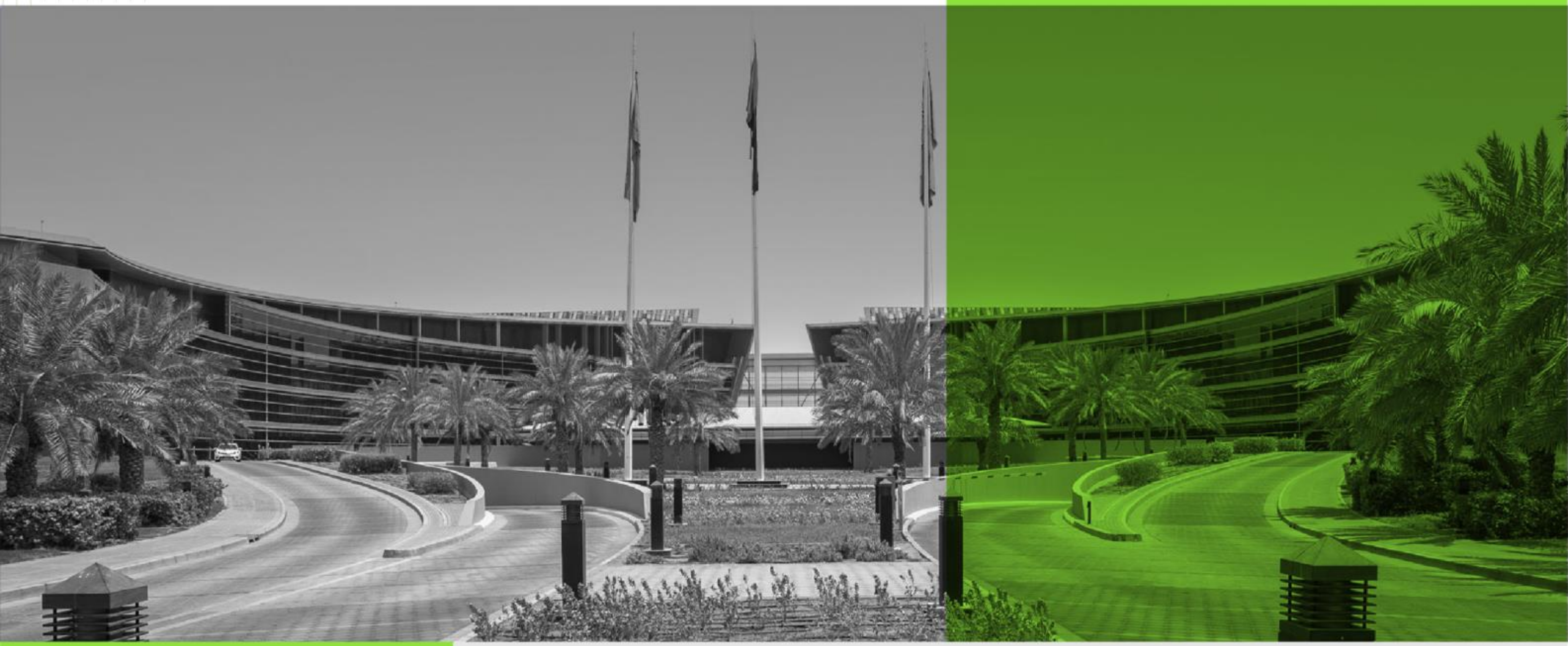

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The thesis is based on investigating the potential of substituting synthetic fertilizer nutrient solutions with organic-based alternatives in hydroponic lettuce cultivation. It explores the effects of various organic solutions on plant growth, yield, and nutrient content, comparing them to traditional synthetic fertilizer usage. Results indicate that while organic solutions may slightly reduce yield compared to synthetics, they lead to higher levels of chlorophyll, carotene, and phenolics in lettuce. The study suggests that organic liquid fertilizers have the potential to support sustainable and nutritious vegetable production.

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