Designing, Fabrication and Evaluation of a Small-Scale Vertical Hydroponic System to Produce Leafy Vegetables

By

Elham Fathidarehnijeh

A thesis submitted to the School of Graduate Studies

In partial fulfillment of the requirements for the degree of

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Boreal Ecosystems and Agricultural Sciences

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Approved:

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Date

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Abstract

The agricultural productivity in Newfoundland and Labrador (NL) faces many challenges, including severe weather conditions, short growing seasons, and poor soil conditions. To address these challenges in NL, researchers should explore innovative methods like hydroponic farming to improve local food production. This study was conducted to design, fabricate, and evaluate a household hydroponic system capable of producing year-round leafy vegetables. A vertical hydroponic system was designed, fabricated and tested along with two other systems including 1) a vertical drip hydroponic system (G-DNA), 2) a vertical wick hydroponic system (C-Tree), and 3) a horizontal deep water culture (DWC) system as the control, under two growth conditions (a grow tent experiment and an experiment without a grow tent). The growth of spinach, water use efficiency (WUE) and nitrogen use efficiency (NUE) in three systems were tested. Results showed that the G-DNA system produced significantly higher spinach yield and outperformed the C-Tree hydroponic system. While G-DNA and C-Tree hydroponic systems had no significant effect on WUE, compared to the DWC system which demonstrated nearly twice the WUE. The G-DNA system exhibited the highest NUE in both environmental conditions, suggesting that spinach in the G-DNA system could absorb more nitrogen from the nutrient solution and yield more with the same amount of absorbed nitrogen compared to DWC and C-Tree systems. These findings indicate that the G-DNA system holds greater potential for improved NUE, and higher spinach yield compared to the C-Tree system. However, the G-DNA and C-Tree systems had no significant effect on WUE.

General summary

Newfoundland and Labrador (NL) confront significant food security challenges due to limited culturable lands, short growing seasons, financial constraints, and extreme weather conditions. The province heavily relies on food imports, with over 90 % of fresh fruits and vegetables sourced from outside of NL. To address food self-sufficiency issues, there is a need to develop innovative methods and sustainable agricultural practices to enhance local food production at affordable prices to local communities to improve food security in the province. Exploring small-scale, simple, and low-cost household hydroponic systems is suggested as an alternative to producing leafy vegetables locally. Household hydroponic systems are favored in areas characterized by extreme climate conditions, offering several advantages such as enhanced vegetable growth and availability, and aesthetic pleasure. Small-scale vertical hydroponic systems have shown promising solutions, demonstrating the potential to increase crop yield compared to soil-based systems, offering adaptability to diverse settings, and addressing the need for a sustainable and cost-effective local food production system.

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List of abbreviations

ANOVA	Analysis of variance
ABS	Acrylonitrile butadiene styrene
aNUE	Absorption N use efficiency
BCR	Benefit cost ratio
BERF	Boreal Ecosystem Research Facility
C-Tree	Christmas tree hydroponic system
DO	Dissolved oxygen
DPP	Discounted payback period
DWC	Deep water culture
EC	Electrical conductivity
FACS	Fertigation automatic control system
FDR	Frequency domain reflectometry
G-DNA	Green-DNA (spiral) hydroponic system
GHG	Greenhouse gas
IoT	Internet of things
ISEs	Ion-selective electrodes
LED	Light emitting diode
LSD	Least significant difference
N	Nitrogen
NFT	Nutrient film technique
NL	Newfoundland and Labrador
NPV	Net present value

NUE	Nutrient use efficiency
PC	Pressure compensating
pNUE	Physiological N use efficiency
PRD	Partial root-zone drying
PVC	Polyvinyl chloride
RDI	Regulated deficit irrigation
RFW	Root fresh weight
RH	Relative humidity
SDW	Shoot dry weight
SFW	Shoot fresh weight
WUE	Water use efficiency

Chapter 1

1. General introduction

1.1. Overview

Newfoundland and Labrador (NL) produces only 10 % of food and is not able to meet the food demand for the population of the province (Quinlan, 2012). Agricultural activities in NL are limited by various factors, including lack of suitable agricultural lands, acidic and shallow soils, and short growing seasons (Quinlan, 2012; NL Natural Resources, 2012). Additionally, NL had the lowest number of agriculture farms among the Canadian provinces, with approximately 344 farms covering only around 20,000 ha in 2021 (Statistics Canada, 2022). The presence of aging farmers and the declining number of skilled people involved in the agricultural sector in NL have led to the abandonment of farms, resulting in a 30.1 % decrease in total farm area from 2016 to 2020 (Quinlan, 2012; Statistics Canada, 2017; Reza, 2019). In 2021, around 23 % of households in NL experienced food insecurity (Statistics Canada, 2023; Hussain & Tarasuk, 2022).

Harsh weather conditions significantly impact agricultural farms in NL, with 75 % of total farms affected by long winter and short growing seasons, 56.3 % by dry periods, and 43.8 % by low temperatures, 37.5 % by high winds, and 25 % by heavy rain as shown in Figure 1.1 (Reza & Sabau, 2022). To meet the food demands of increasing population in the province, there is a need to increase local vegetable production at affordable prices to reduce transportation, storage and environmental cost amid climate change (Gentry, 2019). Additionally, climate change, increasing food prices due to current inflation, and reliance on marine transport to carry food to the island have further motivated to develop innovative tools and practices to grow food crops locally to ensure food security in the Island. One of the innovative approaches is growing food crops in hydroponics, which enables the cultivation of plants in nutrient solution and a soilless growing medium under controlled conditions (Jafarnia et al., 2010; Agrawal et al., 2020).

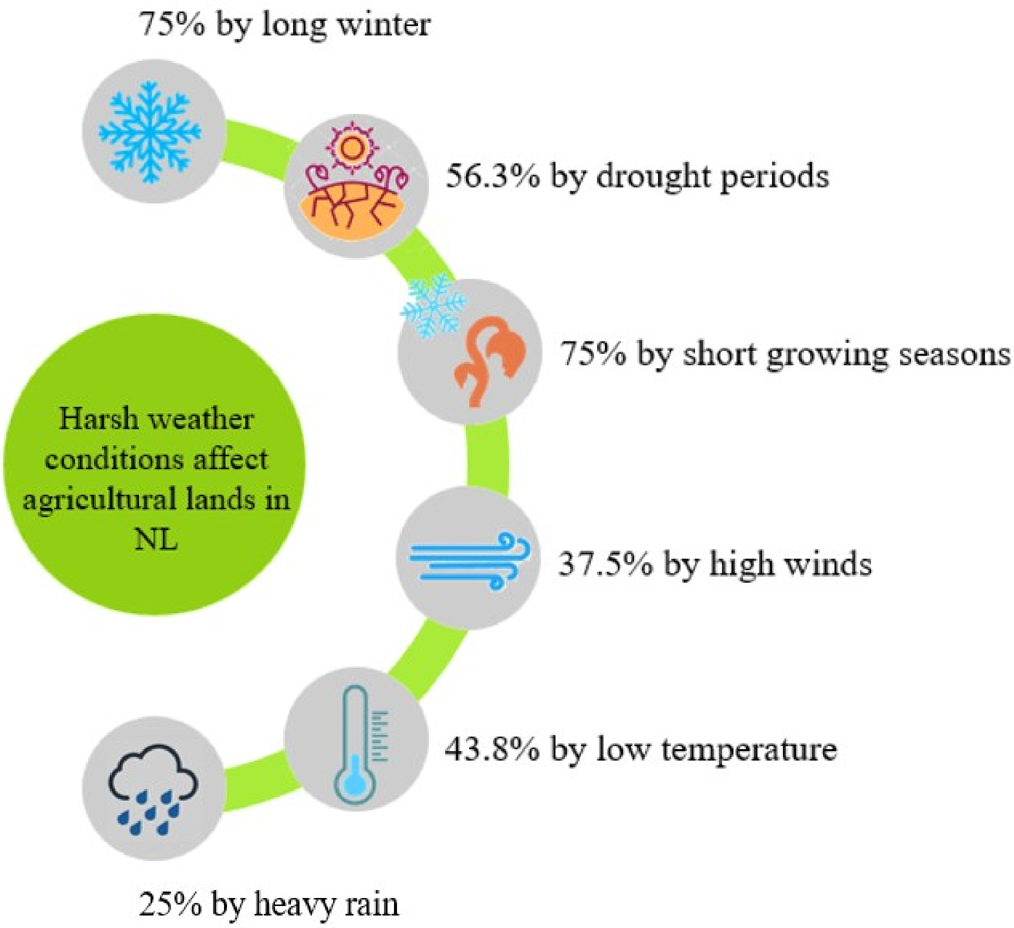

Figure 1.1: Harsh weather conditions affecting agricultural lands in Newfoundland and Labrador (NL)

1.2. Problem statement

Studying the market-available household's hydroponic systems showed pitfalls and shortcomings in some existing hydroponic systems. The common hydroponic system currently available in the market and predominantly employed by household is the deep water culture (DWC) system, in which the plant roots are immersed directly in the nutrient solution. To facilitate respiration process of root system, a small air pump is required to solubilize oxygen for the roots, which relies on power (Gillani et al., 2023). The dependence on power makes the system susceptible to potential issues during power outages, necessitating constant monitoring of both power availability and pump functionality.

The nutrient film technique (NFT) system stands out as another popular hydroponic option available in the market. In this system, a continuous flow of nutrient solution is circulated across the plant roots by using a water pump (Gillani et al., 2023). While industrial growers with a reliable power supply may not be significantly impacted by power outages, this becomes a concern for household growers. In addition, the consistent use of air or water pump in hydroponic systems can lead to increased production expenses, potentially affecting overall profits. An alternative approach to overcome this risk involves exploring other hydroponic methods that do not require continuous pump usage.

Depending on the circumstances, finding the right place for purchasing hydroponic equipment can be a time-consuming and effort-intensive task. Growers may find it necessary to thoroughly research a hydroponic system before making a purchase to ensure its performance, or they may need in-person customer service. Accordingly, online shopping experiences may be affected by factors such as product delivery reliability, the quality of information available, product variety, and the level of customer service provided (Dayananda, 2021). Many growers who opted for online purchases of hydroponic systems might be concerned about receiving substandard equipment, encountering inadequate or lacking after-sales services, dealing with shipping costs, receiving missing or broken parts, facing a lack of instructions, or struggling with the complexity of assembling.

Given the current fresh food production challenges in NL, researchers and stakeholders in the agriculture industry must explore innovative methods, such as vertical household hydroponic farming, to improve the local production of fresh vegetables and fruits. This is essential for providing affordable options to meet the demands of communities and individuals in the province. The information provided here enhances our understanding of the challenges within the market available hydroponics, prompting additional research to identify the most suitable hydroponic system for household use. This study, conducted through collaboration with the industry to meet specific requirements, involves developing a design in consultation with an industrial partner.

1.3. Objectives

This study specifically investigates the viability and efficacy of a newly developed vertical hydroponic system to grow leafy vegetables in households. The specific objectives of the study are:

1. To design, fabricate, and evaluate the performance of a small-scale vertical hydroponic system specifically for household indoor growers for leafy vegetable production.
2. To investigate the water use efficiency (WUE) and nitrogen use efficiency (NUE) of tested leafy vegetable grown in a newly developed vertical hydroponic system.

1.4. Thesis organization

The thesis is organized in a manuscript style and divided into five chapters. The thesis has a general introduction chapter, literature review chapter, technical chapter, stand-alone chapter (manuscript format), and general discussion and conclusion.

Chapter 1: This is the general introduction chapter of the thesis. It provides the overview of the background information, rationale, and objectives of the thesis.

Chapter 2: The chapter reviews the “Current perspective on nutrient solution management strategies to improve the nutrient and water use efficiency in hydroponic systems”.

Chapter 3: This chapter is about “Designing and fabrication of a small-scale vertical hydroponic system (Christmas-tree system) for households”.

Chapter 4: This chapter assesses the “Performance evaluation of two newly designed vertical hydroponic systems for growth, water use, and nitrogen use efficiencies of spinach”.

Chapter 5: This chapter presents an overall discussion about study findings and conclusion. Also, this chapter provides the recommendations for further studies.

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Co-authorship statement

Manuscript based on the chapter 2, entitled “Current perspective on nutrient solution management strategies to improve the nutrient and water use efficiency in hydroponic system” has been published in Canadian Journal of Plant Science [https://doi.org/10.1139/cjps-2023-0034]. Elham Fathidarehnijeh, the thesis author was the primary author and collected the data and drafted the review manuscript. Dr. Lakshman Galagedara (supervisor) was the corresponding and the last author. He helped to design the layout of the manuscript, reviewed, and edited the manuscript. Dr. Muhammad Nadeem and Dr. Mumtaz Cheema (Committee members) helped to design the layout of the manuscript, reviewed and finalized the manuscript. Dr. Raymond Thomas and Dr. Mano Krishnapillai reviewed and edited the manuscript.

Chapter 2

2. Current perspective on nutrient solution management strategies to improve the nutrient and water use efficiency in hydroponic systems

2.1. Abstract

Hydroponics, a soilless cultivation technique using nutrient solutions under controlled conditions, is used for growing vegetables, high-value crops, and flowers. It produces significantly higher yields compared to conventional agriculture despite its higher energy consumption. The success of a hydroponic system relies on the composition of the nutrient solution, which contains all the essential mineral elements necessary for optimal plant growth and high yield. This review delves into the discussion of enhancing nutrient solution management strategies across different hydroponic systems. The aim of this review is to discuss various techniques for monitoring nutrient solutions in order to improve nutrient use efficiency (NUE) and water use efficiency (WUE). The conventional approach of monitoring the hydroponic nutrient solution using electrical conductivity measurement may not provide precise information about ion concentrations, potentially resulting in poor yields or excessive fertilizer usage. To overcome these limitations, alternative management strategies have been developed to enable more accurate monitoring and efficient management. One such strategy is the nitrogen-based approach, where nitrogen concentration becomes the primary controlled element in the nutrient solution and leads to WUE and NUE development by prolonging nutrient solution recirculation. Furthermore, various methods have been devised to improve nutrient solution strategies. These include using ion-selective electrodes to measure individual ions in the hydroponic nutrient solution, using sensors to monitor substrate moisture content, estimating water requirements, and implementing programmed nutrient addition methods. In addition to introducing different management techniques to optimize hydroponic performance, this review provides a better understanding of hydroponic systems.

Keywords:

Hydroponics, closed-loop hydroponics, open hydroponics, nutrient use efficiency, water use efficiency

2.2. Introduction

The global population is rapidly increasing, estimated to reach ~9.7 billion in 2050 (United Nations, 2014). Thus, it is estimated that 70 % more food production will be required to feed this growing population (Silva, 2018). To meet this increasing populations' food and feed demands, there is an urgent need to use innovative approaches to enhance the availability of fresh food produced across the globe (Pascual et al., 2018). However, water shortage is one of the most important challenges for food production, and increasing food production could negatively affect water resources (Mancosu et al., 2015; Nicola et al., 2020). The agricultural sector is the major consumer of freshwater, with over 70 % of annual water withdrawals (FAO, 2017), and some traditional open-field soil-based farming increases water usage due to deep leaching, runoff, and evaporation (Bar-Yosef, 2008; Putra and Yuliando, 2015). On the other hand, climate change will bring drought or uneven precipitation, negatively affecting agricultural activity and productivity (Barbosa et al., 2015; Abukari and Tok, 2016).

Greenhouse cultivation systems increase water and fertilizers productivity compared with open-field soil-based cultivation systems due to better control of environmental conditions and inputs (Rouphael and Colla, 2009; Rosa-Rodríguez et al., 2020). However, it is necessary to minimize water and nutrient consumption to decrease the costs and water requirements in the greenhouse systems as well as to minimize adverse environmental impacts (Rouphael et al., 2004). One of the promising approaches to boost vegetable production to enhance food security is growing vegetables in hydroponics: the cultivation of plants in nutrient solution and a soilless growing medium under controlled environmental conditions (Jafarnia et al., 2010; Agrawal et al., 2020).

The nutrient solution supplies the essential elements containing macro- and micronutrients with optimum concentrations for plant growth and metabolism (Sharma et al., 2018). It is essential to keep the nutrient solution in an optimum range of nutrient concentration by adjusting the solution (Wada, 2019). However, imbalanced nutrients may cause nutrient deficiencies in crops grown in hydroponics, significantly restricting crop production. Additionally, excessive use of fertilizer can increase the cost of production, plant toxicity, and environmental pollution and decrease crop quality (Patra et al., 2016; Rahman and Zhang, 2018). It is important to underline that hydroponically grown plants quickly show the symptoms of nutrient toxicity or deficiency compared to soil-based grown plants (Sathyanarayan et al., 2023).

Due to the reasons aforementioned, the nutrient solution is a substantial factor in hydroponics; thus, proper nutrient solution management is essential to improve nutrient use efficiency (NUE) and water use efficiency (WUE) in hydroponic cultivation systems. This review discusses different nutrient solution management strategies to enhance NUE and WUE in different hydroponics systems.

2.3. Hydroponic systems

The hydroponic system is the technique of growing vegetable crops in a nutrient-rich solution or soilless environments such as rockwool, coir, perlite, peat moss, coconut husk, gravel, coarse sand, mineral wool, vermiculite, or sawdust (Asao, 2012; Sharma et al., 2018). Hydroponics is derived from the Greek words that mean water work, consisting of “hydro” which means water, and “ponos” means labor. The word hydroponics was coined by Professor William Gericke in the 1930s (Sharma et al., 2018). Similar to hydroponics, the floating gardens of Babylon, Egypt, and Mexico in the Aztecs times indicate that water gardens have been practiced for centuries. Similar to the floating raft hydroponic systems, the floating gardens were practiced as a cultivation method (Pachauri et al., 2014). In 1887, the first nutrient solution for soilless cultivation systems was developed by Sachs and Knop (Hershey, 1994; El-Ramady et al., 2014). The hydroponic method is successfully used for fast-growing leafy vegetables and commercial crops, such as lettuce (*Lactuca sativa* L.) (Holmes et al., 2019), spinach (*Spinacia oleracea* L.) (Janeczko and Timmons, 2019), potato (*Solanum tuberosum* L.) (Chang et al., 2012), tomato (*Solanum lycopersicum* L.) (Verdoliva et al., 2021), kale (*Brassica alboglabra* L.) (Yanti et al., 2020), pepper (*Capsicum annuum* L.) (Singh et al., 2019), cucumber (*Cucumis sativus* L.) (Zhang et al., 2023), and strawberry (*Fragaria ananassa* L.) (Talukder et al., 2019).

Hydroponics has multiple advantages compared to open-field soil-based farming (Table 2.1). However, hydroponics has a few limitations, including high initial setup cost, energy, vulnerability to power outage due to water and air pump utilization, and knowledge requirements for operation and maintenance (Domingues et al., 2012; Hashida et al., 2014). Moreover, higher energy consumption in hydroponic systems may increase greenhouse gas emissions (GHG), which can be optimized using longer service life materials and renewable energy. High fuel and electricity utilization, machinery, irrigation systems, and transportation increase energy consumption, which may lead to high GHG emissions (Martinez-Mate et al., 2018).

Delivering a nutrient solution to the root zone is the key process in hydroponics systems. The hydroponic systems employ different techniques to supply nutrient solution, such as deep water culture (DWC), ebb and flow system, nutrient film technique (NFT), wick system, and drip system (Fig. 2.1) (Agrawal et al., 2020). The DWC technique is one of the most common hydroponic methods in which the plant roots are submerged in an aerated nutrient solution (Bodenmiller, 2017). The ebb and flow system is a flood and drain hydroponic system in which the roots are periodically flooded with the nutrient solution through a water pump. A water pump supplies nutrient solution to plants, and the roots are allowed to absorb moisture and uptake nutrients; then, the excess nutrient solution drains to a reservoir, and the roots can take oxygen during this draining time (Nicola et al., 2006).

In the NFT, the roots are constantly submerged in a thin flowing nutrient solution (Suhl et al., 2019). One of the simplest types of hydroponic systems is the wick system in which the nutrient solution is delivered to the roots through wicks via capillary action. Indeed, wicks distribute nutrient solutions from the reservoir to the growing media (Ali et al., 2021). In a drip hydroponic system, the nutrient solution is applied directly to the growing media through drippers, and plant roots absorb water and nutrients from the media (Graham et al., 2011).

Another method of growing leafy vegetables in hydroponics is the vertical hydroponic system, which can increase crop production per unit area to meet the demand for food production in an urban area that suffers from a lack of enough space (Al-Chalabi, 2015). In this system, the nutrient solution is delivered to the top and drained under gravity to the bottom of the vertical hydroponic system (Singh and Dunn, 2017). Researchers have suggested that vertical hydroponics appears to be a promising solution for urban areas to increase land and crop productivity and support local food security targets (Zhang et al., 2018; Martin and Molin, 2019).

Table 2.1: Advantages of hydroponic systems compared to the open-field soil-based cultivation system.

