Evaluation of the efficiency of small-scale and low-cost hydroponic systems designed for household indoor vegetable production.

By

Abiodun Adelowokan

A thesis submitted to the School of Graduate Studies

In partial fulfillment of the requirements for the degree of

Master of Science

Boreal Ecosystems and Agricultural Sciences

School of Science and the Environment

Grenfell Campus

Memorial University of Newfoundland

St. John's, Newfoundland, and Labrador

June 2024

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Approved By:

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Abstract

Vegetables are described as premium food because they provide a balanced diet with essential nutrients needed for a healthy life. Hydroponics farming has been identified as a sustainable method for augmenting vegetable production to fulfill global food requirements; however, it is necessary to understand how indoor gardeners can utilize this technique to enhance their vegetable supply, thereby enhancing consumption and general well-being. This indoor study was conducted in an ambient environment to mimic a typical household. The experimental design was completely randomized in a factorial arrangement with three replications repeated twice. Experimental models were combination of **1)** three hydroponic systems: *i*. Christmas tree (CT) vertical small-scale hydroponic systems; *ii*. Green DNA (GD) vertical hydroponic system, and *iii.* The deep-water culture (DW) (control) and **2)** Light sources: *i*. Light emitting diodes (LED), and *ii*. Fluorescent light (FL). The lettuce crop was grown as a test crop in these hydroponic systems and lights. The results showed that the DW and GD systems produced higher lettuce yield and performed better than CT. The DW system exhibited higher lettuce yield, root dry weight, root-shoot ratio, and photosynthesis rate but was least accepted among the end users in sensory analysis attributes. Generally, LED enhanced yield, antioxidant activity, vitamin and mineral concentration compared to the FL. Therefore, the GD hydroponic system with LED lights demonstrated superior agronomic performance and sensory analysis attributes. Further research is needed to determine if inter/intra lighting of the vertical systems can enhance light penetration to the lower levels for optimal yield.

General summary

Indoor vertical farming is an innovative approach that has the potential to enhance local food production at affordable prices and provide access to fresh leafy vegetable production through small-scale hydroponic systems. Hydroponic farming systems allow fast growth, higher yields, and year-round vegetable production. This study was conducted to evaluate the growth, yield and phytonutrient profile of lettuce grown in small-scale vertical hydroponic systems using LED and FL light sources. The results showed that the deep-water culture (DW) and the Green DNA (GD) system performed better than the Christmas tree (CT) system. Overall, the GD system under the LED lights showed superior agronomic performance and nutritional quality of lettuce. Hence, we may conclude that the GD system under LED lighting can be a promising model for indoor leafy vegetables production.

Acknowledgement

I give all praise to God, my creator, strength, and shield, I am grateful for the immense help that he sent my way through out this program. Thank you, Lord Jesus.

I want to sincerely appreciate my supervisor, Professor Mumtaz Cheema for his support and guidance during this research, I appreciate him for being actively involved at every stage of the experiment. I appreciate the opportunity to learn under his tutelage.

I would also like to thank my co-supervisor, Dr. Lakshman Galagedara, for offering me this opportunity and obtaining funding for this project. His academic advice and counsel were instrumental to the success of this project. I want to extend my sincere gratitude to my research team mates, Kasmika Jeyarasa and Elham Fathidarehnijeh, they worked very hard to ensure the success of this project.

My gratitude also goes to Dr. Thu Pham, Dr. Doyin Adigun, and Dr. Tao for their support in all aspects of my research, and they were instrumental in planning, implementation, laboratory analysis, and data processing. I appreciate our funding partners, Mitacs accelerate and Easy Grow Indoor Garden Centre, for believing in us to execute this research. Special thanks to the Grenfell Campus Research Office and School of Graduate Studies, Memorial University of Newfoundland, for providing tuition fees and stipends. Finally, I would like to thank my family members: My husband, Mr. Oluwakayode Adelowokan, my children, Heritage & Henry Adelowokan, my mother, Mrs Fagbamila Monisola and my siblings. Thank you all for supporting me emotionally, financially, and spiritually. I love you all. I dedicate this work to my late father, Mr. Isaac Fagbamila, I hope your girl made you proud.