Advantages	Hydroponic system	Soil-based farming	References
Weed control	No weeds	Growing regularly	Saijai et al. (2016); Vidhya and Valarmathi (2018)
Pest control	Minimize the need for pesticides	High application of pesticide	Vidhya and Valarmathi (2018)
Soil-borne diseases	No soil-borne diseases	Many soil-borne diseases, insects, nematodes	Ezzahoui et al. (2021)
Water	Efficient water use, able to recycle water	More water consumption, due to low water holding capacity, high evaporation, deep percolation, and runoff	Verdoliva et al. (2021); Kwon et al. (2021)
Fertilizers	Efficient fertilizer use due to no leaching and uniformly distributed to all plant roots by nutrient solution	More fertilizer use, due to leaching and non-uniform distribution to the plants on soil (for example about 60 % nitrogen lost in soil-based cultivation system)	Malyan et al. (2016); Kwon et al. (2021)
Plant growth	Due to controlled conditions, plants can grow faster, and manifold higher yield compared to field conditions.	Slower growth compared to controlled conditions, unstable production amount	Eigenbrod and Gruda (2015); Majid et al. (2021)
Climate conditions	Controlled conditions such as temperature, and humidity	Dependent on meteorological conditions due to uncontrolled conditions	Kwon et al. (2021)
Labor	Less labor requirement	More labor requirement for pest control, weeding, and fertilizer application	Eigenbrod and Gruda (2015); Sreedevi and Kumar (2020);
Environmental effects	Minimize environmental pollution due to eliminating leaching and runoff	Environmental contamination due to nutrients leaching into the groundwater and surface water	Kwon et al. (2021); Stein (2021)

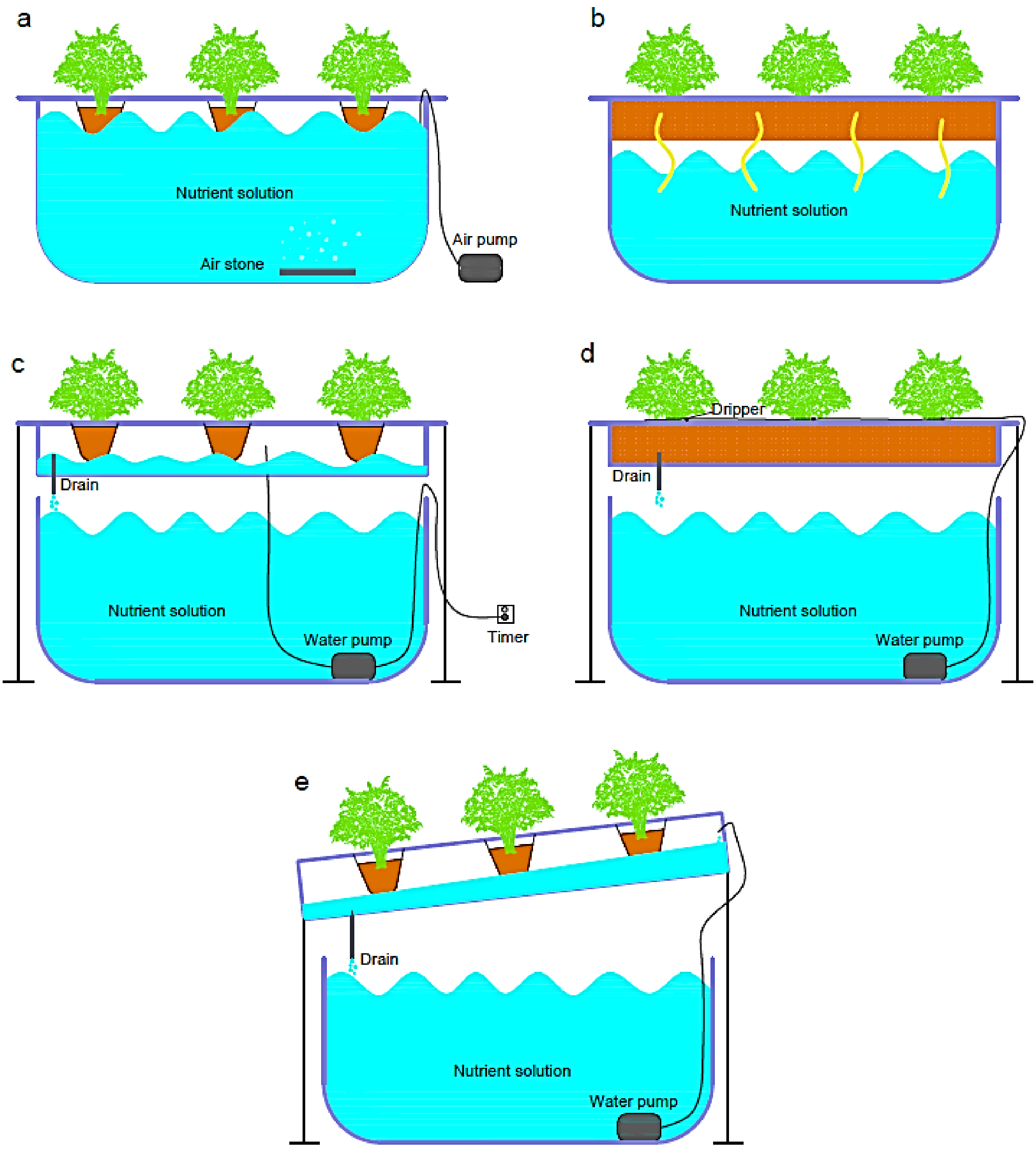

Figure 2.1: Different types of hydroponic systems, deep water culture (DWC) system (a), wick system (b), ebb and flow system (c), drip system (d), and nutrient film technique (NFT) system (e).

2.4. Classification of hydroponics as a recirculation system

Hydroponics increases water and fertilizer productivity due to better control of environment and water and nutrient management by recirculating the nutrient solution (Rouphael and Colla, 2009; Rosa-Rodríguez et al., 2020). Two main hydroponic systems are based on recirculating the nutrient solution, that is, open- and closed-loop hydroponic systems.

2.4.1. Open- and closed-loop hydroponic systems

In open hydroponic systems (Fig. 2.2a), the nutrient solution is drained after passing through the crop root zone, and the nutrient solution is not recirculated back to the root zone after usage (Maboko et al., 2011). Nevertheless, a proper hydroponic system that can reduce water and nutrient application and negative environmental impacts is essential. A closed-loop hydroponic system (Fig. 2.2b) is an effective nutrient solution management approach in which leachate is reused and reduces the negative aspects such as the disposal of nutrient solution to the environment (Rouphael and Colla, 2005a, 2005b; Sanjuan-Delmás et al., 2020). The open hydroponic system can be run as a drip (Mendez-Cifuentes et al., 2020; Fayezizadeh et al., 2021), NFT (Santos et al., 2022), or DWC (Shohael et al., 2017) system, and nutrient solution application in a closed-loop system can be carried out in the form of drip (Verdoliva et al., 2021; Rosa-Rodríguez et al., 2020), NFT (Silva et al., 2020), DWC (Silva et al., 2020; Hebbar et al., 2022), or ebb and flow (Rouphael and Colla, 2005a; Incrocci et al., 2006) system.

Fayezizadeh et al. (2021) compared WUE in tomato production in open- and closed-loop drip hydroponic systems. The authors concluded that closed-loop systems had 54.3 % higher water productivity compared to open systems, with an average WUE of 33.7 g of tomato produced per liter of water used in a closed-loop system followed by the open system with 21.84 g L^{-1}. Furthermore, the closed-loop system reduced fertilizers consumption (2.53 kg) during the entire crop cycle by 96 % compared to the open system (4.95 kg). Accordingly, the closed-loop hydroponic system was able to enhance water and fertilizer savings without a significant crop yield reduction compared to the open hydroponic system. These findings are consistent with Mendez-Cifuentes et al. (2020) who compared an open drip hydroponic system and a closed-loop ebb and flow hydroponic system. The closed-loop system produced 9.5 % lower biomass, compared to the open system. However, the open system consumed twofold water (41 L) to produce 1 kg of fresh tomatoes than the closed-loop system with 22 L of water consumption. Furthermore, fertilizers consumption was around 59 %-75 % lower in the closed-loop system.

Rosa-Rodríguez et al. (2020) and Katsoulas et al. (2013) observed a similar trend that closed-loop hydroponic systems have a higher WUE and NUE than open hydroponics due to the recirculation of the nutrient solution. Maboko et al. (2011) in a study on the plant growth performance in open drip and closed-loop NFT hydroponic systems concluded that the closed-loop system increased the marketable yield of tomato as well as nutrient solution efficiency compared with the open system.

Rouphael and Colla (2005a) compared the WUE of two closed-loop hydroponic systems (drip-irrigation and ebb and flow) while growing zucchini (*Cucurbita pepo* L.). The water requirement of zucchini was 53 % lower in the summer-fall season compared to the spring-summer season due to low air temperature and reduction in the evaporative demand. Likewise, both hydroponic systems had higher WUE in the summer-fall season (around 34 g L^{-1}) compared to the spring-summer season (around 23 g L^{-1}). However, ebb and flow produced higher WUE (reduced water requirement by around 24 %) than drip irrigation during the spring-summer season. During the spring-summer season, the ebb and flow system used 40.5 L of the nutrient solution to produce 1 kg of fruits, while the drip irrigation system needed 44.2 L of the same nutrient solution. A significantly lower WUE was observed in drip irrigation, that is, 22.6 g L^{-1} in the spring-summer season, than in the ebb and flow system by 24.7 g L^{-1}.

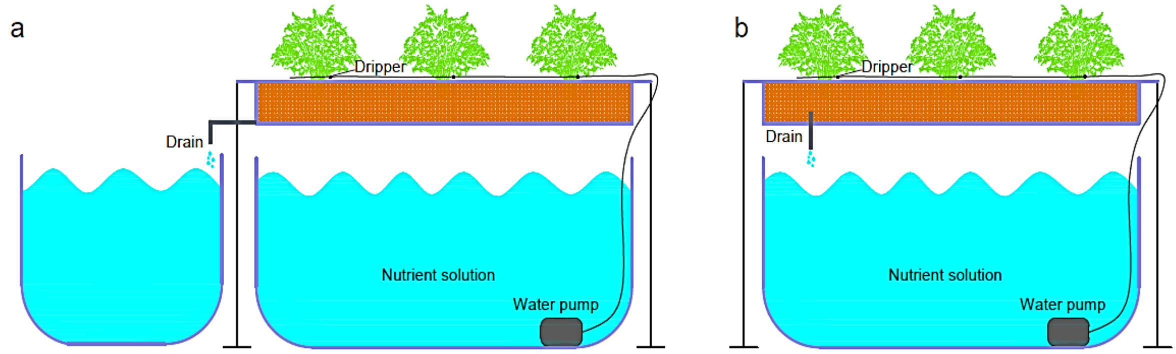

Figure 2.2: Illustration of an open-loop drip hydroponic system (a) and a closed-loop drip hydroponic system (b).

2.4.2. Advantages and disadvantages

The advantages of closed-loop hydroponic systems over open systems include reduced water use, nutrient usage, and environmental pollution (Rouphael and Colla, 2005a; Valenzano et al., 2008; Rodríguez-Jurado et al., 2020; Fayezizadeh et al., 2021). However, the recycling of nutrient solution in closed-loop hydroponic systems can cause excess ions accumulation, such as sodium and chloride, in the substrates and the root zone, resulting in higher salinity (Ehret et al., 2005; Rouphael and Colla, 2005a; Rouphael et al., 2006). High consumption of nutrients by crops from highly concentrated nutrient solutions in a closed-loop system may cause negative effects such as nutrient toxicity and reduction in yield and crop quality (Pardossi et al., 2002).

Nutrient imbalance often occurs in closed-loop hydroponic systems (Ko et al., 2013a). Nutrient concentration can rise in the nutrient solution over time due to water loss by evapotranspiration, which increases the electrical conductivity (EC) of both the nutrient solution and the growing media (Ahn and Son, 2011; Eridani et al., 2017). Therefore, the regular monitoring of ions concentrations or EC in the nutrient solution in a closed-loop system is extremely important (Ko et al., 2013a). The ion imbalance commonly occurs in a long-term crop growth cycle, which leads to a crop yield reduction due to deficiency or toxicity of nutrients (Nakano et al., 2010); therefore, the recycled nutrient solution should be refreshed or changed periodically (Savvas et al., 2005; Incrocci et al., 2006). Moreover, high EC can cause extreme osmotic conditions and plants stomatal conductance reduction (Rodríguez-Ortega et al., 2019; Nemeskéri et al., 2019; Fayezizadeh et al., 2021).

On the other hand, open hydroponics are easy to manage compared to closed-loop hydroponics, as the used nutrient solution is drained; then, a new nutrient solution is prepared and supplied. However, the discharge of nutrient solution, especially containing nitrate nitrogen (NO_3^-–N) and phosphorous, contaminates water resources, which may cause eutrophication in the surface water bodies as well as some diseases such as blue baby syndrome because of high NO_3^-–N concentration in drinking water (Putra and Yuliando, 2015; Zamora-Izquierdo et al., 2019; Kwon et al., 2021). Moreover, open hydroponics indicates low water and nutrients productivity and economic returns due to the high cost of production with increased hydroponics inputs (Kitta et al., 2015).

The closed-loop system is more economically efficient than open hydroponics in terms of water and fertilizer savings, up to 90 % and 85 % in closed-loop versus 85 % and 68 % in open systems (Castillo et al., 2014; AlShrouf, 2017). However, an open hydroponic system prevents salt accumulation in the root zone and growing media (Schröder and Lieth, 2002). The studies described above have been selected to reveal that closed-loop hydroponic systems have higher WUE and NUE than open hydroponic systems due to the recycling of nutrient solution in closed-loop systems. Future research is required to introduce a nutrient solution management technique to resolve ion imbalance in the closed-loop systems, which may lead to a reduction in ion toxicity or deficiency for crops.

2.5. Nutrient solution management in hydroponic systems

Optimal nutrient solution management can lead to a high water and nutrient efficient system. A better management of nutrient solution in hydroponic systems requires optimum pH, EC, or ions concentration (Rijck and Schrevens, 1995). The pH of a nutrient solution is one of the most important factors affecting nutrient availability, uptake, and solubility. The optimum pH range for plants is between 5.5 and 6.5 in which the plants have readily available nutrients (Domingues et al., 2012; Majid et al., 2021; Gillespie et al., 2021). For example, high pH increases the precipitation of calcium and magnesium and reduces the solubility of iron and phosphate in the nutrient solution, which forms the ions as the unavailable nutrients for roots and inhibits the absorption of micronutrients such as iron, copper, zinc, and manganese (Singh et al., 2019; Gillespie et al., 2020; Velazquez-Gonzalez et al., 2022). On the other hand, low pH decreases the absorption of macronutrients, including nitrogen, phosphorus, potassium, calcium, and magnesium (Velazquez-Gonzalez et al., 2022). Although pH stabilization is important in the nutrient solution, the pH fluctuation frequently occurs in hydroponics due to low buffering capacity of the substrates in hydroponics compared to soil. Moreover, roots release anion and cation, such as HCO_3^- and H^+, to absorb nutrients, which leads to unbalanced anion and cation exchange and pH fluctuation in the substrate (Singh et al., 2019). Therefore, an optimum pH range should be maintained for proper plant growth. Adopting the optimal nutrient solution management strategy to reduce water and nutrient consumption and the cost of production to increase crop growth is essential (Rouphael et al., 2016; Gumisiriza et al., 2022).

2.5.1. EC-based management strategy

Since the EC value represents the nutrient concentration of the solution, in most previous studies and general practice, the monitoring of the nutrient solution is based on the measurement of EC few times daily (Wortman, 2015; Majid et al., 2021). Nutrient concentration alteration occurs over time due to plant nutrient uptake, crop growth, and evaporation. When the EC value drops from a specific threshold or exceeds the optimum range of 1.5–2.5 dS m^{-1}, the nutrient solution with a corrected concentration should be recirculated (Rouphael et al., 2016; Majid et al., 2021; Kannan et al., 2022). Plant nutrient uptake decreases the EC depending on the crop growth stage, while evaporation may increase the EC and salt concentration in the coco coir bags or any other substrates (Majid et al., 2021). However, plants uptake more water than mineral nutrients which may, in general, cause an increase in the nutrient concentration and, subsequently, increase the EC or salt concentration in the nutrient solution over time (Eridani et al., 2017; Lee et al., 2017; Son et al., 2020; Fayezizadeh et al., 2021).

EC monitoring is the most commonly used approach as the nutrient solution management strategy because its measurement is fast, simple, low-cost, and can be used directly in situ. However, the EC value indicates only the total amount of dissolved ions in the nutrient solution without indicating the individual ions’ concentrations (macronutrients or micronutrients) in the solution (Massa et al., 2008; Neto et al., 2014). Regardless of the importance of the balanced nutrient feed, plants require a high rate of specific macronutrients such as nitrogen to produce more leaves in leafy vegetables or potassium and calcium to produce high-quality fruits in crops such as tomatoes. Thus, the nutrient solution adjustment requires applying the correct amount of required ions at different growth stages based on the crop requirements (Lee et al., 2017). Additionally, plants’ uptake of each ion is different, which may cause a nutritional imbalance in the solution, leading to some plant physiological disorders (Pardossi et al., 2002; Lee et al., 2017). For example, tomatoes require high amounts of calcium, potassium, and nitrogen for increasing plant growth, productivity, and fruit quality (Lee et al., 2017; Tavallali et al., 2018).

Lee et al. (2017) investigated EC-based nutrient supplementation in a closed-loop hydroponic system for tomato cultivation. The mineral composition or the concentrations of the ions were analyzed to compare the micro- and macronutrients concentration variation with the EC variation. Different techniques were applied to determine the concentrations of the ions, including ion chromatography, ion-specific electrodes, colorimetric, and inductively coupled plasma optical emission spectroscopy. The results showed that EC variation followed the NO_3^-, SO_4^{2-}, Mg^{2+}, Ca^{2+}, and K^+ concentration in the nutrient solution over the crop growth due to slow ions uptake in the initial stage and rapid uptake during the flowering stage. However, the concentration of PO_4^{3-}-P, Na^+, Cl^-, and the other micronutrients did not follow the EC variation. Therefore, a specific ion-based nutrient solution management is necessary compared to the EC-based nutrient control to improve crop growth and yield while minimizing the production cost.

2.5.2. Nitrogen-based management strategy

An effective alternative to manage the nutrient solution in hydroponics is the measurement of macronutrients in the solution, which will help to understand useful information on the main ions in the nutrient solution. The essential nutrients such as NO_3^--N, phosphorous, and potassium can be controlled using ion-selective electrodes, which efficiently control macronutrient supply. This nutrient solution management technique may decrease water and nutrient consumption by prolonging the recirculation of the solution in closed-loop hydroponic systems (Pardossi et al., 2006; Massa et al., 2010).

Among fertilizers, nitrogen is an essential macronutrient required for leaves, crop growth, quality, taste, and enhanced grain yield, as well as biosynthesis of cellular components such as proteins, enzymes, hormones, and amino acids (Goins et al., 2004; Barker and Pilbeam, 2007;

Maathuis, 2009; Geary et al., 2015). Since nitrogen is the most essential nutrient for crop productivity (Robin, 1998), the appropriate management of the nitrogen in the nutrient solution could decrease nitrogen wastage in hydroponic systems (Sonneveld and Voogt, 2009; Massa et al., 2010). The NO_3^--N analysis of the nutrient solution can be conducted in the laboratory or in situ using a reflectometer (Massa et al., 2010) or quick test kits (Maggini et al., 2010).

Massa et al. (2010) compared the effects of three fertigation strategies on the NUE and WUE in a semi-closed hydroponic system for tomato. In strategy A, the recirculating nutrient solution was flushed out whenever the EC value reached 4.5 dS m^{-1}. In strategy B, NO_3^--N was measured with a reflectometer every 2-4 days, and the recirculating nutrient solution was discharged whenever NO_3^--N concentration dropped below 0.07 g L^{-1}. In strategy C, when the EC value reached 4.5 dS m^{-1}, water was added to reduce NO_3^--N concentration below 0.07 g L^{-1}. The results showed that a short-term lack of nutrients and by prolonging the recirculation of nutrient solution due to frequent EC and NO_3^--N concentration measurements reduced the water and fertilizers use and nitrogen losses. Indeed, strategy B led to the highest nitrogen use efficiency, around 344 g g^{-1}, and strategy C resulted in the best WUE of 22 g L^{-1} by prolonging the recirculation of the nutrient solution. The NO_3^--based strategy indicates the nitrogen concentration of the solution; however, the EC-based method exhibits the ions concentration of the solution. The EC-based method does not indicate the amounts of vital elements separately, which may show fertilizers requirement more quickly than the NO_3^--based method. In other words, by accurately monitoring the nitrogen concentration, this nutrient solution management strategy might extend the solution's recirculating time, which can enhance WUE and NUE.

Rouphael et al. (2016) compared two nutrient management strategies, EC based and NO_3^--based, in a hydroponic system to assess the amaryllis (Hippeastrum hybridum) growth and

WUE. In the EC-based strategy, when the EC value exceeded 3 dS m^{-1}, the nutrient solution was discharged, and in the NO_3^--based strategy, the nutrient solution was recharged when the NO_3^--N concentration dropped from 1.42 to 1mol m^{-3}. The results demonstrated that the NO_3^--based strategy did not significantly affect plant growth and quality compared with the EC-based approach. The EC-based strategy increased total water use by about 61.5 % compared with the NO_3^--based strategy, due to higher nutrient solution flushing events. Additionally, the nitrate, phosphate, and potassium losses were 23, 4.5, and 3.5 times higher, respectively, in the EC-based strategy than the NO_3^--based strategy. The number of flowers and flower dry weight was significantly higher in the NO_3^--based strategy. However, both nutrient solution management strategies did not significantly affect the other plant growth parameters, such as stem number, number of leaves, total dry weight, and total leaf area in amaryllis production.

2.5.3. Other nutrient solution management strategies

Neto et al. (2014) developed a fertigation automatic control system (FACS) for tomato cultivation in a hydroponic system. The FACS method estimates transpiration using the Penman‑Monteith model and maintains the EC values of the drained nutrient solution under the specific limits (3 ± 0.8 dS m^{-1}). The plant transpiration was estimated by measuring the atmospheric variables of the cultivation system, including air temperature, air humidity, and solar radiation. The results showed that the FACS strategy improved WUE and NUE due to adjusting fertigation frequency and reducing environmental issues related to the discharge of the nutrient solution.

Another alternative method to manage the nutrient solution is pre-arranged nutrient addition in which some specific elements are added to the nutrient solution in a particular period. Pardossi et al. (2002) compared the conventional EC-based nutrient solution management with the programmed nutrient addition to produce melon (Cucumis melo L.) in an NFT system. In the

EC-based strategy, the EC value was maintained at 2.5 dS m^{-1}, and when NO_3^- concentration dropped below 0.085-0.09 g L^{-1}, the nutrient solution was replaced. In the pre-arranged nutrient solution strategy, nitrogen, phosphorus, and potassium were weekly added to the solution at a recommended rate for melon without EC or ion concentration measurement. The results did not show a significant difference in fruit yield or quality, but pre-arranged nutrient addition decreased water and nutrient consumption by 40 %-60 % compared to the EC-based management method (Pardossi et al., 2002).

Rouphael and Colla (2009) studied the effects of drip irrigation and ebb and flow hydroponic systems on the zucchini squash (*C. pepo* L.) growth with half-strength (1 dS m^{-1}) and full-strength (2 dS m^{-1}) nutrient solution. Zucchini yield was significantly affected by different nutrient solution application methods and nutrient solution concentration. The yield was higher in the drip irrigation system compared to the ebb and flow system. The ebb and flow system resulted in higher EC in the growing media due to capillary action compared to the drip irrigation system, which led to the accumulation of mineral elements in the growing media and resulted in the unavailability of nutrients for plants. The marketable zucchini yield decreased in the half-strength solution compared with a full-strength nutrient solution by around 58 % and 42 % in ebb and flow and drip irrigation systems, respectively. Furthermore, the full-strength nutrient solution resulted in the highest nitrogen, phosphorus, and potassium concentration in leaves in both systems. The lowest plant growth, yield, and mineral concentration in the fruit were observed under the half-strength solution under the ebb and flow system. Similarly, the half-strength solution significantly reduced the fruit yield and mineral concentration in the fruit.

Ko et al. (2013b) claimed that the recycled nutrient solution's renewal (adjustment of the reused nutrient solution) could reduce the ion imbalance in the solution while improving WUE and

NUE in closed-loop and open hydroponic systems. The experiment compared three different nutrient solution renewal intervals of 4, 8, and 12 weeks to investigate the crop yield and the water and nutrient uptake by paprika (*C. annuum* L.). The results indicated that the 12-week renewal period produced the lowest fruit yield, and the highest deviation of cation ratios, Ca^{2+}, K^+, Mg^{2+}, and Na^+, from the initial nutrient values. Authors found higher accumulation of SO_4^{2-}, Na^+, and Cl^- in the nutrient solution under a 12- week period compared to 4- and 8-week periods potentially contributing to the lowest fruit yield. There was no significant difference between the open system under 4- and 8-week intervals regarding total fruit yield. Further, the 4-week renewal period resulted in the best ion balance and the highest uptake of K^+ in the closed-loop hydroponic system. Furthermore, the open hydroponic system observed the highest water and nutrient consumption.

Continuous monitoring of the elements in the nutrient solution using ion-specific nutrient management methods leads to efficient use of nutrients in the solution (Jung et al., 2019). Cho et al. (2018) developed an on-situ ion monitoring system using ion-selective electrodes (ISEs) to measure the concentrations of NO_3^-, K^+, and Ca^{2+} ions in the hydroponic nutrient solution for growing paprika in a greenhouse. The developed ISEs monitored the drainage solution five times daily based on automatic sampling and electrode rinsing. To validate the developed monitoring system, the manually taken samples were analyzed to determine the ion concentrations in the solution using ion chromatography and inductively coupled plasma spectrophotometry. The results showed that the developed monitoring system estimated the NO_3^- concentration in a strong linear relationship with a slope of 0.99 with the ion chromatography results. However, the developed ISEs system overestimated the concentrations of K^+ with a slope of 1.17 and underestimated the concentrations of Ca^{2+} with a slope of 0.75. Despite the deviations in measuring K^+ and Ca^{2+} concentrations, the linear relationships above 0.97 indicate that ISEs could be feasible for nutrient solution management in hydroponic systems. This response is in close agreement with the results of Kim et al. (2023) who showed that the ISE technology can be considered a potential method to control macronutrients in the nutrient solution.

The effects of two different nutrient solution management strategies were evaluated by Solis-Toapanta et al. (2020) on hydroponically grown tomato. In the first treatment, the nutrient solution was replaced biweekly; in the second treatment, the same amount of nutrient was added to the solution biweekly without replacement. The treatment without solution replacement affected the fruit fresh weight by about 18 % compared to biweekly replacement due to the high EC of the nutrient solution. In fact, the EC of the solution with replacement remained up to 2 dS m^{-1}, while the EC value reached around 4.6 dS m^{-1} in the solution by adding nutrients at constant intervals. However, the treatments did not significantly affect the nutrient uptake by tomatoes.

Based on the drawbacks of the open- and closed-loop hydroponic systems, some researchers conducted studies to develop a drainage-free open hydroponic system in which the irrigation schedule was based on the crop water requirement to avoid nutrient solution leaching (Choi et al., 2013a). In this nutrient solution management approach, substrate moisture was measured using a moisture sensor to maintain the moisture content within the plant water requirement level to avoid leaching (Choi et al., 2013a).

Choi et al. (2013a) used three-rod probe frequency domain reflectometry (FDR) sensor to monitor the EC and moisture content of coir substrate in an open drip hydroponic system. The results indicated that an automated irrigation technique at 40 % or 50 % volumetric moisture content led to no leachate in an open hydroponic system, which increased WUE. In other words, using an FDR sensor to manage nutrient solutions based on water demand increased WUE without water stress. In a study by Choi et al. (2013b), an FDR sensor was evaluated in tomato cultivation under a drip hydroponic system with two different irrigation schedules, 40 % or 50 % and 60 % of volumetric moisture content, with a time-clock schedule for the fixed irrigation intervals. The results indicated that no leachate was observed at 40 % or 50 % volumetric moisture content compared to 60 %, and 70 days after transplanting, no leachate was observed at 60 % treatment. Plant growth significantly reduced at 40 % or 50 % moisture content compared to 60 %. Generally, to have an efficient irrigation schedule by FDR, 40 % or 50 % volumetric moisture content at the beginning of crop season during spring and summer was suggested.

The WUE in an open hydroponic system was investigated using FDR sensors and a conventional timer-set system to manage the irrigation schedule in a large hydroponic farm (Choi et al., 2015). The experiments resulted in higher WUE, around 1.9-fold, for the FDR-managed irrigation schedule than the timer-set managed irrigation schedule from autumn to winter and spring to summer crop cycles. In addition to a reduction in drained nutrient solution in the FDR system, 61 % of fertilizer costs were saved compared with a timer-based irrigation schedule. These results are consistent with Choi et al. (2016), who reported a 1.2-fold higher WUE and 41 % fertilizer cost-saving with the FDR schedule system than the timer-based schedule in a hydroponically grown strawberry.

Other nutrient solution management techniques studied are partial root-zone drying (PRD) and regulated deficit irrigation (RDI) methods which are based on the crop water requirement. For example, Hooshmand et al. (2019) investigated the effects of PRD and RDI methods on tomato, consisted of five treatments of PRD at 85 % and 70 % of water requirement of plant, RDI at 85 % and 70 % of water requirement of plant, along with the control treatment in a drip irrigation/fertigation system. The results showed that the highest WUE was observed in PRD at 85 % water requirement, while PRD at 70 % water demand showed the lowest WUE, 16.07 and 9.02 g L^{-1}, respectively. PRD 85 % increased crop growth after the fruiting stage and decreased irrigation water volume, leading to the highest WUE showing the best nutrient solution management approach in a hydroponic cultivation system for the tested crop under drip irrigation.

Goins et al. (2004) compared three nutrient solution management approaches on potato yield and nitrogen use efficiency in an NFT. The first approach included the EC management, 0.3, 0.6, 1.2 dS m^{-1} during the first 42 days and 0.3 dS m^{-1} at the second 42 days, and 1.2 dS m^{-1} as the control with a constant pH of 5.8. The next strategy was 0.07, 0.23, 0.57 g L^{-1} NO_3^{-}–N at the first 42 days and 0.07 g L^{-1} NO_3^{-}–N at the second 42 days, and 0.57 g L^{-1} NO_3^{-}–N as control with the constant EC of 1.2 dS m^{-1} and pH of 5.8. The last management strategy included 0.57 g L^{-1} NO_3^{-}–N with (control) or without pH management or mixed-N sources with or without pH management. The results indicated that the control treatments in all experiments had the highest plant growth and total plant dry mass. The lower nitrogen reduced plant canopy, root, and tuber dry weight at 0.07 and 0.23 g L^{-1} NO_3^{-}–N treatments compared to the other treatments in this experiment, which revealed that nitrogen supply reduction after tuber initiation produced almost the same biomass as the control. High nitrogen supply during the early growth stage is enough for plants to accumulate sufficient internal nitrogen reserve capacity to sustain high yield in the presence of low nitrogen supply, which can lead to high NUE. The findings are consistent with Alva et al. (2002) and Walker et al. (2001), who observed that increasing nitrogen concentration increased potato yield.

Some research employed Internet of Things (IoT) technology to monitor the nutrient solution and automate hydroponic cultivation systems. In this methodology, the EC and pH of the nutrient solution undergo measurement, transmitting these data to a microcontroller.

Subsequently, the data are evaluated, facilitating control over the nutrient solution through the operation of a relay switch (Ludwig et al., 2013). Furthermore, to achieve effective control and monitoring of hydroponics, the application of artificial intelligence, specifically machine learning, is essential (Mehra et al., 2018). Incorporating sensors for nutrient solution monitoring and using artificial neural networks result in automatic hydroponic system control. In many studies, several inputs, including pH, EC, water level, temperature, humidity, light intensity, and plant age, were used for giving output decisions and predicting the values of pH and EC in automatically controlling the hydroponics (Pitakphongmetha et al., 2016).

Tatas et al. (2022) designed IoT-based control and monitoring of hydroponic systems by employing wireless sensors to monitor the essential parameters and control of the pump. The system monitors the nutrient solution quality, including pH, EC, dissolved oxygen, temperature, air temperature, and humidity to ensure that crops are in an optimum condition. The sensors network transmitted the collected data to the user through a web-based tool to monitor the crop health and system performance. Afterward, a fuzzy inference engine controlled the duration for nutrient solution supply. Another study by Stevens et al. (2023) developed an IoT-based sensor system to monitor nitrogen changes in the nutrient solution for lettuce cultivation. To evaluate the accuracy of the system, samples of nutrient solution were analyzed for nitrogen concentration in a laboratory. The results presented that the IoT system successfully monitored changes in the nitrogen concentration in the DWC hydroponic system.

In their study, Chowdhury et al. (2020) conducted an evaluation of an IoT-based automated vertical NFT hydroponic system to store, monitor, and control the system parameters for remote monitoring. This innovative system was designed for cultivation of a variety of crops, including lettuce, cucumber, tomato, strawberry, mint (*Mentha piperita* L.), coriander (*Coriandrum sativum*), and pepper. The core of the system was a microcontroller, and various sensors were employed to monitor all the system parameters. Once the data were transmitted to the user, the system adjusted and maintained the growth parameters within a specific range for the crops. The results demonstrated the effectiveness of this automated system in monitoring environmental parameters and regulating nutrient and water supply to facilitate the stable growth of plants.

Arora et al. (2021) conducted a study where they employed machine learning to control an automated dosing system. Probes and sensors continuously measured plant-affecting factors including pH, temperature, and EC, transmitting data to the controller every 5 min. If values deviated from optimal thresholds, the system activated the solenoid valve to adjust the nutrient solution. The research concluded that microcontrollers and sensors can enable automatic monitoring and control of EC and pH in hydroponic nutrient solutions. Rau et al. (2017) designed a smart IoT-based sensing and actuation system for rice cultivation by controlling the concentration of magnesium and nitrogen in a hydroponic solution and monitoring the greenhouse’ s environmental parameters. In another study by Bakhtar et al. (2018), supplying nutrient solution was conducted using a microcontroller kit connected to a wireless sensor network with the internet. The input data considered pH and water level for spinach; then, the real-time value and the required value were compared. If the values did not match, the required amount of nutrient value was sent to the user to adjust the nutrient solution.

The above studies demonstrate that the common nutrient solution management technique, the EC-based strategy, presents the total amount of ions concentrations in the nutrient solution. In other words, the EC value cannot be considered an appropriate indicator of the vital elements for plants in the nutrient solution. Based on the results of the present literature, it is suggested that an EC-based nutrient solution management strategy can be applied along with another nutrient solution management technique to successfully improve crop growth, WUE, and NUE, thus reducing the cost of production and negative environmental impacts. Moreover, with the advent of IoT technology, many hydroponic monitoring systems have been developed, many of which are accompanied by mobile applications. In terms of incorporating intelligence, specifically machine learning, to analyze the captured data for precise plant growth control in hydroponics, there has been a notable research effort focused on applying artificial neural networks. Figure 2.3 shows that the different types of hydroponic systems align with different strategies to manage the nutrient solution.

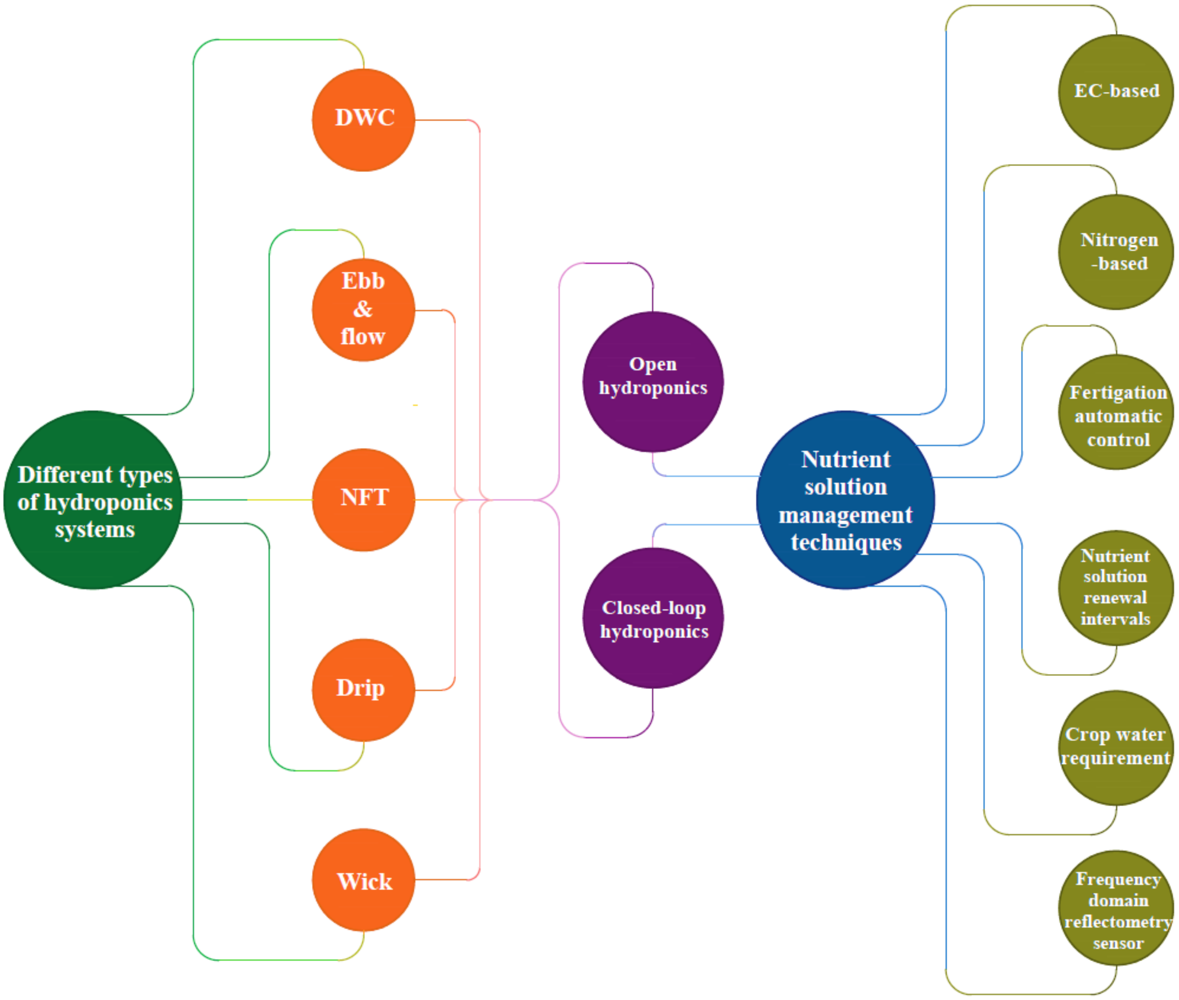

Figure 2.3: Different hydroponic systems and different nutrient solution management techniques. DWC, deep water culture; NFT, nutrient film technique.

2.6. Effectiveness of hydroponics for water and nutrient enhancement

2.6.1. Nutrient use efficiency

Unlike the open-field soil-based cultivation system, the success of a hydroponic system enormously depends on the appropriate nutrient solution directly applied to the system (Djidonou and Leskovar, 2019; Kwon et al., 2021). The nutrient solutions for hydroponic systems differ from fertilizers used for soil-based agriculture. Hydroponic systems use high concentrations and more extensive elements since the buffering capacity and micro nutrient content are lower in the hydroponic growing media compared to soil-based cultivation system (Huang, 2009; Seaman, 2017). Several factors affect NUE in hydroponic systems, including recycling of nutrient solution, types of hydroponic system, and crop varieties (Kwon et al., 2021).

A simple change in the nutrient solution application, such as recycling of nutrient solution, can improve NUE in hydroponic systems (Bar-Yosef, 2008; Grewal et al., 2011). In five hydroponic systems, open- and closed-loop beds, open and closed-loop bags, and a DWC system, NUE was evaluated for tomato production by Castillo et al. (2014). The nutrient solution was supplied using drip tape to the bag and bed hydroponics. Recirculating the nutrient solution resulted in 35 %-41 % higher nutrient savings than the open hydroponic systems. The closed-loop bag had the highest NUE, followed by the closed-loop bed system. Furthermore, it was observed that the closed-loop bag system exhibited higher WUE compared to the closed-loop bed system. This difference can be attributed to the larger exposed surface area in the bed system, which resulted in increased evapotranspiration and subsequent water consumption. Further, DWC and closed-loop bags produced a higher yield than open hydroponics, showing the possibility of fertilizer saving without affecting crop growth, which is aligned with Oztekin et al. (2007). This is consistent with findings by Rosa-Rodríguez et al. (2020), who reported

22.69 % higher NUE in a closed-loop drip hydroponic system than in open drip hydroponics for tomato production.

Grewal et al. (2011) investigated the effect of recycling drainage water in a closed-loop drip hydroponic system on water and nutrient usage for cucumber production in a greenhouse. Results indicated that the recycling of drainage water reduced 33 % of potable water consumption for cucumber production, 49.1 g L^{-1} of WUE, which was the exact yield as the typical yield for the region. Moreover, the results demonstrated that the plants took up 41 % of the total applied nitrogen of the recycling irrigation solution, reducing the cost of fertilizers by reusing the wastewater. The study revealed that the drainage water recycling led to 566 kg ha^{-1} nitrogen reusage.

As an essential nutrient to crop growth, the nitrogen concentration in the plant is an indication of the applied nitrogen concentration in the growth media or nutrient solution. A higher nitrogen concentration in the solution resulted in higher nitrogen in plants when it is unable to convert all the absorbed nitrogen to dry matter or other structures like cellulose (Walker et al., 2001; Stefanelli et al., 2011). Djidonou and Leskova (2019) investigated the application of different nitrogen concentrations (containing half of the nitrate form and half in the ammonium form), from 100 to 400 mg L^{-1}, to find the optimum nitrogen concentration to maximize the lettuce yield in a closed-loop NFT hydroponic system. The results revealed that the accumulated nitrogen in lettuce is increased by increasing nitrogen in the nutrient solution. Moreover, fresh weight yield increased as the nitrogen concentration increased to 300 mg L^{-1}. Furthermore, nitrogen use efficiency was reduced by increasing the nitrogen concentration, and 400 mg L^{-1} nitrogen concentration caused the lowest nitrogen use efficiency, which means that high nitrogen concentrations did not proportionally produce higher yield. Therefore, the optimum range of the solution nitrogen concentration of 100-150 mg L^{-1} was suggested to maximize lettuce yield.

2.6.2. Water use efficiency

Plants' water consumption may be affected by the cultivation system. Hydroponics facilitates easy water absorption by crops, leading to higher WUE (Rouphael et al., 2004; Tomasi et al., 2015). Studies indicate that the soil-based cultivation system is the least water-efficient system compared to hydroponic systems (Sanyé-Mengual et al., 2015; Barbosa et al., 2015; Verdoliva et al., 2021; Majid et al., 2021).

Rouphael et al. (2004) compared the WUE in soil-based and closed-loop hydroponic systems with three growing media, that is, coco-fiber, perlite, and pumice. The results showed higher water consumption in the soil-based system, due to excess leaching and higher application rate of water, compared to the closed-loop hydroponic systems. Closed-loop hydroponic systems with pumice, coco-fiber, and perlite increased WUE by 114 %, 76 %, and 76 %, respectively, compared to the soil-based system. Furthermore, the hydroponic systems produced 33 % (coco-fiber), 23 % (pumice), and 19 % (perlite) higher yield of zucchini squash as well as higher carbohydrate concentration compared to the soil-based system. In a study by Majid et al. (2021), the NFT system indicated 64 % water saving compared to the soil-based system.

Reusing the nutrient solution in closed-loop hydroponics decreases water consumption and raises WUE (Rosa-Rodríguez et al., 2020). Grewal et al. (2011) investigated the effect of recycling drainage water in a closed-loop hydroponic system on the WUE and NUE and the environmental impact of the drainage water discharge.

It is important to underline that climate factors, such as high air temperature and solar radiation, increase plant water consumption (Rouphael and Colla, 2005b; Williams Ayarna et al., 2020). High temperature leads to stomatal closure, photosynthesis rate depletion, respiratory deficit, and WUE reduction (Rouphael et al., 2008). Hebbar et al. (2022), in an open farm hydroponic system, reported that high vapor pressure losses due to high temperature and low humidity during summer resulted in higher water use and WUE reduction. Table 2.2 presents some studies on the effects of different conditions on WUE in hydroponic systems.

Table 2.2: Comparison of water use efficiency (WUE) under different conditions of hydroponics.

Cultivation systems	Plant	WUE (g L^{-1})	Reference
Soil-based and hydroponics	Lettuce (*Lactuca sativa* L.)	50 in hydroponics 4 in conventional soil-based	Barbosa et al. (2015)
Closed-loop DWC and Closed-loop NFT hydroponics	Chicory (*Cichorium endivia* L.)	60.7 in DWC 45.5 in NFT	Silva et al. (2020)
Closed-loop drip and Closed-loop ebb and flow hydroponics	Zucchini (*Cucurbita pepo* L.)	22.6 in drip in spring-summer, 33.7 in drip in summer-fall, 24.7 in ebb and flow in spring-summer, 34.1 in ebb and flow in summer-fall	Rouphael and Colla (2005)
Soil-based, closed-loop drip, and closed-loop DWC hydroponics in glasshouse	Tomato (*Solanum lycopersicum* L.)	12.4 in DWC 9.9 in drip hydroponics 4.4 in soil-based	Verdoliva et al. (2021)
Closed-loop drip and closed-loop ebb and flow hydroponics	Tomato (*Solanum lycopersicum* L.)	32.7 in ebb and flow 29.2 in drip hydroponics	Incrocci et al. (2006)
Closed-loop DWC hydroponics	Coconut (*Cocos nucifera* L.)	3.35 during summer 6.6 during monsoon	Hebbar et al. (2022)
Open and closed-loop drip hydroponics	Tomato (*Solanum lycopersicum* L.)	59.5 in closed-loop hydroponics 46.0 in open hydroponics	Rosa-Rodríguez et al. (2020)

2.7. Summary and future perspectives

This review revealed the need to emphasize the importance of hydroponics to further enhance food security due to challenges faced by the conventional agriculture industry impacted by extreme weather and poor soil conditions. A hydroponic system is essential in improving agricultural productivity as a sustainable and resource efficient system to achieve food security. Innovative approaches to overcome the overuse of water and fertilizers are required to keep up with the increasing food demand while minimizing negative environmental impacts. This review discusses different nutrient solution management strategies to enhance nutrient use efficiency (NUE) and water use efficiency (WUE) in hydroponic systems. From the overview on the recirculation of the nutrient solution, closed-loop hydroponic systems have shown success in increasing NUE and WUE compared to open hydroponics, around 90 % and 85 % water and nutrients savings, respectively, compared to open hydroponic systems.

On the other hand, innovative techniques are required to manage the nutrient solution to operate the hydroponic system at an optimum level to maximize productivity and minimize the cost of production. The EC-based strategy is the simplest method. However, it cannot follow the nutrient variations in the solution over time. Hence, ion-based strategies have been studied to improve the quality of the nutrient solution, thus increasing the yield. Monitoring the concentration of nutrients could be the most effective contribution to reducing water and fertilizer consumption and achieving the ambition of having an eco-friendly hydroponic system. The nutrient-based strategy can reduce water and nutrient consumption by up to 60 % more than the EC-based technique.