Co-authorship statement

Manuscripts based on Chapter 3, entitled "***Evaluating the Performance of small-scale indoor vertical hydroponics systems for lettuce production.***" and Chapter 4, "***Effect of LED and Fluorescent lamps on the growth, yield, and phytonutrient profile of lettuce plant in various hydroponic systems in an indoor environment***" will be submitted to Scientia Horticulturae (Adelowokan A., Fathidarehnijeh E., Jeyarasa, K., Adigun O., Galagedara, L., Cheema, M. 2024) and (Adelowokan A., Pham T., Galagedara, L., Cheema, M. 2024), respectively. Abiodun Adelowokan, the thesis author, will be the primary author, and Dr. Cheema (supervisor). For the work in Chapters 2 and 3, Dr. Lakshman and Dr. Cheema wrote the research grants. Dr. Cheema developed the layout of this research trial and helped interpret the results. Ms Fathidarehnijeh and Jeyarasa designed and fabricated the prototype of the vertical hydroponic systems in consultation with Dr. Galagedara who managed the overall project, and Ms. Adelowokan was responsible for the data collection, analysis, and writing of the manuscript. Dr. Thu H. Pham helped in the analytical and statistical analysis. All authors helped in manuscript editing.

Table of contents

List of tables

List of figures

List of Abbreviations

ABTS - 2,2-azinobis (3-ethylbenzothiazoline-6-sulfonic acid)

ANOVA – Analysis of variance

AS- Aeroponic system

ASE – Accelerated solvent extractor

B – Boron

B- Blue

BERF – Boreal Ecosystem Research Facility

BHT - Butylated hydroxytoluene

Ca – Calcium

$Ca(NO_3)_2$ - Calcium nitrate

CEC: controlled environment cultivation

CHU – Crop heating units

CO_2 - carbon dioxide

CT – Christmas tree

CT x FL – Christmas tree + fluorescent light

CT x LED – Christmas tree + LED light

Cu – Copper

CWF- Cool-white fluorescent

DFT- Deep film technique

DLI - Daily light integral

DNA- Deoxyribonucleic acid

DWT – Dry weight

DW- Deep-water Culture

DW x FL - Deep – water culture + fluorescent light

DW x LED – Deep – water culture + LED

EC – Electrical conductivity

EDTA – Ethylenediaminetetraacetic acid

EFS- Ebb flow system

FAO - Food and agriculture organizations

Fe – Iron

$FeCl_3.6H_20$ – Ferric (III) chloride hexahydrate

FL – Fluorescent lights

FRAP – Ferric reducing ability of plasma.

FRS- Floating raft system

FW – Fresh weight

G- Green

g $plant^{-1}$ = gram per plant

GD – Green-DNA

GDD – Growing degree days

GD x FL – Green-DNA + fluorescent light

GD x LED – Green-DNA+ LED

GH – Greenhouse

GT – Grow tent

H_20 - Water

HAA – Hydrophilic antioxidant activity

HID - High - intensity discharge

HPC - Hydrophilic phenolic content

HPLC –High-performance liquid chromatography

HPS - High-pressure sodium

HS - Hydroponic systems

ICP-MS - Inductively Coupled Plasma Mass Spectrometry

IL – Incandescence lamps

K – Potassium

KED - Kinetic energy discrimination

L1 – Layer 1

L2 - Layer 2

L3 - Layer 3

L4- Layer 4

LA - Leaf area.