Different approaches to managing the nutrient solution have shown some success and have become appropriate alternatives for nutrient solution management due to reducing water and fertilizer consumption. Fertigation scheduling by measuring the atmospheric variables enhanced NUE and WUE due to fertigation frequency adjustment according to plant transpiration estimation. Additionally, deficit irrigation with partial root-zone drying (PRD) in 85 % of the plant water requirement increased crop growth and WUE. Likewise, utilizing an frequency domain reflectometry (FDR) sensor to monitor substrate moisture and EC increased WUE without water stress. Besides, FDR can save 41 %‑61 % of the fertilizer costs and lead to 1.2- to 1.9-fold higher WUE compared to a time-based schedule. Although these studies indicate that monitoring sensors increase NUE and WUE, providing the required equipment might be costly. Therefore, a pre-arranged nutrient solution addition can be effortless and affordable if the crop requirements are accessible.

This review has introduced several opportunities to attain a productive and efficient hydroponic system to increase crop yield, WUE, NUE, and environmental pollution control while minimizing the cost of inputs. Although an open hydroponic system has some advantages, the major disadvantages of using the open system are waste of water and fertilizer along with the environmental pollution resulting from used nutrient solution discharge. Studying the possibility of reusing nutrient-rich hydroponic waste to cultivate plants in hydroponics can introduce an environmentally friendly cultivation system. Next to nitrogen, phosphorus and potassium are essential nutrients for plant growth and productivity, and their limitation affects crop yield and quality. Therefore, phosphorus and potassium need to be investigated to control the nutrient solution along with nitrogen to maximize the hydroponic performance. In addition, some nutrient solution strategies discussed in this review are costly, infeasible, or time-consuming. Thus, further studies could introduce the most straightforward nutrient solution management strategies, which make the techniques more appealing and practical to growers.

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Chapter 3

3. Designing and fabrication of a small-scale vertical hydroponic system (Christmas-tree system) for households

3.1. Abstract

Although there is an increasing demand for local food production, the limited technical knowledge regarding new crop production systems hinders the practicality of implementing new technologies. Household hydroponic systems have the potential to bring numerous benefits, including improved vegetable growth and availability, aesthetic pleasure, and the promotion of fresh air. Vertical hydroponics serves as a viable solution to increase productivity per area by expanding crop production into the vertical dimension. By utilizing a vertical household hydroponic system, it becomes possible to exert full control over factors such as temperature, humidity, and light while requiring minimal space, enabling food cultivation in any location. This study was conducted to design and fabricate a small-scale vertical hydroponic system suitable for households. Another objective was to modify and test an already fabricated vertical hydroponic design. The methods employed included designing, fabricating prototypes, conducting initial product testing, making modifications, and ultimately fabricating the final product. The expected results of this project include the successful design of AutoCAD and Solidworks models and the successful construction of the functional prototype. To ensure easy assembly and cost-effectiveness during the fabrication process, locally available materials, including ABS pipe, a plastic container, small water pump, and disposable cups, were utilized. The final prototype occupied a space of 0.66 m^2, measuring 1.17 m in height, 0.81 m in width, and 0.81 m in length, with a crop capacity of 18 plants. In terms of the already fabricated vertical hydroponic system, pressure compensating drippers were used to provide a uniform flow rate and water distribution in the system.

Keywords:

Closed-loop hydroponics, drip hydroponics, indoor farming, vertical gardening, wick system

3.2. Introduction

Agriculture faces complex challenges between now and 2050 to produce 60 % more food to feed nine billion people (United Nations, 2019). Additionally, there is a notable trend of rapid urbanization, with projections indicating that approximately two-thirds of the global population will move to urban areas in 2050 (Turra et al., 2013). However, climate change, water scarcity, degradation of land resources and lack of arable lands for crop production necessitate to find alternate farming methods (Lal, 2015; Majid et al., 2021). Hydroponic is a technique of growing plants using a water-based nutrient solution rather than soil, and can include an aggregate substrate, or growing media, such as vermiculite, coconut coir, or perlite. Hydroponic cultivation system is more feasible due to its higher crop productivity, water and nutrient savings, environmental friendliness, and continuous production capacity (Massa et al., 2020).

The adaptability of hydroponics makes it possible to set up a small-scale greenhouse in the backyard, or in the kitchen (Barbosa et al., 2015), however, to set up a commercial greenhouse needs a high initial investment. Household vertical hydroponics is preferred in regions with extreme climate conditions (Chowdhury et al., 2020). Many people spend most of their time indoors, whether it be at home in their workplaces. A small-scale household hydroponic system brings aesthetic appeal, improves air quality, and offers access to fresh vegetables (Romanova et al., 2019). Additionally, this hydroponics facilitate year-round production of own fresh vegetables at low cost. Many vegetables, such as leafy vegetables are suitable for indoor farming due to their rapid growth and low photosynthetic energy requirement (Shamshiri et al., 2018).

One of the promising approaches is small-scale vertical hydroponic system, which can be used for leafy vegetables production to meet the food demand in urban settings that suffers from spatial constraints (Al-Chalabi, 2015). A vertical hydroponic system could be either an indoor or outdoor cultivation system and is considered as a sustainable way to produce plants in multiple vertical layers to maximize space utilization (Despommier, 2013). The nutrient solution is delivered to the top and drained at the bottom of the vertical hydroponic system (Singh & Dunn, 2017). The vertical hydroponic system offers several advantages compared to other hydroponic systems (Pinstrup-Andersen, 2018; Despommier, 2013) which include:

- High-density yield per unit area
- Minimizing the horizontal occupation
- Applicable anywhere, even in small places like kitchens, living rooms, and balconies.
- Year-round crop production
- High water use efficiency

Despite numerous studies on hydroponic systems, designing and testing of small-scale vertical hydroponic systems for households are limited. Indoor hydroponics offers the potential to produce fresh crops with a short growing cycle year-round (Rusu et al., 2021). Accordingly, numerous hydroponic systems are available in the market, providing home gardening opportunities for people to grow crops. However, people have many challenges when choosing a particular hydroponic system. The information presented here contributes to a more nuanced comprehension of the challenges of the market available hydroponics, which leads to further research to determine the optimal hydroponic system for households. This study was carried out based on industrial collaboration to fulfill the requirements, and the design has been developed in consultation with the industrial partner. This study aims to design and fabricate a small-scale, low-cost vertical hydroponic system for households and modification of an existing vertical hydroponic system.

3.3. Material and Methods

3.3.1. Develop design ideas

Various designs were conceptualized and generated using AutoCAD software (Fig. 3.1 & 3.2), aligning with the research goals. After comparing the proposed designs, it was observed that utilizing a single light source positioned at the top of the hydroponic systems did not adequately provide coverage for the plants in lower levels (Fig. 3.1a, 3.1b, 3.1c, 3.1d). Consequently, Figure 3.1a was modified into Figure 3.1d by implementing a new structure, while Figure 3.1e incorporated a central vertical light source capable of providing enough light to the crops across all layers.

On the other hand, green wall hydroponic systems are better suited for consistent and permanent utilization, given their lack of portability. Therefore, relocating the green wall in front of a window during the summer becomes impractical, hindering the possibility of utilizing natural light and limiting options for cost reduction (Fig. 3.2).

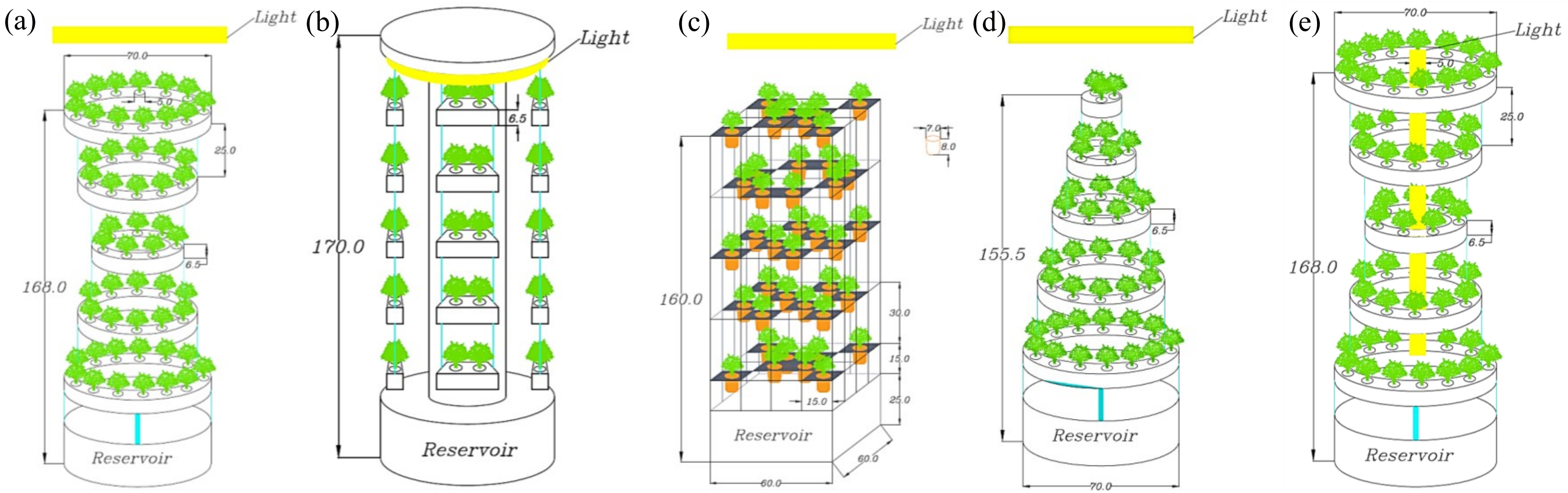

Figure 3.1: The scheme of vertical hydroponic systems with the light at the top of the systems (a, b, c, d) and central vertical light (e).

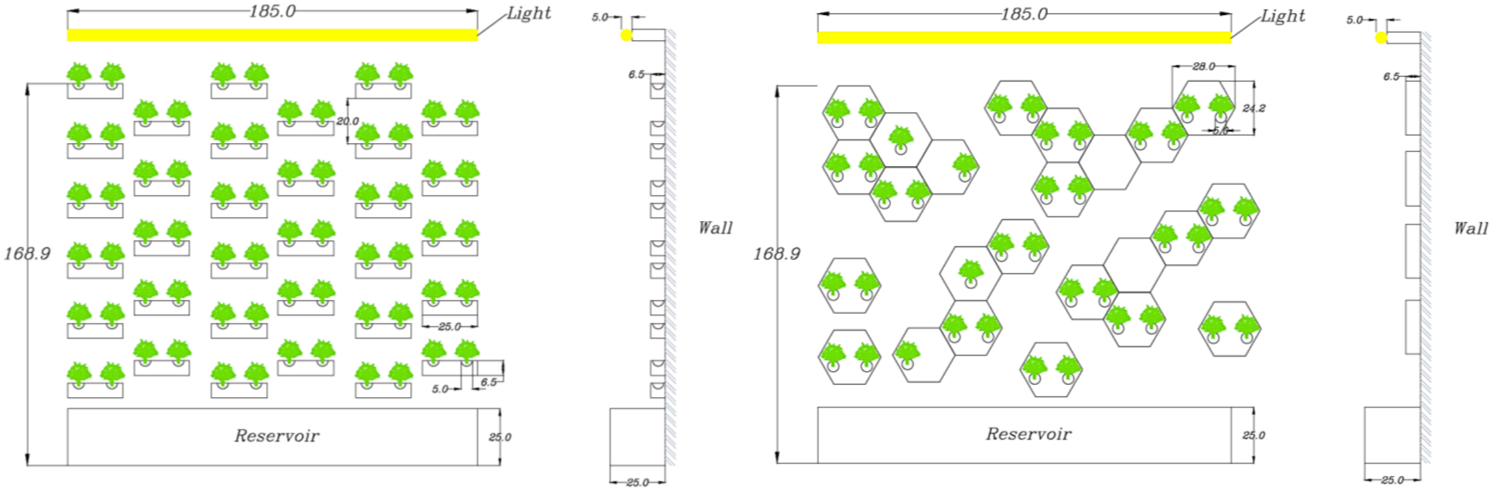

Figure 3.2: The scheme of green wall hydroponic systems

3.3.2. Select the best design

Before making any decision, the industrial partner was consulted to finalize the best design. By modifying and simplification of Figure 3.1d, a vertical and small-scale hydroponic system was designed, and named as Christmas tree (C-Tree) due to its resemblance to a Christmas tree (Fig. 3.3). The designed vertical hydroponic system was developed to grow leafy vegetables, micro greens, and some fruits under the household conditions. The C-Tree system incorporates several noteworthy features, including its portability, versatility to serve as a Christmas tree, comprehensive light coverage for all crops in each level, easy application of nutrient solution , and the added aesthetic appeal it brings. The design of the system is divided into three main subsections:

- The structure of the vertical hydroponic system
- Nutrient solution application system including the reservoir
- Mineral nutrient and pH-controlling techniques

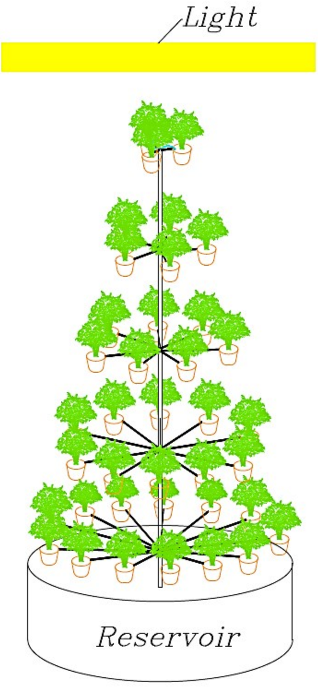

Figure 3.3: The initial scheme of the C-Tree hydroponic system

3.3.3. Nutrient solution application and monitoring method

The design incorporated a closed-loop technique to ensure cost-effectiveness, leveraging on its high water and nutrient use efficiency. The fabrication of the vertical hydroponic system employs a wick system, a self-feeding cultivation method where the nutrient solution is supplied to the plants through a cotton wick or other fibrous materials via capillary action (Lee & Lee, 2015; Shrestha & Dunn, 2010). Although the wick system is typically used for indoor cultivation systems due to its simplicity, it can't be used for large plants with high water requirements (Harris, 1988).

The reasons behind the wick system selection were simplicity of setup, easy operation, and low energy consumption. In fact, in this method, the nutrient solution is delivered to the growing cups, where the wicks are submerged, through a water pump once or twice daily. Unlike systems like NFT that require a continuous water pump, or DWC, which requires an air pump, the vertical hydroponic system under discussion does not depend on the continuous operation of either of these pumps. In this particular design, the utilization of the ebb & flow system was deemed impractical due to the need for frequent drainage of the nutrient solution from each growing cup back into the reservoir.

Since the C-Tree hydroponic system has been designed as a household system, the simplicity of nutrient solution management is essential. Accordingly, the electrical conductivity and pH measurement strategies were implemented to control nutrient solution in the designed hydroponic system.

3.3.4. Create an AutoCAD modeling and fabrication process for the prototype

The outline of the C-Tree system, including detailed dimensions, different vertical levels, and the number of cups, was drawn using AutoCAD software (Fig. 3.4). The structure of the hydroponic system consists of a central vertical pipe, reservoir, pump, arms, and tubing. The C-Tree system contains three vertical layers: 3 cups in the top layer, 6 cups in the middle layer, and 9 cups in the bottom layer.

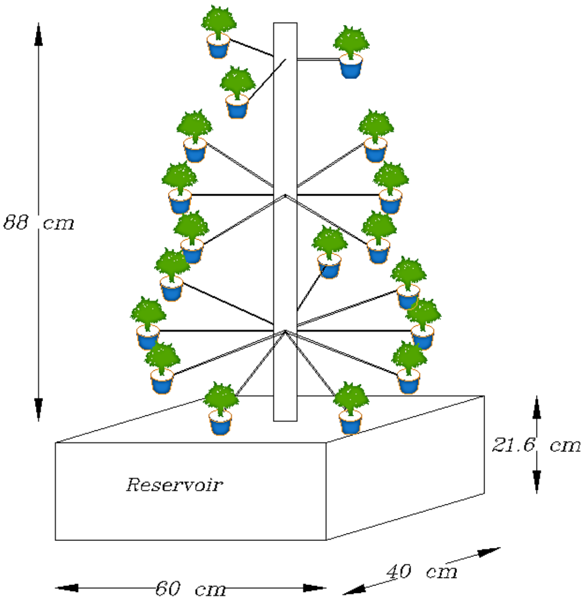

Figure 3.4: The scheme of the initial model of the C-Tree hydroponic system

3.4. Results and Discussion

3.4.1. Fabrication process for the prototype

The designed vertical C-Tree hydroponic system was fabricated in the Boreal Ecosystem Research Facility (BERF) lab, Grenfell Campus, Memorial University of Newfoundland, Corner Brook, NL, Canada. The prototype was created using locally available, and low-cost materials to reduce the initial costs.

The C-Tree system contains a central axis to which other parts are connected. In choosing the materials for the central axis, price, availability, and durability were considered. Therefore, acrylonitrile butadiene styrene (ABS) pipe (4 cm diameter) was used to hold the arms and transfer of nutrient solution from the reservoir at the bottom to cups. The actual dimensions of the system were 110 cm in height, 83 cm in length, and 83 cm in width. A high-density plastic reservoir with 36.5 L capacity was used as a horizontal support for the central ABS pipe. To accommodate the ABS pipe in the center of the lid and allow the power cord of the pump to pass through, a hole saw was used to make an opening in the reservoir's lid. Additionally, a smaller hole was made specifically for the passage of the pump's power cord. To securely attach the pipe to the lid, a 7.6 cm polyvinyl chloride (PVC) flange and a 7.6 cm to 5 cm PVC adapter were used and these components were fastened together using bolts. The next step was joining the arms of the central ABS pipe. The aluminum angle leg mill (Fig. 3.5a) was used as the arms, and zinc plated corner brace (Fig. 3.5b) was used to connect the arms to the pipe.

Figure 3.5: Aluminum angle leg (a), and zinc corner brace (b)

To ensure adequate light distribution for plants at lower levels, shorter-length arms were strategically positioned on the top levels of the system. The cups were securely held in place by attaching steel hose clamps to these arms. The drip tubes were used to connect the cups for the nutrient solution delivery. Accordingly, a drip tube was connected at one end to a water pump inside the reservoir, while at the other end, it was attached to one of the cups located at the top level of the system via the central ABS pipe (Fig. 3.6). A drip tube was affixed at the bottom of the cup in the top level and connected to one of the cups in the second level. This arrangement facilitated the transfer of nutrient solution from the first level to the second level and continued downwards to reach the bottom level of the system. To ensure the transfer of the nutrient solution, a drip tube connected one cup from the bottom level to the cup in the second level, following a similar arrangement. Each level's cups were interlinked using drip tubes, facilitating the flow of the nutrient solution. In order to maintain a constant water level of 2 cm in each cup, elbows were installed in the middle of the drip tubes between the cups (Fig. 3.6).

Figure 3.6: The constructed initial prototype of the C-Tree hydroponic system

3.4.2. Modification of the initial prototype

The hydroponic system was tested to evaluate its performance, mainly focussing on nutrient solution circulation. Due to the manual and simple construction using locally available materials, there was a tendency for the cups to shift from their intended positions, resulting in inadequate water transfer to certain cups. Therefore, a new design was introduced, incorporating an improved irrigation method to address this issue. A new design of the C-Tree hydroponic system, with detailed dimensions, is shown in Figures 3.7 and 3.8 (by Solidworks). The final prototype occupied an area of 0.66 m^2 with a dimension of 1.17 m in height, 0.81 m in width, and 0.81 m in length, and a crop planting capacity of 18 plants (planting cups).

To serve as the central axis, a 5 cm diameter ABS pipe was used to hold the arms in place, and the pipe was pierced using a drill to join the arms to the pipe. For the initial prototype, a high-density plastic reservoir with a capacity of 49 L was used to house the central ABS pipe and store the nutrient solution. Two holes were created in the reservoir's lid to fix the ABS pipe and allow the pump's power cord to pass through. To ensure the stability of the central pipe, a flange and adapter were installed.

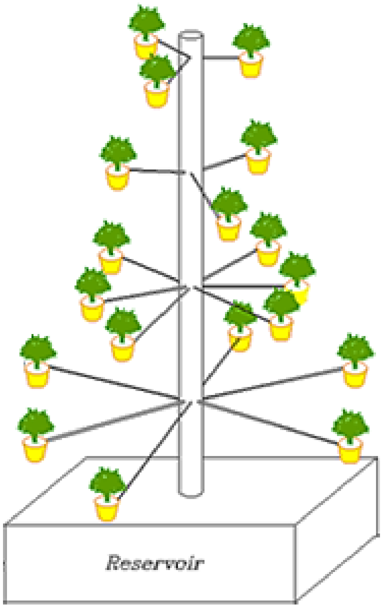

Figure 3.7: The layout of the C-Tree hydroponic system

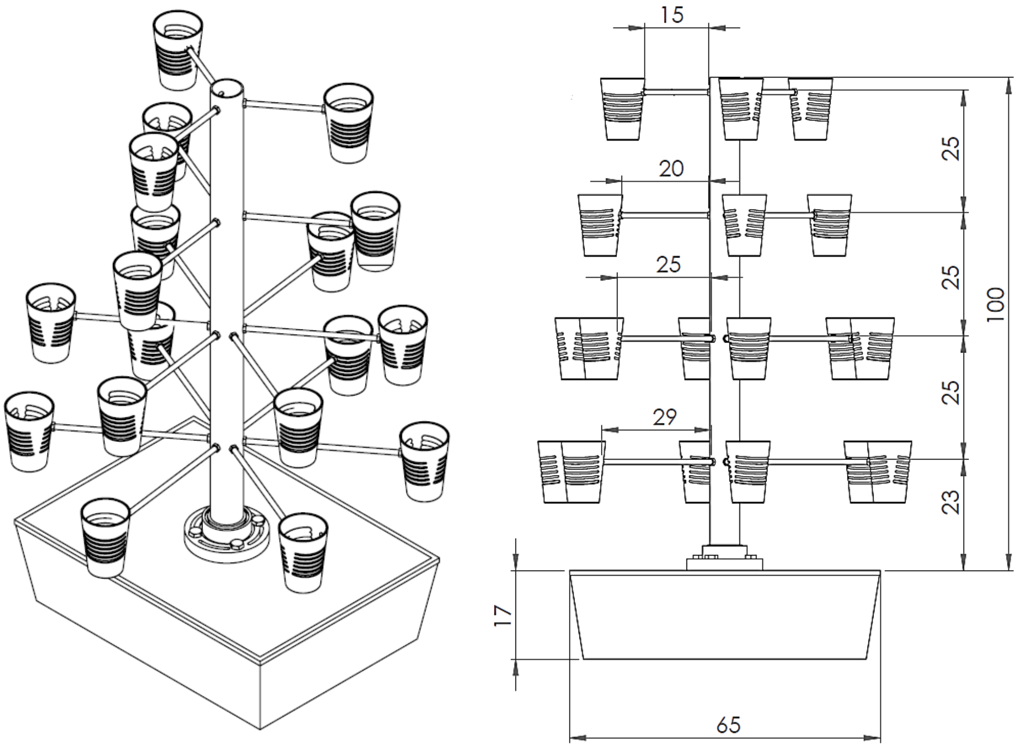

Figure 3.8: The 3D layout and dimensions of the C-Tree system (dimensions are in cm)

The stainless-steel threaded rods were used as arms, as shown in Fig. 3.9a. They were in different lengths at different levels. Each arm extending from the central vertical ABS pipe accommodated a cup measuring 9 cm in diameter and 12.5 cm in height (Fig. 3.9b). Within this cup, there was a net cup with dimensions of 7.5 cm in diameter and 7 cm in height (Fig. 3.9c). Cups were connected through drip tubes facilitating the supply or drainage of the nutrient solution to or from each cup. The upper cups were connected to the lower levels through a tube to transfer the nutrient solution (Fig. 3.10). The height of the draining drip tubes in each cup was 2 cm to keep a constant nutrient solution level in each cup. The C-Tree hydroponic system comprised four levels, with a total height of 1.17 m, and contains a total of 18 cups. The distribution of cups across the levels is as follows: three cups in both the first and second levels, and six cups in each of the third and fourth levels. After drying the glue, a leak test was carried out from the entire system after setting up the nutrient solution supply to find any probable holes or cracks in the system. After setting up the structure, the next step was to arrange the wick system. Four cotton wicks were placed in each net cup to transfer the nutrient solution to the growing media through capillary action.

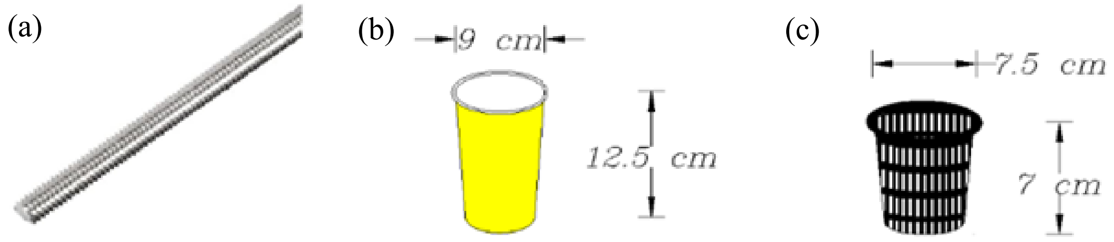

Figure 3.9: Threaded rod (a), grow cup (b), and net cup (c)

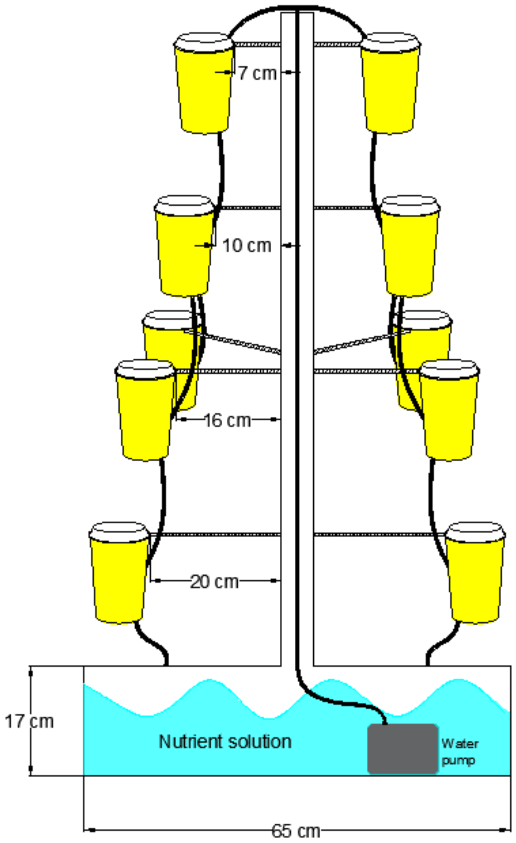

Figure 3.10: The cross section of the irrigation system in the C-Tree system

A submersible water pump of 16 watt, with a water flow rate of 1100 L h^{-1} and a max head of 1.8 m, was used for lifting the nutrient solution to the top level of the C-Tree (Fig. 3.11). Nutrient solution was pumped from the reservoir to the top- level cups through polyethylene drip tubes. Then, the nutrient solution flows down from the top level to the lower level of the system by gravitational force and circulates within the entire level. Subsequently, nutrient solution flows down to the lower levels in a similar way. At the bottom level of each cup, the nutrient solution is directed through the drip tubes back into the reservoir for recirculation.

Figure 3.11: Submersible water pump

The prototype of the C-Tree hydroponic system that has been built is shown in Figure 3.12, and a C-Tree 3D model is shown in Figure 3.13 (by 3ds Max).

Figure 3.12: The final constructed C-Tree hydroponic system

Figure 3.13: The drawing of the C-Tree system

3.5. Modification of an existing vertical hydroponic system

In 2021, another master's student of the Boreal Ecosystems and Agricultural Sciences program at the Memorial University of Newfoundland designed a household vertical hydroponic system. Based on the structure of the hydroponic system, it was named Green-DNA (double helix) hydroponic system (G-DNA), features a structure where two lines of cups wind around a central pipe (Fig. 3.14). Similar to the C-Tree system, an ABS pipe was fixed at the top of the reservoir. The G-DNA systems utilized the same size of ABS pipe, reservoir, flange, adapter, and water pump as the C-Tree system. Each line in the G-DNA system consists of 9 growing cups, measuring 10 cm in diameter and 10 cm in height. Threatened rods connected the cups to the central pipe, a similar configuration used in the C-Tree system. The nutrient solution is supplied to the growing cups using a drip irrigation system containing one 4 L h^{-1} dripper per cup. Upper cups are connected to the lower cups through drip tubes. A submersible water pump transfers the nutrient solution from the reservoir to the cups, and the leachate is collected from the bottom of each cup back to the reservoir through gravity. The final prototype occupied an area of 0.46 m^2 with a dimension of 1.35 m in height, 0.70 m width, and 0.65 m in length, and a crop capacity of 18 plants per unit.

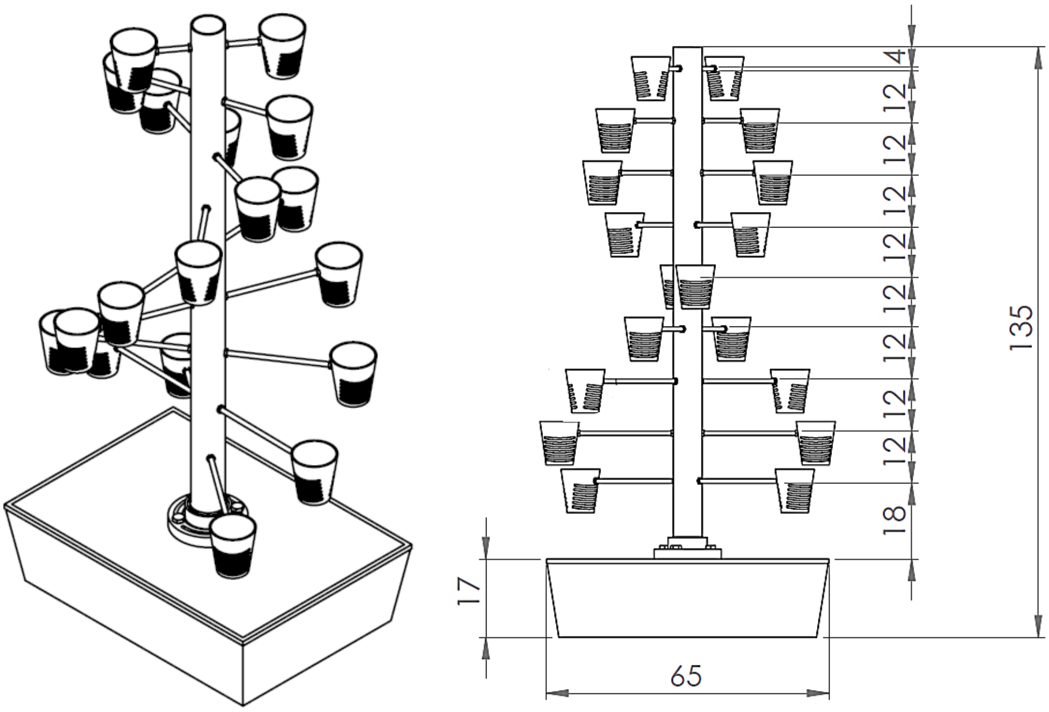

Figure 3.14: The dimensions of the G-DNA hydroponic system

Since the drip system was chosen as the irrigation method for the G-DNA hydroponic system, pressure loss occurred through the system due to the use of regular (non-pressure compensating) drippers. Pressure loss resulted in non-uniform water distribution for plants from to top the bottom. Therefore, pressure compensating (PC) drippers were used in this system to provide a uniform flow rate, which delivers a constant flow rate over a wide range of pressures (Fig. 3.15a). Moreover, a 0.65 cm drip tube shut-off valve was placed in the middle of each line to ensure uniformity distribution and small change in flow rate under the range of pressures and different heights in the system (Fig. 3.15b). In other words, the valve was utilized to divide the irrigation section into two parts on each line of the system. Utilizing the shut-off valve leads to irrigating the five top cups in each line first, then the four lower cups to maintain sufficient pressure to provide uniform irrigation. The average flow rate in the system was about 3.7 L h^{-1}. The final construction of the G-DNA system is shown in Figure 3.16.

Figure 3.15: Pressure compensating (PC) dripper (a), and drip tube shut-off valve (b)

Figure 3.16: The green DNA (G-DNA) hydroponic system

3.6. Conclusion

A small-scale vertical hydroponic system suitable for household use was designed, fabricated, and completed the initial testing. The proposed design considered several factors, including minimal space needs, portability, aesthetic appeal, user-friendliness, and cost-effectiveness.

The design of the C-Tree hydroponic system was prompted by the potential for lower-layered plants to receive light when artificial light is positioned at the top. The initial prototype demonstrated uneven distribution of the nutrient solution by the supply system and the bending of the arms. However, through the testing process, the final modified design showed improved uniformity in the distribution of the nutrient solution in each cup at each level. The C-Tree system takes a space of 0.66 m^2, with a capacity of 18 plants, making it suitable for households. Apart from this, it is conceivable to incorporate additional layers or increase the number of cups in each layer to optimize the utilization of the limited space. The completion of the C-Tree hydroponic system in design and fabrication was successfully done. In terms of the G-DNA system, pressure compensating drippers were used to provide a uniform flow rate and water distribution in the system. The evaluation of the proposed hydroponic systems with crop trials is explained in the next chapter.

3.7. References

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Co-authorship statement

A manuscript based on chapter 4, entitled “Performance evaluation of two newly designed vertical hydroponic systems for growth, water use and nitrogen use efficiencies of spinach” will be submitted to the Canadian Journal of Plant Science. Elham Fathidarehnijeh, the thesis author, will be the main author, who designed the study, conducted all experiments, and collected, analyzed data, and drafted the manuscript. Dr. Lakshman Galagedara (supervisor) will be the corresponding and the last author. He helped to design the study and analyze the data, gave expert opinions, reviewed, and edited the manuscript. Dr. Muhammad Nadeem and Dr. Mumtaz Cheema (Committee members) will be the second and third authors, helped to analyze the data, reviewed and finalized the manuscript. Dr. Raymond Thomas and Dr. Mano Krishnapillai reviewed and edited the manuscript.

Chapter 4

4. Performance evaluation of two newly designed vertical hydroponic systems for growth, water use and nitrogen use efficiencies of spinach

4.1. Abstract

Newfoundland and Labrador (NL) experiences some challenges in producing fresh leafy vegetables due to long winters and short, cool summers. To address this issue, it is necessary to implement some policies that encourage interest in agriculture, with a focus on sustainable practices such as hydroponics. Adopting small household hydroponic systems is proposed as an alternative to locally producing leafy vegetables. Therefore, it is essential to design and develop a household hydroponic system capable of sustaining year-round production of leafy vegetables to meet household demands. This study aims to evaluate the performance of two newly designed vertical hydroponic systems for their feasibility in growing leafy vegetables. Spinach (*Spinacia oleracea* L.) was used as a test crop and growth, water use efficiency (WUE), and nitrogen use efficiency (NUE) of the two vertical systems were evaluated. The experimental treatments were comprised of three hydroponic systems: 1) a vertical drip hydroponic system (G-DNA), 2) a vertical wick hydroponic system (C-Tree), and 3) a horizontal deep water culture (DWC) system as the control, under two variable growth conditions (grow tent experiment, and without grow tent experiment). In the grow tent experiment, the utilization of a grow tent facilitated the control of the growth conditions. The second experiment was without a grow tent which was much closer to conditions of the real household environment. Spinach seeds were sown in a growth chamber, and after reaching the two true leaf stage, seedlings were transplanted into the hydroponic systems. Crop growth was monitored throughout both experiments, and growth parameters were measured at harvest.

Results indicated that the G-DNA system outperformed the C-Tree hydroponic system for spinach growth. The vertical hydroponic systems did not notably impact the WUE. However, DWC showed improved WUE, almost twofold compared to the vertical hydroponic systems. The G-DNA had the highest NUE in both environmental conditions, indicating that spinach in the G-DNA system could take up more N from the nutrient solution and produce more yield in the same amount of absorbed N than the C-Tree system. These results suggest that the G-DNA system has a higher potential to offer better NUE and higher feasibility to produce leafy vegetables compared with the C-Tree system.

Keywords:

Crop growth, controlled environment, nutrient solution, recirculating hydroponics, household system

4.2. Introduction

Newfoundland and Labrador (NL) faces considerable challenges in food security due to a lack of suitable agricultural land, short growing seasons, inadequate financial resources, and conventional farming approaches (Quinlan, 2012; NL Natural Resources, 2012). These challenges have adverse effects on the agricultural sector, and the food supply in the province is dependent on imported foods, of which more than 90 % of the fresh fruits and vegetables are produced outside the province (Quinlan, 2012; Food First NL, 2016). Therefore, some policies should be implemented to raise interest in agriculture and promote a sustainable agricultural industry, including hydroponics and vertical agriculture. There is a need to develop, design and test small household hydroponic systems as an alternative that can be used to produce leafy vegetables to fulfill a household leafy vegetable requirement in NL.

The vertical hydroponic system emerges as a promising approach in hydroponics, demonstrating the capacity to enhance crop yield per unit area (Al-Chalabi, 2015). The need for a sustainable and less costly source of food production has led to research on vertical hydroponic systems. The vertical hydroponic system is a combination of vertical production and hydroponic methods that are proven to be useful (Borrero, 2021). Compared to traditional agricultural methods, the vertical hydroponic system increases yield density per unit area and adaptability to various settings (Despommier, 2013).

The hydroponic systems allow the growth of various plant species, and leafy vegetables have shown promising growth habits in hydroponic systems (Sharma et al., 2018). For instance, Majid et al. (2021) mentioned that lettuce produced significantly higher yield in hydroponic systems compared to a conventional soil-based cultivation system. The water use efficiency (WUE) and nitrogen use efficiency (NUE) were recorded higher in hydroponic systems (Barbosa et al., 2015; Castillo et al., 2014). Therefore, the vertical hydroponic systems in households could provide a better solution to support fresh leafy vegetable supplies, improve WUE, NUE as well as would fit best in limited available space area in a house and use available passive heat.

Spinach (*Spinacia oleracea* L.) is a fast-growing leafy plant that performs well in cool weather conditions and short-day lengths (Simko et al., 2014). Spinach plant is susceptible to nitrogen (N) deficiency, necessitating high N fertilization for optimal growth and quality (Chan-Navarrete et al., 2014). Nitrogen is an essential element for the growth and development of plants, and its mild deficiency can lead to leaf chlorosis, stunted growth, and reduced crop yields (Sathyanarayan et al., 2023). We used spinach as a test crop to evaluate its performance in two newly developed vertical hydroponic systems compared with a DWC system (Control). Although hydroponic systems directly supply nutrients to plants as roots are submerged in a nutrient solution, exploring the newly developed vertical hydroponic system would enhance our understanding of the efficacy of the newly developed vertical hydroponic systems. Implementing a vertical hydroponic system with high WUE, NUE and optimized leafy vegetable production can minimize fertilizer wastage and decrease resource contamination. Therefore, we aimed to conduct experiments using vertical hydroponic systems with the following objectives:

I. To assess the growth performance of spinach in three different hydroponic systems.
II. To determine the WUE and NUE of spinach grown in vertical hydroponic systems and deep-water culture system.

4.3. Material and Methods

4.3.1. The Experimental Site

The proposed research project was conducted in the RecPlex facility, Grenfell Campus, Memorial University of Newfoundland and Labrador, Corner Brook, Newfoundland, Canada (48˚ 56′ 29″ N, 57˚ 56′ 06″ W) during 2022 spring and summer.

4.3.2. Experimental Treatments

Three hydroponic systems, Green DNA system (G-DNA), Christmas tree system (C-Tree), and deep water culture system (DWC) were evaluated based on the crop growth, WUE, NUE, and financial analysis. The C-Tree and the G-DNA systems, which were designed and fabricated, were compared with a horizontal DWC system, as a control, each consisting of 18 plants in total (Fig. 4.1). The experiment was laid out in a completely randomized design with three replications. The DWC system served as the control treatment and included 18 net cups, each measuring 5 cm in diameter and 5 cm in height. Additionally, a 4-watt air pump and an air stone were used in the DWC system to periodically aerate the nutrient solution and maintain availability of dissolved oxygen (DO) to the plant roots system.

The hydroponic systems were evaluated under two different environmental conditions: including a grow tent (experiment 1) and without a grow tent (experiment 2). Grow tent provided controlled environmental conditions whereas without grow tent grow conditions were tested as a real household conditions. A VIVOSUN hydroponic grow tent, Ontario, California, USA measuring 244×122×203 cm^3 was used a reflecting sheet inside to enhance light reflection as shown in Figure 4.1. The grow tent was used to control environmental conditions such as light, temperature, and relative humidity. On the other hand, without grow tent experiment involved keeping the hydroponic systems in the building. This experiment aimed to test the performance of the hydroponic systems under ambient conditions mimicking household environmental conditions.

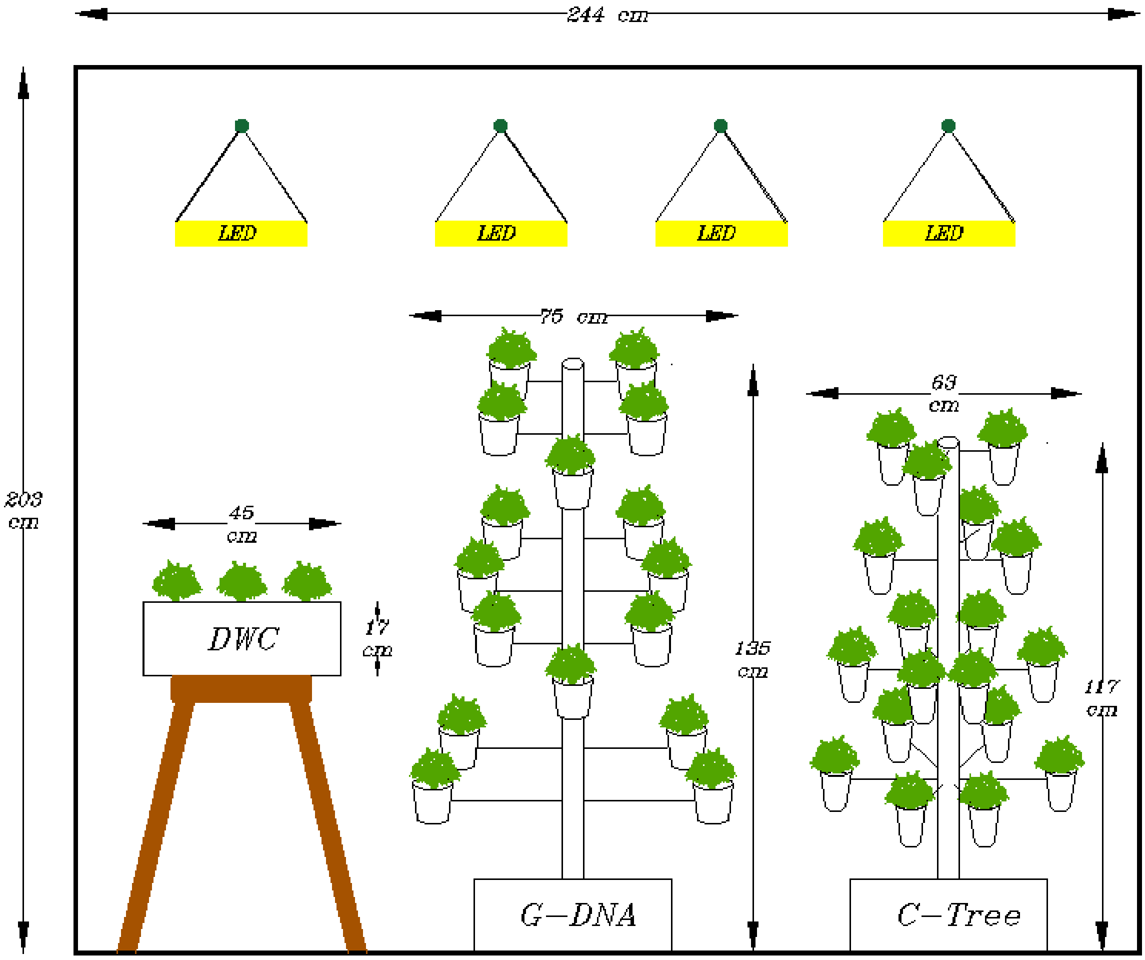

Figure 4.1: Diagram schematic sketch depicting the front view of the grow tent with two vertical hydroponic systems and a deep water culture system. LED lights were installed at the top to provide uniform lighting throughout the experiment.

4.3.3. Nutrient solution

A complete nutrient solution was sourced from 3 Part Masterblend Nutrient Kit, GECKO grow, Calgary, Alberta, Canada. Nutrient solution was applied as 7.5 % nitrate - N, 0.5 % ammoniacal nitrogen, 15 % phosphorus oxide, 36 % potassium oxide, 0.5 % magnesium, 0.2 % boron, 0.05 % chelated copper, 0.4 % chelated iron, 0.2 % chelated manganese, 0.01 % molybdenum, and 0.05 % chelated zinc. The nutrient solution chemical properties including EC, pH, and DO of the hydroponic systems, were measured daily to ensure they remained within the desired ranges and were adjusted accordingly (Table 4.1).

The EC was measured using a handheld EC meter (Bluelab, New Zealand) and was maintained in an optimum EC range of 1.8 - 2.3 dS m^{-1} for spinach by adding fertilizer to the nutrient solution based on the instructions of the fertilizer (Table 4.1). The pH measurement was performed using a handheld pH meter (Bluelab, New Zealand), and the pH value of the nutrient solution was maintained between the optimum range of 5.5 and 6.5 (Table 4.1). Adjustment to the pH was made with pH up and down solutions (Technaflora Plant Products Ltd., British Colombia, Canada).

Table 4.1: Optimum range of EC and pH values for spinach.

Parameter	**Value**	**Reference**
EC (dS m^{-1})	1.8 to 2.3	Shrestha & Dunn (2017)
	1.2 to 1.4	Janeczko & Timmons (2019)
	1.9 to 2.2	Lara et al. (2021)
	1.5	Lin et al. (2014)
	2.0	Gao et al. (2020)
pH	6.0 to 7.0	Shrestha & Dunn (2017)
	5.5 to 6.0	D'Imperio et al. (2019)
	5.7 to 6.0	Lara et al. (2021)
	5.7 to 6.3	Janeczko & Timmons (2019)
	5.7	Lin et al. (2014)
	6.5	Gao et al. (2020)

To ensure adequate oxygen supply, an air pump and air stone to provide DO to the submerged roots were used. The DO level in the DWC system's nutrient solution was measured using a DO meter (HI98193 Portable DO and BOD Meter, Hanna Instruments, USA) and was maintained around 9 mg L^{-1} by a 4 W air pump and air stone (Uniclife UL40, China).

4.3.4. Growth environmental monitoring

The temperature and relative humidity (RH) from transplanting to harvesting were recorded using a real-time data logger (REED SD-9300 Data Logging Environmental Meter, Canada) placed in the growing area. An electric greenhouse heater fan (iPower Electric Greenhouse Heater Fan, USA) was used to uniformly adjust the temperature inside the grow tent. Further, an air filtration kit (VIVOSUN 440 CFM inline fan, USA) was used for air circulation and ventilation inside the grow tent.

The average minimum and maximum temperature and relative humidity under both environmental conditions are shown in Table 4.2. Both average minimum and maximum temperatures were lower in experiment 1 than experiment 2. Although the minimum temperature values were similar in both environmental conditions, experiment 2 experienced a higher maximum temperature of 30.1 °C compared to experiment 1. The relative humidity was higher in experiment 1 than in experiment 2.

Table 4.2: Average minimum temperature (Tmin), average maximum temperature (Tmax), and relative humidity (RH) recorded during each environmental conditions (experiment 1: with grow tent; experiment 2: without grow tent).

Experiment	Tmin (°C)	Tmax (°C)	RH (%)
Experiment 1	23.2	26.5	65.2
Experiment 2	24.8	30.1	60.1

The artificial light source utilized in this study was a full-spectrum light-emitting diodes (LEDs). The LEDs produce a narrow light spectrum, consumes low energy, produces minimal heat, and has a long-life expectancy (Goto, 2012; Watanabe, 2009; Gonzalez, 2012; Darko et al., 2014). Four LEDs were fixed at the top of the hydroponic systems (Fig. 4.1) to produce enough light intensity for spinach, and the photoperiod was set at 14/10 h day and night (Jin et al., 2013). The light intensity was measured during the experiment using a real-time data logger (REED SD-9300 Data Logging Environmental Meter, Canada) at different heights of vertical hydroponic systems. The light intensity in experiment 1 was 777, 353, 203, and 140 µmol m^{-2} s^{-1} in levels 1 to 4 of the vertical systems (40, 65, 90, and 115 cm from the LEDs), respectively. Light intensity decreased from upper to lower levels in the vertical hydroponic systems because of the distance from the light sources. The light intensity was lower in experiment 2 compared to experiment 1 due to the lack of grow tent and reflected sheets in the growth area. Due to lack of any natural light in the growing area, the light intensity was fixed in experiment 2. The light intensity in experiment 2 was 704, 315, 148, and 83 µmol m^{-2} s^{-1} in levels 1 to 4 (40, 65, 90, and 115 cm from the LEDs), respectively. The light intensity in the DWC system was 345 and 303 µmol m^{-2} s^{-1} in experiment 1 and 2 (77.5 cm from the LED), respectively.

4.3.5. Growing media

In this study, coconut coir, a by-product of the coconut industry, was used as the growing medium, which is widely recognized and employed as a cultivation substrate in the hydroponics.

4.3.6. Seed germination and transplanting

The spinach plant used in this study is "*Bloomsdale*" variety, which was obtained from the Halifax Seed Company (Halifax, NS), Canada. The process for germinating spinach seeds involved soaking them in distilled water for 10 h. Subsequently, the seeds were sown in planting trays using coconut coir as the growing media inside a growth chamber. A thin layer of coconut coir was then used to cover the seeds, and the growing media was daily hydrated with plain water daily until sprouts appeared. After the sprouts emerged, they were irrigated with a half-strength nutrient solution before being transplanted. During the seedling stage, the planting trays were placed in an environment with a temperature of 20 °C during the day and 15 °C during the night, with RH ranging between 65 % and 75 %. Once the seedlings reached the two true leaf stage, they were transplanted into the hydroponic systems (Table 4.3).

Table 4.3: Dates of the two experiments in the two different environmental conditions (experiment 1: with grow tent, and experiment 2: without grow tent) for spinach.

Treatment	Sowing	Transplanting	Harvest
Experiment 1	21/06/2022	09/07/2022	05/08/2022
Experiment 2	23/07/2022	10/08/2022	06/09/2022

4.3.7. Leaf gas exchange parameters

Leaf gas exchange parameters included stomatal conductance, photosynthesis rate, and transpiration rate of the mature leaves and were measured using a portable photosynthesis system (LI-COR 6400, LI-COR Inc., Lincoln, NE, USA).

4.3.8. Plant growth parameters measurements

Plants were harvested at the end of the experiments, and data were collected from four plants per replicate. Plant height, shoot fresh weight (SFW), and root fresh weight (RFW) were measured. Then, the leaves were oven-dried at 70°C for 48 h and shoot dry weight (SDW) was measured to estimate the constant weight by a weighing balance (Ko et al., 2013).

4.3.9. Water use efficiency

Total water used was recorded by measuring the volume of applied water daily during the study period. A pot without a plant was placed in the experimental unit to estimate the transpiration loss in each culture system. Then, the total water uptake was estimated by subtracting evaporation loss from the total water used. The WUE is the ratio of the fresh weight of aerial biomass (yield) to total water uptake (Eq. 4.1) (Verdoliva et al., 2021; Ayarna et al., 2020).

$$\mathrm{WUE} = \frac{\text{Shoot fresh weight (g plant}^{-1}\text{)}}{\text{Total water uptake (L plant}^{-1}\text{)}} \tag{4.1}$$

4.3.10. Nitrogen use efficiency

NUE has been defined in various ways, encompassing physiological, absorption, and agronomical aspects (Good et al., 2004; Pathak et al., 2008). Physiological NUE, or N utilization efficiency (pNUE), refers to the total dry matter per total N uptake, agronomical NUE represents the ratio of total dry matter to the total N applied, and absorption NUE or N uptake efficiency (aNUE) denotes the ratio of total N uptake to total applied N (Nguyen et al., 2014; Djidonou & Leskovar, 2019). These distinct NUE definitions are considered to realize the balance between plant yield and an environmentally friendly system. Nitrogen concentrations were measured in 0.15 g of dry biomass by an elemental analyzer (LECO CNS-928 Analyzer). The respective NUEs were calculated using Equations 4.2, 4.3, and 4.4 (Chan-Navarrete et al., 2014; Nguyen et al., 2014; Goins et al., 2004):

$$pNUE\ (N\ utilization\ efficiency) = \frac{Total\ dry\ weight\ (g\ plant^{-1})}{Total\ N\ uptake\ (g\ plant^{-1})} \tag{4.2}$$

$$NUE\ (N\ use\ efficiency) = \frac{Total\ dry\ weight\ (g\ plant^{-1})}{Total\ N\ applied\ (g\ plant^{-1})} \tag{4.3}$$

$$aNUE\ (N\ uptake\ efficiency) = \frac{Total\ N\ uptake\ (g\ plant^{-1})}{Total\ N\ applied\ (g\ plant^{-1})} \tag{4.4}$$

4.3.11. Financial analysis

In this study, we conducted a financial analysis to determine the most feasible hydroponic system among three hydroponic systems investigated in this study. The results are presented in Appendix A. The financial analysis was conducted using the capital budgeting technique, a way of assessing the financial feasibility of an investment project (Grafiadellis et al., 2000). Three capital budgeting techniques, namely Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Discounted Payback Period (DPP), were utilized to measure capital productivity.

NPV helps determine the present value of all future earnings generated by a project. A positive NPV indicates that the investment will be profitable, whereas a negative NPV suggests that the investment is not worthwhile, and it should be rejected (Khambalkar et al., 2013). NPV is calculated using the following formula (Souza et al., 2019; Kibria & Saha, 2011):

$$NPV = \sum_{t=1}^{n} \frac{(R_t - C_t)}{(1+i)^t} \tag{4.5}$$

Where R_t is the revenues in the year t; C_t is the costs in the year t; n is the project life; t is the period of occurrence of R_t, and C_t; i is the discount rate. Whereas BCR indicates the ratio of the present value of revenues to the present value of costs at a given discount rate of a project and is calculated using the following formula (Kibria & Saha, 2011):

$$BCR = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \Bigg/ \sum_{t=1}^{n} \frac{C_t}{(1+i)^t} \tag{4.6}$$

If a project has a BCR greater than one, it indicates a profitable investment, while a BCR less than one suggests a non-profitable investment (Khambalkar et al., 2013). The DPP assesses the economic feasibility of an investment in terms of time, representing the duration or number of years required to recover the initial investment from the discounted net cash flows (Puccini, 2011). For this financial analysis study of three hydroponic systems under two environmental conditions, a 10-year life period and a 10 % discount rate were used based on the interest rate of medium and long-term loans in Canada.

4.3.12. Statistical analysis

The dataset was subjected to one-way analysis of variance (ANOVA) to determine the effects of the hydroponic systems on spinach growth, leaf gas exchange parameters, WUE, and NUE using XLSTAT 2023 software. Where treatment effects were significant, the means were compared with Fisher's Least Significant Difference (LSD) at alpha 0.05. Prior to data analysis, normality of the data set was tested using Shapiro-Wilk test.

4.4. Results

4.4.1. Crop growth parameters

The hydroponic systems had significant ($p < 0.05$) effects on shoot length, root length, RFW, SFW, and SDW of spinach (Table 4.4; Fig. 4.2 & 4.3). Results indicated that the G-DNA system exhibited higher SFW and SDW than the C-Tree system in both environmental conditions. Table 4.4 indicates that the G-DNA system exhibited higher SFW than the C-Tree system, around 24.85±2.56 and 21.19±0.52 g plant^{-1} in experiment 1 and 2, respectively. However, there was no significant differences between G-DNA and C-Tree systems in most of the growth parameters tested. In comparison with the control, the DWC produced significantly ($p < 0.05$) higher growth parameters, followed by G-DNA and C-Tree. A higher SFW (41.06±2.88 g plant^{-1}) was observed in DWC system in experiment 1, whereas the lowest (15.64±0.61 g plant^{-1}) was recorded in C-Tree system in experiment 2 (Table 4.4).

Regarding the experiments, plant growth parameters were slightly higher in experiment 1 than experiment 2 (Table 4.4). In both environmental conditions, overall growth parameter values were increased remarkably by the DWC system compared to G-DNA and C-Tree systems (Table 4.4).

Table 4.4: Spinach growth effected by different hydroponic systems. Shoot length, root length, root fresh weight, shoot fresh weight, and shoot dry weight of spinach in three hydroponic systems including deep water culture (DWC), green DNA (G-DNA), and Christmas tree (C-Tree) during two environmental conditions (Experiment 1: with grow tent, Experiment 2: without grow tent).

Experiments	**Hydroponic systems**	**Shoot length (cm)**	**Root length (cm)**	**Root fresh weight (g plant^{-1})**	**Shoot fresh weight (g plant^{-1})**	**Shoot dry weight (g plant^{-1})**
Experiment 1	DWC	28.90±1.19 a	41.88±2.33 a	5.94±0.82 a	41.06±2.88 a	2.95±0.15 a
	G-DNA	22.98±0.48 b	13.05±0.68 c	1.88±0.30 b	24.85±2.56 b	2.14±0.28 ab
	C-Tree	22.75±1.44 b	18.42±0.64 b	1.33±0.08 b	18.98±2.32 b	2.08±0.38 b
Experiment 2	DWC	20.03±1.22 b	39.58±3.95 a	5.52±1.06 a	35.38±4.47 a	1.83±0.29 a
	G-DNA	23.23±0.36 a	15.33±0.47 b	2.03±0.29 b	21.19±0.52 b	1.75±0.15 a
	C-Tree	22.49±0.59 a	13.53±0.77 b	1.43±0.27 b	15.64±0.61 b	0.97±0.14 b

Values are expressed as mean ± standard error for 3 replicates for each plant. Different letters within each experiment indicate significant differences among three hydroponic systems using Fisher's least significant difference test at 0.05 alpha.

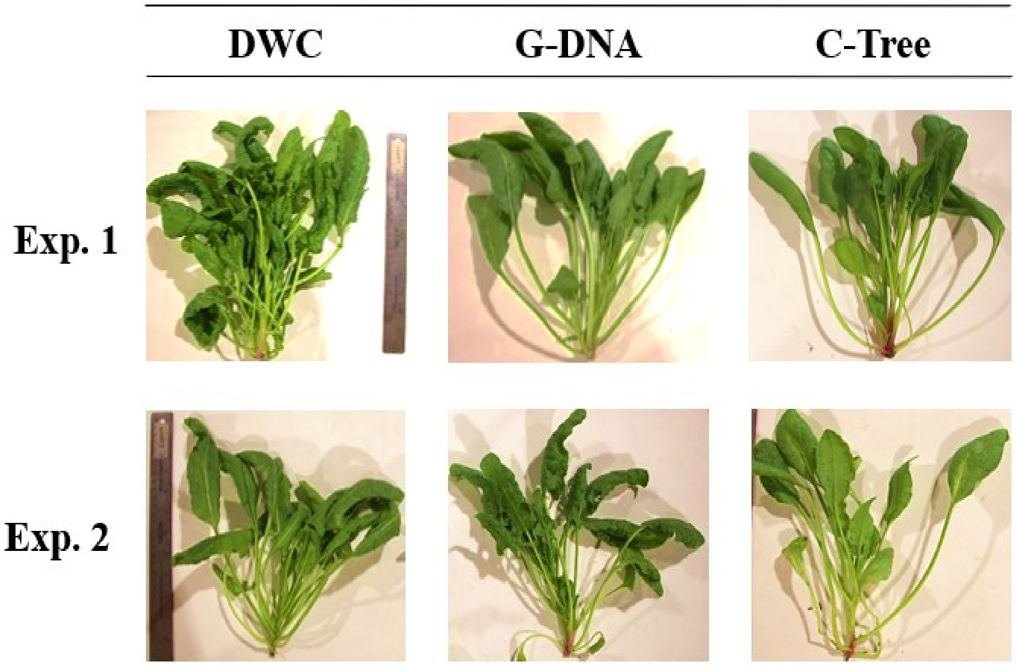

Figure 4.2: Pictorial view of spinach grown in three hydroponic systems (DWC, G-DNA, and C-Tree) under two environmental conditions (Experiment 1: with grow tent, Experiment 2: without grow tent).

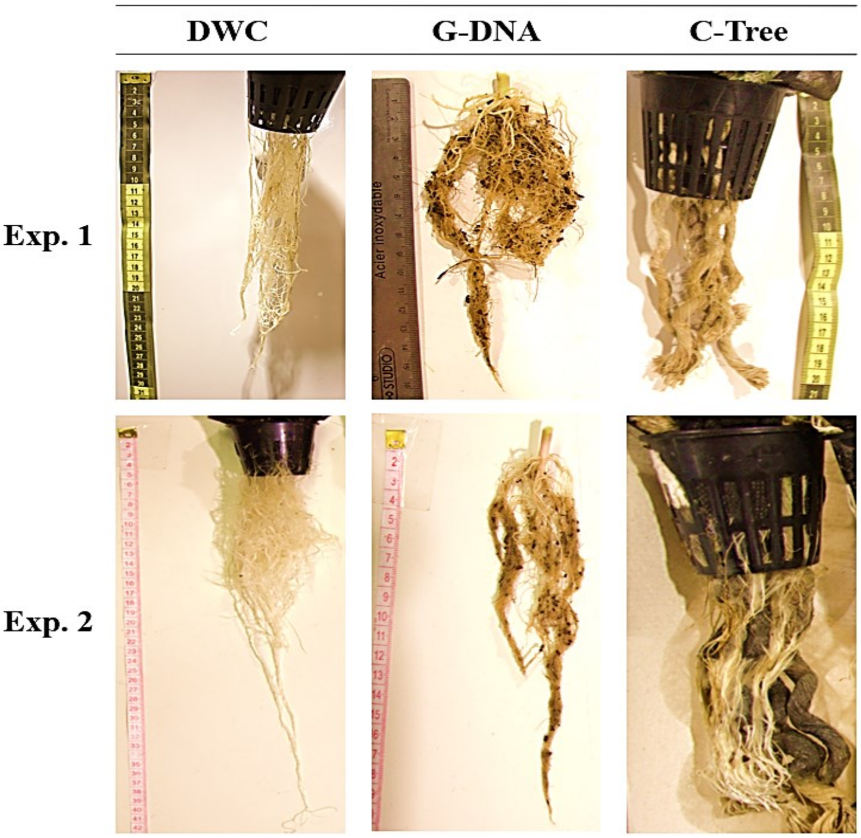

Figure 4.3: Root growth response of spinach grown in three hydroponic systems (DWC, G-DNA, and C-Tree) under two environmental conditions (Experiment 1: with grow tent, Experiment 2: without grow tent).

The hydroponic systems had significant ($p < 0.05$) effects on photosynthetic rate, stomatal conductance, and transpiration rate of spinach (Table 4.5). The G-DNA system exhibited significantly higher photosynthesis rate values (12.07±0.66 and 11.83±0.57 µmol m^{-2} s^{-1} in experiment 1 and 2 respectively) than the C-Tree system in both experiments. Similarly, the G-DNA indicated about 8 % higher stomatal conductance values than the C-Tree system. However, the vertical hydroponic systems had a non-significant effect on transpiration rate. Compared to the control, the DWC system showed significantly higher photosynthesis rate, stomatal conductance, and transpiration rate than the G-DNA and C-Tree systems (Table 4.5). Photosynthetic parameters were higher in experiment 1 compared with experiment 2 (Table 4.5). In general, the highest photosynthetic rate (13.99±0.19 µmol m^{-2} s^{-1}) was observed in DWC system in experiment 1, whereas the lowest (10.50±0.37 µmol m^{-2} s^{-1}) was recorded in C-Tree system in experiment 2 (Table 4.5).

Table 4.5: Photosynthetic rate, stomatal conductance, and transpiration rate of spinach in three hydroponic systems including deep water culture (DWC), green DNA (G-DNA), and Christmas tree (C-Tree) during two environmental conditions (Experiment 1: with grow tent, Experiment 2: without grow tent).

Experiments	**Hydroponic systems**	**Photosynthetic rate (μmol m^{-2} s^{-1})**	**Stomatal conductance (mmol H_2O m^{-2} s^{-1})**	**Transpiration rate (mmol H_2O m^{-2} s^{-1})**
Experiment 1	DWC	13.99±0.19 a	263.17±2.45 a	3.58±0.05 a
	G-DNA	12.07±0.66 b	130.50±4.90 b	2.16±0.07 b
	C-Tree	11.36±0.34 b	120.08±2.27 c	2.09±0.04 b
Experiment 2	DWC	13.41±0.35 a	258.67±5.93 a	3.55±0.09 a
	G-DNA	11.83±0.57 b	120.67±3.93 b	2.00±0.06 b
	C-Tree	10.50±0.37 c	114.08±2.95 b	1.96±0.06 b

Values are expressed as mean ± standard error for 3 replicates for each plant. Different letters within each experiment indicate significant differences among three hydroponic systems using Fisher's least significant difference test at 0.05 alpha.

4.4.2. Water use efficiency

The comparison between the WUE and water transpired of the growing systems is presented in Fig. 4.4 & 4.5. The vertical hydroponic systems had non-significant ($p < 0.05$) effects on WUE, whereas WUE values were significantly different between the vertical hydroponic systems and the control system in both experiments. C-Tree system observed the lowest WUE (16.12±0.63 g FW L^{-1}) in experiment 2 compared to other hydroponic systems in spinach production (Fig. 4.4b). The highest WUE values were observed in DWC system, 39.13±2.75 g FW L^{-1} and 39.31±4.97 g FW L^{-1} in experiment 1 and 2, respectively. In general, WUE values varied in order of DWC > G-DNA > C-Tree (Fig. 4.4a-b). Hydroponic systems had significant ($p < 0.05$) effects on transpired water in spinach production (Fig. 4.5a-b). Spinach grown in the G-DNA system significantly used the highest volume of water (1.15±0.01 L plant^{-1}) to produce the same fresh product in comparison with the C-Tree (1.05±0.01 L plant^{-1}) and DWC (0.95±0.01 L plant^{-1}). Compared to control, the vertical systems (G-DNA and C-Tree) consumed the highest amount of water to produce the fresh product. Spinach significantly consumed more water in experiment 1 than experiment 2 (Fig. 4.5a-b).

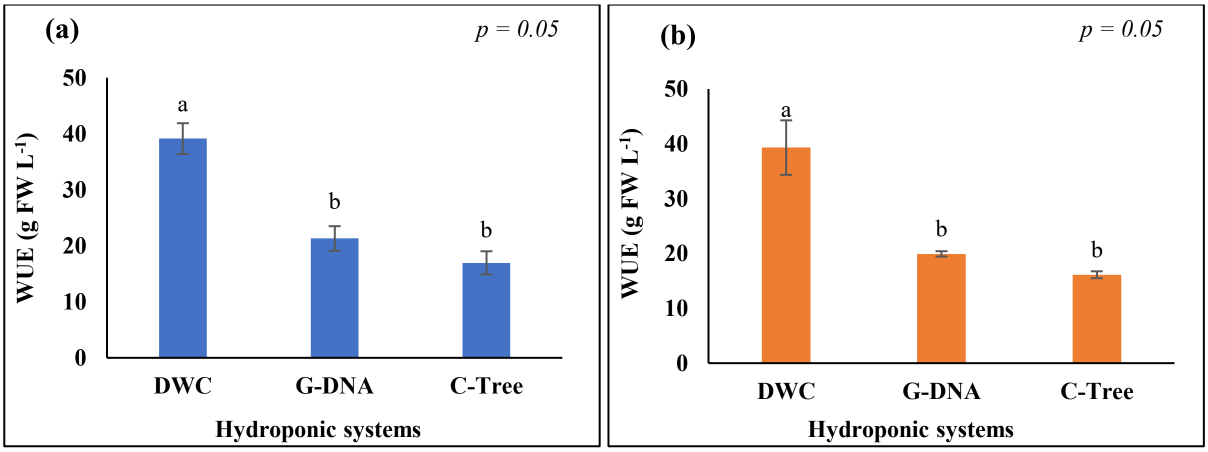

Figure 4.4: Water use efficiency (WUE) of spinach plants grown in three hydroponic systems in experiment 1 (with grow tent) (a) and experiment 2 (without grow tent) (b). Three hydroponic systems include deep water culture (DWC), green DNA (G-DNA), and Christmas tree (C-Tree). Vertical bars show the means of three replications ± standard error. Bars sharing the same letter do not differ significantly at LSD ≤ 0.05.

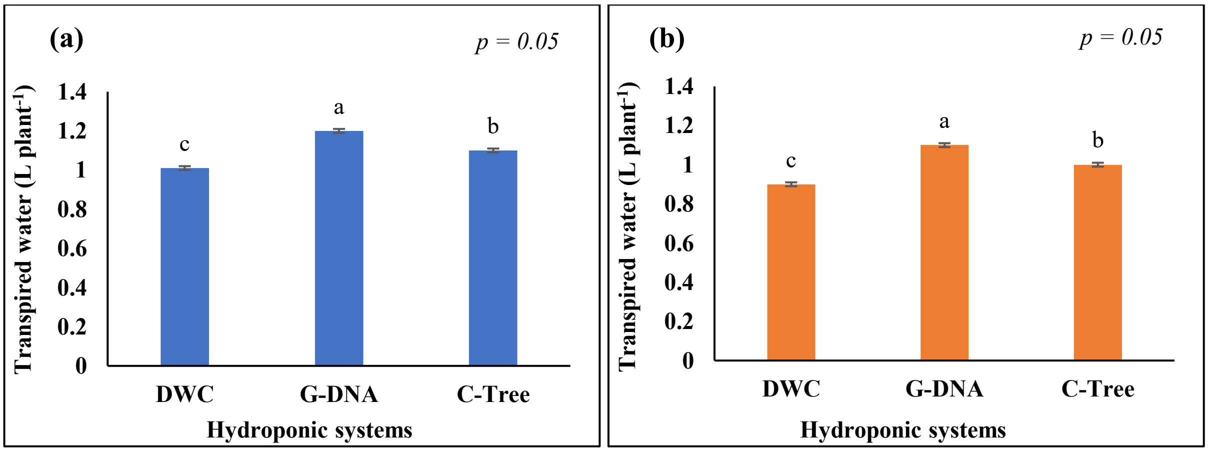

Figure 4.5: Transpired water of spinach plants grown in three hydroponic systems in experiment 1 (with grow tent) (a) and experiment 2 (without grow tent) (b). Three hydroponic systems include deep water culture (DWC), green DNA (G-DNA), and Christmas tree (C-Tree). Vertical bars show the means of three replications ± standard error. Bars sharing the same letter do not differ significantly at LSD ≤ 0.05.

4.4.3. Nitrogen use efficiency

Hydroponic systems had significant ($p < 0.05$) effects on N uptake by spinach (Fig. 4.6a-b). Nitrogen absorption was significantly higher in G-DNA (0.15±0.02 g plant^{-1}) compared with the C-Tree (0.07±0.01 g plant^{-1}) system in both experiments. Nitrogen absorption in the vertical systems (G-DNA and C-Tree) were significantly lower compared to the control system. The absorbed N in spinach was significantly higher in experiment 1 compared to experiment 2 (Fig. 4.6a-b).

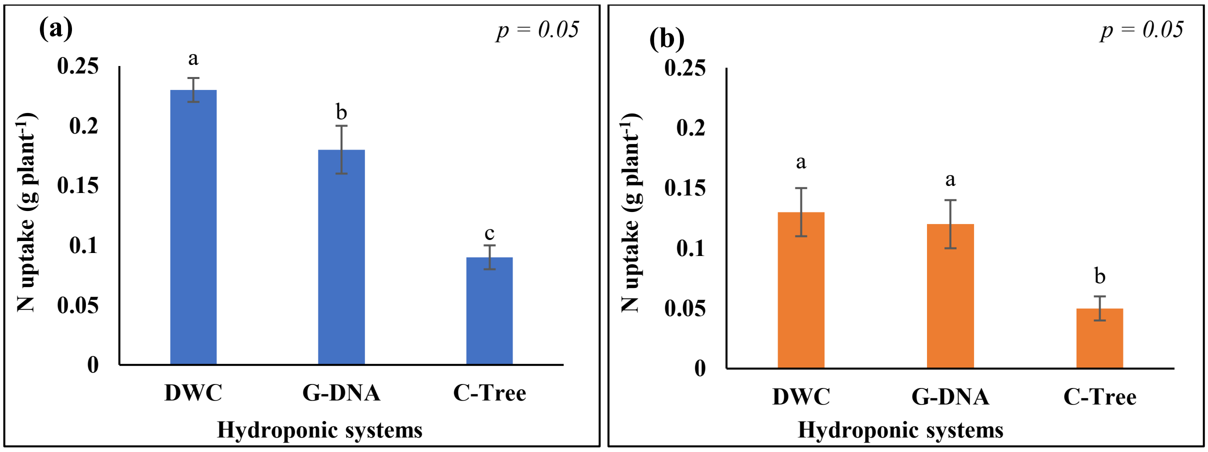

Figure 4.6: Nitrogen uptake of spinach plants grown in three hydroponic systems in experiment 1 (with grow tent) (a) and experiment 2 (without grow tent) (b). Three hydroponic systems include deep water culture (DWC), green DNA (G-DNA), and Christmas tree (C-Tree). Vertical bars show the means of three replications ± standard error. Bars sharing the same letter do not differ significantly at LSD ≤ 0.05.

NUEs in DWC, G-DNA, and C-Tree systems under experiments 1 and 2 are shown in Table 4.6, which revealed significant ($p < 0.05$) effects of the hydroponic systems on the NUEs parameters. Regarding pNUE, the highest value observed in the C-Tree (20.28±0.76 g DW g^{-1} N), followed by the DWC system (16.86±0.05 g DW g^{-1} N) in experiment 2. The control system in experiment 1 had the lowest pNUE (14.72±0.22 g DW g^{-1} N) (Table 4.6). Experiment 2 had significantly higher pNUE than the experiment 1.

Similarly, the hydroponic systems had significant ($p < 0.05$) effects on aNUE and NUE parameters (Table 4.6). The DWC system had the highest aNUE (0.96±0.07 g N g^{-1} N) in experiment 1, followed by the G-DNA (0.95±0.12 g N g^{-1} N) in experiment 2 (Table 4.6). The G-DNA system had the highest NUE values, 15.79±1.99 g DW g^{-1} N and 15.51±2.41 g DW g^{-1} N in experiment 2 and 1, respectively. The results indicate that spinach grown in G-DNA system, was able to take up more N from the nutrient solution and produce more yield in the same amount of absorbed N than the DWC and C-Tree systems. The C-Tree system observed the lowest values of NUE (8.70±0.95 g DW g^{-1} N) (Table 4.6).

Table 4.6: Physiological N use efficiency (pNUE), absorption N use efficiency (aNUE), and agronomic N use efficiency (NUE) of spinach in three hydroponic systems: deep water culture (DWC), green DNA (G-DNA), and Christmas tree (C-Tree) during two environmental conditions (Experiment 1: with grow tent, Experiment 2: without grow tent).

Experiments	Hydroponic systems	pNUE (g DW g^{-1} N)	aNUE (g N g^{-1} N)	NUE (g DW g^{-1} N)
Experiment 1	DWC	14.72±0.22 b	0.96±0.07 a	14.05±0.98 a
	G-DNA	16.73±1.08 a	0.91±0.11 a	15.51±2.41 a
	C-Tree	15.53±0.08 ab	0.56±0.08 b	8.72±1.31 b
Experiment 2	DWC	16.86±0.05 b	0.71±0.12 ab	11.98±2.08 ab
	G-DNA	16.57±0.17 b	0.95±0.12 a	15.79±1.99 a
	C-Tree	20.28±0.76 a	0.44±0.09 b	8.69±1.51 b

Values are expressed as mean ± standard error for 3 replicates for each plant. Different letters within each experiment indicate significant differences among three hydroponic systems using Fisher's least significant difference test at 0.05 alpha.

4.4.4. Financial assessment

The NPV estimated of the hydroponic systems for spinach under experiment 1 and experiment 2 have been presented in Appendix A, Tables A.6 and A.7, respectively. The results revealed a negative NPV of all three hydroponic systems under the spinach cultivation under both experiments makes the investment non-profitable for spinach cultivation (Appendix A, Tables A.6 & A.7). The positive NPVs were observed in the lettuce cultivation cycle due to higher yield for DWC and G-DNA systems, demonstrating that these two hydroponic systems are profitable for lettuce production (Appendix A, Table A.8). However, the highest NPV of 807.78 C$ belonged to the DWC system for lettuce production, which reveals that the benefits from the investment exceed the costs, thus making the investment profitable. It should be noted that lower required initial costs and higher lettuce yield per crop cycle declare that the DWC and G-DNA systems are economically viable. Nevertheless, the negative NPV of the C-Tree systems in the lettuce cultivation revealed that this system was not viable (Appendix A, Table A.8).

The payback period is important to estimate the recovery time of capital investment. The DPP was found to be 2.1 years for DWC and 4.3 years for G-DNA systems for lettuce production. This indicates a reasonable timeframe to get back the initial investment, and the return on investment was achieved over the fifth year for the C-Tree system for lettuce production (Appendix A, Table A.8). The BCR of 1.47 was observed in the DWC system for lettuce, reinforcing the system's profitability of previously established by NPV estimates (Appendix A, Table A.9). Likewise, the BCR value for G-DNA system was greater than one for lettuce cultivation, which indicates the profitability of the G-DNA system in lettuce production. Similar to NPV, the BCR values for DWC, G-DNA and C-Tree systems revealed that these systems are not financially profitable for spinach cultivation. The NPV and BCR values indicate that the DWC system as a financially rewarding hydroponic option when compared to the two vertical hydroponic systems tested in this experiment.

4.5. Discussion

Although the data shown in Table 4.4 demonstrate that the spinach growth was affected by the hydroponic systems, the vertical hydroponic systems had non-significant effects on most of the crop growth parameters. Nevertheless, the G-DNA system significantly produced higher SFW compared to the C-Tree system. SFW is an important parameter that demonstrates the performance of a household hydroponic system. Plant growth is most often limited due to non-availability of resources, particularly water and essential nutrients in the growing medium. The G-DNA system employed a drip irrigation system, delivering the nutrient solution directly onto the surface of the growing medium. Additionally, the growing medium retained moisture and nutrients around the spinach root system for plant's consumption. The C-Tree system, which employed a wick system, showed the lowest spinach growth, perhaps due to the ineffectiveness of the cotton wicks in delivering the enough nutrient solution to the plants. This is contrary to the results of Kaur et al. (2019), in which the wick system produced more tomato yield than the drip hydroponic system. Also, Ferrarezi & Testezlaf (2016) observed higher lettuce productivity under wick hydroponic system compared with NFT system. Compared with the control, DWC system resulted in higher yield compared to the G-DNA and C-Tree systems, due to constant nutrient solution supply to spinach roots in the DWC system. As the root system developed in the DWC system, roots were submerged in water and nutrients, thereby leading to higher spinach growth.

Plant growth may be limited due to different environmental variables such as high or low air temperature, low humidity, and insufficient light intensity (Lu et al., 2015; Gent, 2017). Temperature above the optimum range is one of the major abiotic stresses which threats crop productivity (Mathur et al., 2014). Photosynthesis plays a key role in crop development and is the earliest function which is impaired under high air temperature in plants (Ashraf & Harris, 2013). Stomatal closure driven by heat stress leads to low photosynthesis rate and respiration reduction, which inhibits crop growth (Greer & Weedon, 2012; Haghighi et al., 2014). In the current study, spinach plants in experiment 2 experienced higher air temperature (30.1 °C), which led to limitation in growth and yield of spinach, and significantly reduced stomatal conductance (Tables 4.4 & 4.5). This is consistent with the findings of previous studies, in which high temperature reduced crop growth. Gent (2016) observed that the lowest spinach fresh weight (28.8 g plant^{-1}) occurred at the highest temperature at 23.5 °C and the highest fresh weight (66.5 g plant^{-1}) observed at 16.1 °C. Lefsrud et al. (2005) reported that leaf tissue of spinach was significantly impacted by air temperature. Shoot fresh weight of spinach increased as the temperature increased from 10 to 20 °C, then decreased by exceeding the temperature above the optimum range for spinach at 25 °C. It should be noted that spinach experienced high temperature of 26.5 °C and 30.1 °C in experiment 1 and experiment 2, respectively, which are higher than the standard temperature in the cultivation of spinach.

RH being one of the important factors in photosynthesis rate and other physiological processes of plants, which is the result of a combination of plants transpiration, evaporation, and ventilation (Arena et al., 2020; Lysenko et al. 2023). With increasing air temperature rises, RH decreases. High RH leads to lower leaf water stress and increases stomatal conductance, which causes photosynthetic rate enhancement in the plants (Suzuki et al., 2015; Grossiord et al., 2020). Higher RH in experiment 1 resulted in higher spinach growth parameters than experiment 2, as well as higher photosynthetic parameters in experiment 1 (Tables 4.4 & 4.5). Studies conducted by Suzuki et al. (2015) also reported higher growth of tomato when plants were grown in higher RH.

Light plays an essential role in plant development, and indoor growing systems require artificial light as the main source or supplementary (Kozai & Niu, 2016). Low light intensity leads to lack of sufficient energy and the closure of stomata, which restricts the photosynthesis rate (Wang et al., 2017; Pascual et al., 2017; Liu et al., 2014). Plants undergo physiological and morphological changes in response to low light intensity, and they can be adapted to such conditions by increasing plant height to maximize light absorption (Steinger et al., 2003). The observed relatively higher spinach yield under greater light intensity in experiment 1 aligns with finding from other studies (Table 4.4) (Nguyen et al., 2019; Grzegorzewska et al., 2023). Grzegorzewska et al. (2023) reported that the hydroponic systems produced around 10 % higher fresh weight of lettuce from 160 to 200 µmol m^{-2} s^{-2} of light intensity. Pennisi et al. (2020) found that lettuce and basil exhibited an increase in both fresh weight and dry weight as the light intensity enhanced from 100 to 250 µmol m^{-2} s^{-2}.

Less water consumption while maintaining adequate biomass is one of the most important objectives in agricultural production (Fernández et al., 2018). WUE was inversely proportional to water consumption; hence, G-DNA (1.15±0.01 L $plant^{-1}$) and C-Tree (1.05±0.01 L $plant^{-1}$) with high water consumption indicated low WUE (Fig. 4.4 & 4.5). The high water consumption in the G-DNA system might be due to the evaporation of water from the substrate's surface. The pots in the G-DNA system had an open and wide surface compared to the DWC and C-Tree systems, resulting in high evaporation loss. The results showed that the C-Tree (wick) and G-DNA (drip) systems required more water to produce the same yield compared to the DWC system. Although we expected lower water consumption in C-Tree with the wick system as the system supplies water through the capillarity, C-Tree system required more water than DWC system. These findings agree with the findings of Verdoliva et al. (2021), who found that the DWC system used less water compared to the drip hydroponic system. It is imperative to understand that high water consumption may not increase plant productivity and WUE (Hatfield & Dold, 2019; Hebbar et al., 2022). Less water consumption and high yield in DWC led to the highest WUE in this system (39.31±4.97 g FW L^{-1}) (Fig. 4.4a-b).

High air temperature, low RH, and lack of sufficient light affect water loss in plants as a reaction to physiological response and cause low WUE (Solymosi & Schoefs, 2010; Fu et al., 2017). The reduced water consumption in experiment 2 could potentially be due to both lower yield and decreased plant transpiration resulting from high air temperature and low RH (Fig. 4.5a-b).

Different factors influence N uptake by plants, including light intensity, temperature, water availability, N availability, plant demand, and root development (Overeem, 2015; Gent, 2014). Higher water and N availability resulted from drip irrigation in G-DNA system enhanced N uptake compared to C-Tree system (Fig. 4.6a-b). Apparently, the wick irrigation method used in the C-Tree system was unable to deliver sufficient water and fertilizer for spinach growth as expected (Ali et al., 2021). Increased root biomass, longer root length, and abundant root hairs in DWC systems play an important role in facilitating N absorption from the nutrient solution. This leads to enhanced roots contact with the nutrient solution (Subramanian et al., 2010). In addition, high water and N availability due to roots submersion in the nutrient solution increased N uptake in DWC in comparison to the less water and N availability in G-DNA (drip) and C-Tree (wick) systems (Fig. 4.6a-b).

Light intensity is considered one of the main factors influencing N concentration in leafy vegetables, and plants under low light intensity utilize less N (Gruda, 2005). The study conducted by Grzegorzewska et al. (2023) showed that lettuce leaves contained higher N content at elevated light intensities, while Xie et al. (2019) observed a reduced N uptake in different rice varieties when exposed to lower light intensities. Additionally, temperature is a key factor in the N uptake rate in plants due to the effects on the transpiration rate and crop growth (Overeem, 2015). Our study shows a higher N uptake rate by spinach in experiment 1, almost two folds compared to experiment 2, with high light intensity and different weather conditions (Fig. 4.6).

The C-Tree system (20.28±0.76 g DW g^{-1} N) had the highest value of pNUE, followed by the DWC system (16.86±0.05 g DW g^{-1} N) (Table 4.6). Among the systems studied, the DWC system (0.96±0.07 g N g^{-1} N) showed the highest aNUE, followed by the G-DNA (0.95±0.12 g N g^{-1} N), due to the nutrient-rich root zone environment and the substantial N uptake by spinach. The lowest aNUE was observed in the C-Tree system (0.44±0.09 g N g^{-1} N) due to either the unavailability of the nutrient solution for the roots or the incapacity of the cotton wicks to transport ions from the solution to the root zone. Although N leaching is not a concern in a closed-loop hydroponic system, rapid uptake of N from the nutrient solution can reduce the potential N loss through denitrification and volatilization (Goins et al., 2004). Consequently, experiment 1 had a higher aNUE than experiment 2, attributed to an increased

N supply, consequently leading to an uptake of N by the plants (Table 4.6). Hydroponic systems significantly affected the NUE, and G-DNA system had the highest NUE (15.79±1.99 g DW g^{-1} N) (Table 4.6). The C-Tree system presented the lowest NUE value (8.69±1.51 g DW g^{-1} N) due to low crop growth and N supply (Table 4.6).

We employed the BCR and NPV metrics to evaluate the financial analysis of hydroponic systems. Our results indicated that the G-DNA and DWC hydroponic systems are viable for lettuce production, whereas they do not yield profitability for spinach production. The total revenue generated from lettuce cultivation was higher than spinach, showing how lettuce offers a more favorable return in the hydroponic systems. Lettuce, being a high-value crop, likely account for the profitability observed in its production (Table A.8). High temperature had an adverse impact on spinach production, leading to a decrease in yield and non-profitability of the systems in spinach production. Under normal environmental conditions and the ideal temperature, spinach cultivation could also have been profitable. The major fixed costs are the grow tent and lighting system in experiment 1, while it was only the lighting system in experiment 2. Likewise, the lighting is the main part of variable costs, almost 50 %, in each system and in both experiments (Tables A.2, A.3, A.4).

In lettuce production, NPV of the G-DNA system (433.72 C$) was higher than the C-Tree system and G-DNA system is a more interesting investment than the C-Tree hydroponic system. Regarding the control system, NPV of the DWC system (807.78 C$) was almost two-fold higher than the NPV in the G-DNA system (Table A.8). The BCR values observed a similar pattern to the NPV results indicating the profitability of G-DNA and DWC in lettuce cultivation under (Table A.9). DPP for the hydroponic systems under the spinach production exceeds the life period of the systems, which confirms that the hydroponic systems are not profitable for spinach production due to low production under high temperature (Tables A.6 & A.7). Overall, the G-DNA and DWC system was shown as financially viable systems in lettuce production. However, all three hydroponic systems could be profitable under ideal environmental condition in the spinach cultivation. Eliminating costly equipment such as grow tent and steel hardware set can reduce initial project costs.

The designed C-Tree system has the advantages of small size, simple structure, ease of operation, and low energy consumption, but it still exhibits some shortcomings. Plant cultivation in hydroponics relies on special attention relating to air temperature, relative humidity, light intensity, water circulation, and nutrient solution quality. The designed hydroponic system in this study has several areas for improvement, particularly how hydroponics requires a controlled environment, especially in maintaining the temperature and relative humidity in an optimum range. Moreover, using a light source at the top of the hydroponic system led to low light intensity at the lower levels of the C-Tree system. Additionally, the wick system was selected as the nutrient solution application system in the C-Tree system in order to reduce energy consumption. However, the wick system did not work properly and changing to another nutrient solution application method can be more effective.

We recommend certain adjustments to enhance the efficiency of the C-Tree system. Temperature and humidity need to be monitored and controlled to avoid reducing plant growth and meet expectations. Consequently, employing vertical artificial light sources can mitigate the adverse impact of insufficient light intensity in the lower layers of the growing pots. To improve the nutrient solution application method, a system in which the roots directly interface with the nutrient solution may be more effective.

4.6. Conclusion

Although indoor hydroponic systems have been introduced as a possible solution to ensure local food production, household hydroponic systems have yet to be compared to identify the most efficient cultivation systems. Climate conditions, water and nutrient availability are very important for crop growth and development, especially in hydroponic systems. This research confirmed that an optimum response exists between environmental conditions and plant growth, and spinach grown in a controlled condition showed higher crop growth. The reduced growth parameters could be associated with high air temperature, low RH, and low light intensity in experiment 2. G-DNA produced higher spinach growth parameters, WUE, and NUE compared to C-Tree system, irrespective of the environmental conditions. Although the hydroponic systems were not profitable in spinach production, the G-DNA system could be profitable for lettuce production. It is important to underline that these small-scale hydroponic systems used in this study could be promising and profitable if high-value plants were grown in the systems. More research needs to be carried out to evaluate the profitability of the production of other vegetables using hydroponic systems. It can be concluded that the G-DNA system could be used as a sustainable and feasible household cultivation system for leafy vegetable production.

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Chapter 5

5. General conclusions and recommendations

5.1. General discussion

The objectives of the present study were:

I. to design, fabricate, and evaluate a small-scale, low-cost vertical hydroponic system for leafy vegetable production in household environments.

II. to evaluate the growth performance of spinach under different hydroponic systems and growing conditions.

III. to determine the water use efficiency (WUE) and nitrogen use efficiency (NUE) of spinach grown in hydroponic systems

The above-mentioned objectives were achieved in two different steps: details are given in chapter 3 (Design and fabrication of a small-scale and low-cost vertical hydroponic system for households) and in chapter 4 (Performance evaluation of two newly designed vertical hydroponic systems for growth, WUE, NUE, and financial feasibility of spinach (*Spinacia oleracea* L.).

In chapter 3, a small-scale vertical hydroponic system for households was designed and fabricated. A vertical household hydroponic system has the potential to offer various advantages, such as increasing vegetable production per unit area, increased availability of fresh vegetables, and aesthetic appeal.

After designing a vertical hydroponic system, a Christmas-tree system (C-Tree), the prototype was created and tested without growing crops to assess the nutrient distribution system and identify any potential leaks. Thereafter, the system was modified and improved, and the final product was created. To ensure ease of assembly and cost-effectiveness during fabrication, locally available materials were utilized. Additionally, another vertical hydroponic system, namely Green DNA (G-DNA), which had been designed, fabricated and the initial testing was completed, modified and tested.

In chapter 4, the two newly designed vertical hydroponic systems, C-Tree and G-DNA, were investigated to evaluate the performance for spinach growth, WUE, and NUE. A horizontal hydroponic system, deep water culture (DWC), which is the commonly used system at household level, was used as the control. The experiments were conducted under two environmental conditions (the hydroponic systems inside a grow tent – experiment 1, and without a grow tent – experiment 2). Spinach showed higher growth performances in G-DNA system than the C-Tree system, specifically as shoot fresh biomass/weight (SFW), 23.02±1.34 g plant^{-1} and 17.31±1.22 g plant^{-1} of SFW, respectively. Low availability of the nutrient solution in the growing medium through the wick system might have limited the spinach growth and yield in the C-Tree system compared to the G-DNA system, which supplied the nutrient solution through a drip irrigation system. Conversely, the DWC produced higher SFW due to easily accessible nutrients and water when roots are submerged in the nutrient solution. In general, the results of this study demonstrated that spinach cultivated under the G-DNA system exhibited higher growth and yield and showed superior performance compared to the C-Tree hydroponic system. Although the growth conditions did not show any significant effect on most of spinach growth parameters, the experiment 1 experienced comparatively higher performance values than the experiment 2, potentially due to lower temperatures, higher relative humidity, and higher light intensity in the experiment 1. Using a grow tent to regulate microclimate conditions in experiment 1 might have influenced crop growth in contrast to experiment 2.

WUE was inversely proportional to water consumption, with the DWC system exhibiting the highest value of 39.31±4.97 g FW L^{-1}. However, the WUE did not show significant changes with vertical hydroponic systems. The study emphasized that high water consumption does not necessarily enhance plant productivity and WUE. G-DNA and C-Tree exhibited high water consumption (1.15±0.01 L $plant^{-1}$ and 1.05±0.01 L $plant^{-1}$) and low WUE (20.62±1.35 g FW L^{-1} and 16.12±0.63 g FW L^{-1}), respectively, compared to the DWC system (0.96±0.01 L $plant^{-1}$ of water consumption and 39.22±3.86 g FW L^{-1} of WUE). Factors such as air temperature, humidity, and light intensity influence plant growth, thus water consumption and WUE.

Various factors, including water and nitrogen (N) availability influence N uptake by plants. The DWC system showed enhanced N uptake due to increased root contact with the nutrient solution. Notably, the G-DNA system displayed the highest NUE (15.79±1.99 g DW g^{-1} N) among three hydroponic systems, while the C-Tree system showed the lowest NUE value (8.69±1.51 g DW g^{-1} N). This suggests that spinach grown in the G-DNA system could uptake more N from the nutrient solution and consequently higher yield with the same amount of absorbed N compared to the DWC and C-Tree systems.

However, a financial evaluation disclosed that hydroponic systems were not economically viable for spinach production under either growth conditions tested. The combination of higher investment costs and lower spinach yield in hydroponic systems rendered them unfeasible for spinach production projects. The reason behind this might be the limited spinach growth due to air temperature above the optimum range for spinach production. High temperature had an adverse impact on spinach production, leading to a decrease in yield and non-profitability of the systems in spinach production. Under normal environmental conditions and the ideal temperature, spinach cultivation could also have been profitable.

In summary, these findings imply that the G-DNA system has the potential to provide superior NUE and greater feasibility for cultivating leafy vegetables.

5.2. Recommendations

It needs to be pointed out that due to the limited scope of this study, the design might not be comprehensive, particularly when applied to the real household conditions. Therefore, there needs to be further investigation along with more modifications.

Further studies and modifications must focus on:

- Developing and adjusting the irrigation system within the designed hydroponic system to enhance water and nutrient availability for optimal root nourishment, thereby promoting crop growth and yield.
- Assessing the performance of hydroponic systems with continuous monitoring of the environmental variables in household settings.
- Employing detailed simulation and 3D printing fabrication techniques to create a robust hydroponic system, aiming to reduce imperfections and enhance overall efficiency.

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Appendix A

Financial analysis

In this study, the total costs, and expected future revenues based on the crop harvest and market price were used to do the financial analysis for comparing the three hydroponic systems. Therefore, two types of costs were used: initial investment and operational costs. Fixed costs were considered as investment costs to start up the project and were recorded at the beginning of the experiment during the fabrication phase. On the other hand, operational costs refer to the cash flow necessary for the ongoing operation and development of hydroponic systems that produce 18 bunches of spinach over each crop cycle. Table A.1 shows the fixed costs of three hydroponic systems in experiment 1 (with grow tent) and experiment 2 (without grow tent). Tables A.2 and A.3 show the operational costs of three hydroponic systems in spinach cultivation in experiment 1 and experiment 2, respectively. The crop cycle is around one month between the transplanting and harvesting of spinach. Therefore, 11 crop cycles could be taken in a year to estimate the operational costs per year. The expected future cash flows were estimated based on the average yield of spinach at harvest (Table A.5). Total income was calculated based on the average sale price in the local markets in Corner Brook, NL, Canada. The price in the local grocery stores was 3.32 C$ per 100 g of spinach as of June 2023.

Financial assessment of the hydroponic systems would give a better result if different crops were considered. In this regard, lettuce was discussed as another example for the financial analysis. In a concurrent study conducted by Adelowokan et al. (2023 – verbal communication), lettuce was grown using the same hydroponic systems used in this study. Their experiment was carried out in similar conditions in which 18 heads of lettuce were grown in DWC, G-DNA, and C-Tree hydroponic systems inside a grow tent. The fixed costs were equal to the spinach cultivation experiment in experiment 1 (with grow tent), which are presented in Table A.1 and the operation costs in the lettuce cultivation are presented in Table A.4. As the crop cycle is around 50 days for lettuce, 10 crop cycles could be taken in a year.

The expected future cash flows were estimated based on the average lettuce yield at harvest (Table A.5). Total income was calculated based on the average sale price in the local markets in Corner Brook, NL, Canada. The price in the local grocery stores ranged from 1.8 C$ for a head of lettuce weighing less than 130 g, 2.1 C$ weighing around 180 g, to 2.3 C$ per head of lettuce weighing more than 190 g, 1.8 C$ as of June 2023.

Table A. 1: Total fixed costs of three hydroponic systems in experiment 1 (with grow tent) and experiment 2 (without grow tent)

Item	**Unit cost (C$)**	**DWC**		**G-DNA**		**C-Tree**	
		Quantity	**Cost (C$)**	**Quantity**	**Cost (C$)**	**Quantity**	**Cost (C$)**
Fixed costs in experiment 1 (C$)			**339.30**		**533.39**		**501.50**
Fixed costs in experiment 2 (C$)			**179.30**		**373.39**		**341.50**
Grow tent	160	1	160	1	160	1	160
Reservoir	17	1	17	1	17	1	17
ABS pipe	15.5	-	-	1	15.5	1	15.5
PVC flange and adapter	16	-	-	1	16	1	16
Threated rods (m)	3	-	-	3.5	10.5	4.5	13.5
Disposable cups	0.2	-	-	-	-	18	3.6
Plastic planters	1.2	-	-	18	21.6	-	-
3-inch net pots	1.1	-	-	-	-	18	19.8
2-inch net pots	0.9	18	16.2	-	-	-	-
Bolts, nuts, and washers	1.2	-	-	76	91.2	76	91.2
¼-inch tube (m)	0.5	-	-	12.5	6.3	8	4.0
Drippers	0.4	-	-	18	7.2	-	-
Shut-off valve	2.8	-	-	2	5.6	-	-
Barbed elbows, and tees	0.6	-	-	40	24	4	2.4
Water pump	29	-	-	1	29	1	29
Air pump and air stone	25.3	1	25.3	-	-	-	-
LED (300 W)	115	1	115	1	115	1	115
Miscellaneous items	-	-	5.8	-	14.5	-	14.54

m: meter; (Currency unit: CAD)

Table A. 2: The total variable costs of three hydroponic systems in experiment 1 (with grow tent) in spinach cultivation

Item	**Unit cost (C$)**	**DWC**		**G-DNA**		**C-Tree**	
		Quantity	**Cost (C$)**	**Quantity**	**Cost (C$)**	**Quantity**	**Cost (C$)**
Variable costs per crop cycle (C$)			**19.85**		**19.25**		**23.63**
Variable costs per year (C$)			**218.35**		**211.75**		**259.93**
Pump (kWh)	0.12	2.88	0.36	0.48	0.06	0.48	0.06
Lighting (kWh)	0.12	81	10	81	10	81	10
Water (L)	Free	-	-	-	-	-	-
Fertilizers (g)	0.02	96.25	1.4	76.25	1.1	61.25	0.9
pH test strips (80 strips)	7	30	2.6	30	2.6	30	2.6
Seeds (g)	2.3	0.3	0.7	0.3	0.7	0.3	0.7
Seedlings grow trays	2	1	2	1	2	1	2
Growing media (g)	0.7	4	2.8	4	2.8	4	2.8
Cotton ropes (m)	2.3	-	-	-	-	2	4.6

The price of electricity, approximately 0.12 cents per kWh was obtained from Newfoundland and Labrador Hydro (myNLhydro, 2023). g: gram, m: meter, kWh: Kilowatt per hour, L: Liter; (Currency unit: CAD)

Table A. 3: The total variable costs of three hydroponic systems in experiment 2 (without grow tent) in spinach cultivation

Item	**Unit cost (C$)**	**DWC**		**G-DNA**		**C-Tree**	
		Quantity	**Cost (C$)**	**Quantity**	**Cost (C$)**	**Quantity**	**Cost (C$)**
Variable costs per crop cycle (C$)			**19.48**		**18.88**		**23.35**
Variable costs per year (C$)			**214.28**		**207.68**		**256.85**
Pump (kWh)	0.12	2.88	0.36	0.48	0.06	0.48	0.06
Lighting (kWh)	0.12	81	10	81	10	81	10
Water (L)	Free	-	-	-	-	-	-
Fertilizers (g)	0.02	71.5	1.1	51.5	0.8	42.75	0.6
pH test strips (80 strips)	7	30	2.6	30	2.6	30	2.6
Seeds (g)	2.3	0.3	0.7	0.3	0.7	0.3	0.7
Seedlings grow trays	2	1	2	1	2	1	2
Growing media (g)	0.7	4	2.8	4	2.8	4	2.8
Cotton ropes (m)	2.3	-	-	-	-	2	4.6

The price of electricity, approximately 0.12 cents per kWh was obtained from Newfoundland and Labrador Hydro (myNLhydro, 2023). g: gram, m: meter, kWh: Kilowatt per hour, L: Liter; (Currency unit: CAD)

Table A. 4: The total variable costs of three hydroponic systems in experiment 1 (with grow tent) in lettuce cultivation

Item	**Unit cost (C$)**	**DWC**		**G-DNA**		**C-Tree**	
		Quantity	**Cost (C$)**	**Quantity**	**Cost (C$)**	**Quantity**	**Cost (C$)**
Variable costs per crop cycle (C$)			**22.73**		**22.06**		**26.39**
Variable costs per year (C$)			**227.3**		**220.6**		**263.9**
Pump (kWh)	0.12	3.36	0.41	0.84	0.1	0.84	0.1
Lighting (kWh)	0.12	94.5	11.7	94.5	11.7	94.5	11.7
Water (L)	Free	-	-	-	-	-	-
Fertilizers (g)	0.02	116	1.7	92	1.4	74	1.1
pH test strips (80 strips)	7	35	3.1	35	3.1	35	3.1
Seeds (g)	3.5	0.3	1.1	0.3	1.1	0.3	1.1
Seedlings grow trays	2	1	2	1	2	1	2
Growing media (g)	0.7	4	2.8	4	2.8	4	2.8
Cotton ropes (m)	2.3	-	-	-	-	2	4.6

The price of electricity, approximately 0.12 cents per kWh was obtained from Newfoundland and Labrador Hydro (myNLhydro, 2023). g: gram, m: meter, kWh: Kilowatt per hour, L: Liter; (Currency unit: CAD)

Table A. 5: Yield and potential income of spinach in experiment 1 (with grow tent) and experiment 2 (without grow tent) and the lettuce in experiment 1 (with grow tent).

Crop type		**DWC**		**G-DNA**		**C-Tree**	
		Exp. 1	**Exp. 2**	**Exp. 1**	**Exp. 2**	**Exp. 1**	**Exp. 2**
Spinach	**Average yield per plant (g)**	41.06	35.40	24.85	21.19	18.98	15.64
	Total yield (g)	739.08	637.20	447.30	381.42	341.64	281.52
	Income per crop cycle (C$)	24.54	21.16	14.85	12.66	11.34	9.35
	Total income per year (C$)	269.91	232.71	163.35	139.29	124.77	102.81
Lettuce	**Average yield per plant (g)**	190.60	-	177.70	-	130.80	-
	Total yield (g)	3,430.80	-	3,198.60	-	2,354.40	-
	Income per crop cycle (C$)	41.4	-	37.80	-	32.40	-
	Total income per year (C$)	414.00	-	378.00	-	324.00	-

(Currency unit: CAD)

Table A. 6: Financial analysis for net present value (NPV) at 10 % discount rate for production of spinach under three hydroponic systems in 10 years in experiment 1 (with grow tent).

Year	**DWC**				**G-DNA**				**C-Tree**			
	Cash outflows (C$)	**Cash inflows (C$)**	**Present value (C$)**	**Payback period**	**Cash outflows (C$)**	**Cash inflows (C$)**	**Present value (C$)**	**Payback period**	**Cash outflows (C$)**	**Cash inflows (C$)**	**Present value (C$)**	**Payback period**
0	339.30	0	-339.30		533.39	0	-533.39		501.50	0	-501.50	
1	218.31	269.91	46.91	46.91	211.75	163.35	-44.00	-44.00	259.88	124.77	-122.83	-122.83
2	218.31	269.91	42.64	89.55	211.75	163.35	-40.00	-84.00	259.88	124.77	-111.66	-234.49
3	218.31	269.91	38.77	128.32	211.75	163.35	-36.36	-120.36	259.88	124.77	-101.51	-336.00
4	218.31	269.91	35.24	163.56	211.75	163.35	-33.06	-153.42	259.88	124.77	-92.28	-428.28
5	218.31	269.91	32.04	195.60	211.75	163.35	-30.05	-183.47	259.88	124.77	-83.89	-512.18
6	218.31	269.91	29.13	224.73	211.75	163.35	-27.32	-210.79	259.88	124.77	-76.27	-588.44
7	218.31	269.91	26.48	251.21	211.75	163.35	-24.84	-235.63	259.88	124.77	-69.33	-657.78
8	218.31	269.91	24.07	275.28	211.75	163.35	-22.58	-258.21	259.88	124.77	-63.03	-720.81
9	218.31	269.91	21.88	297.16	211.75	163.35	-20.53	-278.73	259.88	124.77	-57.30	-778.11
10	218.31	269.91	19.89	317.06	211.75	163.35	-18.66	-297.39	259.88	124.77	-52.09	-830.20
NPV (C$)			**-22.24**				**-830.78**				**-1,331.70**	

Table A. 7: Financial analysis for net present value NPV at 10 % discount rate for production of spinach under three hydroponic systems in 10 years in experiment 2 (without grow tent).

Year	**DWC**				**G-DNA**				**C-Tree**			
	Cash outflows (C$)	**Cash inflows (C$)**	**Present value (C$)**	**Payback period**	**Cash outflows (C$)**	**Cash inflows (C$)**	**Present value (C$)**	**Payback period**	**Cash outflows (C$)**	**Cash inflows (C$)**	**Present value (C$)**	**Payback period**
0	179.30	0	-179.30		373.39	0	-373.39		341.50	0	-341.50	
1	214.23	232.71	16.80	16.80	207.67	139.29	-62.16	-62.16	256.83	102.81	-140.01	-140.01
2	214.23	232.71	15.27	32.07	207.67	139.29	-56.51	-118.67	256.83	102.81	-127.28	-267.30
3	214.23	232.71	13.88	45.95	207.67	139.29	-51.37	-170.04	256.83	102.81	-115.71	-383.01
4	214.23	232.71	12.62	58.57	207.67	139.29	-46.70	-216.74	256.83	102.81	-105.19	-488.20
5	214.23	232.71	11.47	70.04	207.67	139.29	-42.46	-259.19	256.83	102.81	-95.63	-583.84
6	214.23	232.71	10.43	80.47	207.67	139.29	-38.60	-297.79	256.83	102.81	-86.94	-670.77
7	214.23	232.71	9.48	89.95	207.67	139.29	-35.09	-332.88	256.83	102.81	-79.03	-749.81
8	214.23	232.71	8.62	98.57	207.67	139.29	-31.90	-364.77	256.83	102.81	-71.85	-821.66
9	214.23	232.71	7.84	106.41	207.67	139.29	-29.00	-393.77	256.83	102.81	-65.32	-886.97
10	214.23	232.71	7.12	113.53	207.67	139.29	-26.36	-420.13	256.83	102.81	-59.38	-946.35
NPV (C$)			**-65.77**				**-793.52**				**-1,287.85**	

Table A. 8: Financial analysis for net present value (NPV) at 10 % discount rate for production of lettuce under three hydroponic systems in 10 years in experiment 1 (with grow tent).

Year	DWC				G-DNA				C-Tree			
	Cash outflows (C$)	Cash inflows (C$)	Present value (C$)	Payback period	Cash outflows (C$)	Cash inflows (C$)	Present value (C$)	Payback period	Cash outflows (C$)	Cash inflows (C$)	Present value (C$)	Payback period
0	339.30	0	-339.30		533.39	0	-533.39		501.50	0	-501.50	
1	227.32	414.00	169.71	169.71	220.61	378.00	143.08	143.08	263.91	324.00	54.63	54.63
2	227.32	414.00	154.28	323.99	220.61	378.00	130.08	273.16	263.91	324.00	49.66	104.29
3	227.32	414.00	140.26	464.25	220.61	378.00	118.25	391.41	263.91	324.00	45.15	149.44
4	227.32	414.00	127.51	591.76	220.61	378.00	107.50	498.92	263.91	324.00	41.04	190.49
5	227.32	414.00	115.91	707.67	220.61	378.00	97.73	596.64	263.91	324.00	37.31	227.80
6	227.32	414.00	105.38	813.05	220.61	378.00	88.84	685.49	263.91	324.00	33.92	261.72
7	227.32	414.00	95.80	908.85	220.61	378.00	80.77	766.26	263.91	324.00	30.84	292.56
8	227.32	414.00	87.09	995.93	220.61	378.00	73.43	839.68	263.91	324.00	28.03	320.59
9	227.32	414.00	79.17	1075.11	220.61	378.00	66.75	906.43	263.91	324.00	25.49	346.08
10	227.32	414.00	71.97	1147.08	220.61	378.00	60.68	967.11	263.91	324.00	23.17	369.25
NPV (C$)			**807.78**				**433.72**				**-132.25**	

Table A. 9: Financial analysis for benefit cost ratio (BCR) at 10 % discount rate for production of spinach and lettuce under three hydroponic systems in 10 years in experiment 1 (with grow tent) and experiment 2 (without grow tent).

Crop type	Experiment	DWC			G-DNA			C-Tree		
		Present value of costs (C$)	Present value of benefits (C$)	BCR	Present value of costs (C$)	Present value of benefits (C$)	BCR	Present value of costs (C$)	Present value of benefits (C$)	BCR
Spinach	**Experiment 1**	1,680.73	1,658.49	0.99	1,834.52	1,003.74	0.55	2,098.34	766.64	0.37
	Experiment 2	1,495.64	1,429.87	0.96	1,649.43	855.90	0.52	1,919.58	631.73	0.33
Lettuce	**Experiment 1**	1,736.07	2,543.85	1.47	1,888.92	2,322.65	1.23	2,123.09	1,990.84	0.94

Appendix B

Publications:

Fathidarehnijeh, E., Nadeem, M., Cheema, M., Thomas, R., Krishnapillai, M., & Galagedara, L. (2023). Current perspective on nutrient solution management strategies to improve the nutrient and water use efficiency in hydroponic systems. *Canadian Journal of Plant Science*. https://doi.org/10.1139/cjps-2023-0034. (Status: Published).

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OPEN ACCESS | Review

Current perspective on nutrient solution management strategies to improve the nutrient and water use efficiency in hydroponic systems

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Abstract

Hydroponics, a soilless cultivation technique using nutrient solutions under controlled conditions, is used for growing vegetables, high-value crops, and flowers. It produces significantly higher yields compared to conventional agriculture despite its higher energy consumption. The success of a hydroponic system relies on the composition of the nutrient solution, which contains all the essential mineral elements necessary for optimal plant growth and high yield. This review delves into the discussion of enhancing nutrient solution management strategies across different hydroponic systems. The aim of this review is to discuss various techniques for monitoring nutrient solutions in order to improve nutrient use efficiency (NUE) and water use efficiency (WUE). The conventional approach of monitoring the hydroponic nutrient solution using electrical conductivity measurement may not provide precise information about ion concentrations, potentially resulting in poor yields or excessive fertilizer usage. To overcome these limitations, alternative management strategies have been developed to enable more accurate monitoring and efficient management. One such strategy is the nitrogen-based approach, where nitrogen concentration becomes the primary controlled element in the nutrient solution and leads to WUE and NUE development by prolonging nutrient solution recirculation. Furthermore, various methods have been devised to improve nutrient solution strategies. These include using ion-selective electrodes to measure individual ions in the hydroponic nutrient solution, using sensors to monitor substrate moisture content, estimating water requirements, and implementing programmed nutrient addition methods. In addition to introducing different management techniques to optimize hydroponic performance, this review provides a better understanding of hydroponic systems.

Key words: hydroponics, closed-loop hydroponics, open hydroponics, nutrient use efficiency, water use efficiency

1. Introduction

The global population is rapidly increasing, estimated to reach ~9.7 billion in 2050 (United Nations 2014). Thus, it is estimated that 70% more food production will be required to feed this growing population (Silva 2018). To meet this increasing populations' food and feed demands, there is an urgent need to use innovative approaches to enhance the availability of fresh food produced across the globe (Pascual et al. 2018). However, water shortage is one of the most important challenges for food production, and increasing food production could negatively affect water resources (Mancosu et al. 2015; Nicola et al. 2020). The agricultural sector is the major consumer of freshwater, with over 70% of annual water withdrawals (FAO 2017), and some traditional open-field soil-based farming increases water usage due to deep leaching, runoff, and evaporation (Bar-Yosef 2008; Putra and Yuliando 2015). On the other hand, climate change will bring drought or uneven precipitation, negatively affecting agricultural activity and productivity (Barbosa et al. 2015; Abukari and Tok 2016).

Greenhouse cultivation systems increase water and fertilizers productivity compared with open-field soil-based cultivation systems due to better control of environmental conditions and inputs (Rouphael and Colla 2009; Rosa-Rodriguez et al. 2020). However, it is necessary to minimize water and nutrient consumption to decrease the costs and water requirements in the greenhouse systems as well as to minimize adverse environmental impacts (Rouphael et al. 2004). One of the promising approaches to boost vegetable production to enhance food security is growing vegetables in hydroponics: the cultivation of plants in nutrient solution and a soilless growing medium under controlled environmental conditions (Jafarnia et al. 2010; Agrawal et al. 2020).

The nutrient solution supplies the essential elements containing macro- and micronutrients with optimum concentrations for plant growth and metabolism (Sharma et al.

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