LAA – Lipophilic antioxidant activity

LED – Light emitting diodes

LI – Layer 1

LIL – Low-intensity lights

LPC - Lipophilic phenolics content

LS – Light sources

LSD – Least significant difference

Mg $(SO_4)_2$ - Magnesium sulphate

MH - Metal halide

Mn – Manganese

MTBE - Methyl tert-Butyl Ether

MUN- Memorial University of Newfoundland

N – Nitrogen

NFT- Nutrient film technique

NL – Newfoundland labrador

P - Phosphorus

PAR- Photosynthetic active radiation

pH- the potential of hydrogen

PPFD - Photosynthetic photon flux density

QE – Quercetin equivalent

R – Red

RB- Red+Blue

RH- Relative humidity

SE – Standard error

SPAD - Soil plant analysis development

TAA – Total antioxidant activity

TE – Trolox equivalents

TPC - Total phenolic content

TPTZ – 2,4,6-tripyridyl-s-triazine

UN- United nations

VHS – Vertical hydroponic systems

WHO - World health organization

W- White

Zn – Zinc

μL = Microliter

μmol m^{-2} S^{-2} = Micromoles per meter per second

Chapter 1

1.General Introduction

1.1. Overview

The agricultural productivity of Newfoundland and Labrador (NL) is constrained by a combination of factors, including extreme weather conditions, short growing season, low crop heating units (CHU) or growing degree days (GDD), and acidic, shallow, and stony soils (Quinlan, 2012; GovNL, 2012). Hence, local food production is approximately 10-12% of the total food requirement of the NL people (GovNL, 2018). It was reported that NL holds only 1.8% of Canada's total field vegetable farms (4,125), 0.2% of the total planted area of field vegetables, and 0.1% of field vegetables produced in Canada (Statistica, 2022; Hussain & Tarasuk, 2022). As a result, the province had the lowest levels of fruit and vegetable intake and the highest prevalence rates of diabetes and obesity compared to other regions in Canada (Statistica, 2019; Statistica, 2022). On the other hand, NL is geographically separated from mainland Canada and is surrounded by oceans. As a result, providing sufficient food to NL communities is a daunting task due to the long travel distances between communities and transportation difficulty during severe weather conditions. Hence, it causes a significant rise in the cost of the food transported by the ferries, impacts food availability and shelf life, and diminishes the quality of fruits and vegetables available for consumption (Food first NL, 2015).

Shortage of nutritious food and dependence on processed and less nutritious food choices contribute to health issues (Statistica, 2023). Many NL residents are consistently confronted with the dilemma of restricted availability of nutritious food options or convenient access to less wholesome alternatives. This phenomenon may be linked to the food production and distribution system; for example, communities/inhabitants are far away from operational food establishments, and a significant proportion lack access. Therefore, residents are presented with the choice to procure commodities mostly provided by convenience shops, primarily processed and canned food products (FoodFirst NL, 2015; Reza & Sabau, 2022). Hence, eating healthy food in NL is a luxury because healthy food options are scarce, expensive, or of poor quality (FoodFirst NL, 2015). Recent reports stated that approximately 23% of households in NL faced food insecurity (Statistica, 2023; Hussain & Tarasuk, 2022). This situation necessitates researchers and agriculture industry stakeholders to use innovative approaches to enhance the local production of fresh vegetables and fruits at affordable prices to meet the needs of NL communities and people amidst climate change (Gentry, 2019). One way to enhance local food production sustainably and innovatively is to produce vegetables in hydroponics. Hydroponics, a method of growing crops in nutrient solution or soilless culture or media, is crucial in cultivating rapidly growing crops with increased yield, enhanced quality, and substantial revenue generation. Leafy vegetables such as lettuce, salad greens, and other high-value crops can be cultivated in hydroponics systems (Birkby, 2016; Maucieri et al., 2019).

One of the most popular hydroponic systems is growing vegetables using the nutrient film technique (NFT). In the NFT system, the plant's roots grow in shallow but continuously flowing nutrient solutions to supply sufficient water and nutrients to the plants. This system requires technical know-how as it needs precise control over the nutrient solution's flow (Megantoro & Ma'arif 2020). Without proper knowledge and expertise, the nutrient solution distribution may be uneven. It relies heavily on electrical pumps to circulate nutrient solutions, which may potentially cause higher operational costs (Gillani et al., 2023). Another commonly used hydroponic system is the deep-water culture (DW) system, which requires space for the nutrient reservoir because its root is constantly immersed in the nutrient solution. Meanwhile, space may be constrained in an indoor environment (Hamza et al., 2022). The DW system needs adequate aeration in the plant's root zone to promote respiration (Gillani et al., 2023). Therefore, just like NFT, DW relies heavily on electrical pumps for nutrient circulation, and this may potentially cause higher operational costs (Gillani et al., 2023). Thus, seeking other hydroponics farming methods like the wick and drip irrigation system that could potentially increase vegetable production without additional pressure on existing resources, *i.e.*, the type that uses abundantly and locally available material, is imperative. Indoor vertical hydroponic systems offer promising strategies to produce year-round fresh vegetables, space maximization, and enhanced crop yields with multiple crop growth cycles (Boylan, 2020). Therefore, the feasibility of growing leafy vegetables in small-scale and low-cost vertical hydroponic systems under household conditions must be investigated with minimal economic implications on users' resources. In this study, we hypothesized that lettuce grown in an indoor vertical hydroponic system would exhibit superior growth, yield, and sensory attributes compared to those grown in the commercially available DW system and also that the light-emitting diodes (LED) would enhance lettuce's growth, yield, and phytochemical profile of lettuce in the designed vertical hydroponic systems compared to those cultivated under fluorescent lamps (FL). The specific objectives of this study were:

1. To evaluate the agronomic performance of different small-scale hydroponic systems for lettuce production designed for indoor growers.

2. To investigate the effects of LED and FL lights on lettuce's growth, yield, and phytochemical profile of lettuce grown in vertical hydroponic systems.

3. To access the sensory attributes of lettuce grown in the vertical hydroponic systems compared to the commercially available.

1.2. Thesis organization

This thesis work follows a manuscript style and is grouped into five chapters. It consists of a general introduction chapter, a literature review chapter, stand-alone chapters 3 and 4 (manuscript format), and the final chapter for general discussion and summary.

Chapter 1: This is the thesis's general introductory chapter. It summarizes the background information, the rationale and justification of the study, the problem statement, and the specific objectives of the research project.

Chapter 2: Review past work on the subject matter.

Chapter 3: Report on "Evaluating the performance of small-scale indoor vertical hydroponics systems for lettuce production."

Chapter 4: Assesses the "Effect of light emitting diode and fluorescent lamps on the growth, yield, and phytonutrient profile of lettuce plants grown in small-scale vertical hydroponic systems".

Chapter 5: Summarizes the work, conclusion, and recommendations for further studies.

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Chapter 2

1. Literature Review

2.1. Hydroponics farming: upsides and downsides

The premise that agricultural production is under a growing pressure to provide larger yields as global population growth and food demand rises was one of the initial motivations for vertical farming (Despommier, 2010). To feed the world's estimated 9.8 billion residents in 2050, the world's agricultural sector must increase its output by 60% (FAO, 2011; UN, 2015). The cultivation of crops in an enclosed space is known as indoor farming (Boylan, 2020). Hydroponics is a farming method that uses growth media other than soil and a liquid nutrient solution containing all the essential nutrients needed to sustain plant growth and development (Savvas, 2003; Jones Jr, 2014). Today, the hydroponics cultivation technique is becoming increasingly popular due to its efficient utilization of resources and high yields (Jensen, 1997; Sharma et al., 2018). Hydroponically grown plants are of higher quality than their soil-grown counterparts because they are clean, and well nourished by a nutrient-rich liquid solution to produce crops with excellent quality (Bugbee, 2003; Hayden, 2006; Petropoulos et al., 2016). One of the most significant advantages of hydroponics farming is the flexibility of its operational site, wherever it is most convenient for them to cultivate plants in a near-best environment. Regardless of weather, soil condition, or agricultural land's availability crops can be cultivated indoors and hydroponically anywhere in the world, all year round. (Teixeira, 1996; Despommier, 2010; Manzocco et al., 2011; Domingues et al., 2012). Hydroponics is an efficient method for water management. Actually, hydroponically grown lettuce uses 85 - 90% less water than traditional farming (AlShrouf, 2017; Sharma et al., 2018; Pradhan & Deo, 2019) because the nutrients required for plant growth are dissolved in water and used by the plant's parched roots when needed which ensures maximum yield with the efficient use of resources (Jensen, 1997; Eigenbrod & Gruda, 2015). Another advantage of hydroponics farming is its protection against soil-borne diseases and some harmful pests, thereby minimizing or eradicating the need for herbicides and pesticides (Sharma et al., 2018; Boylan, 2020). The system's ability to obtain higher output per unit area makes it a more viable option compared to conventional agriculture, especially in populated and pricey land areas. According to Despommier (2010), a vertical farm may produce six times more yield than its traditionally grown equivalent production system. In addition, many commercial hydroponic systems are automated which are anticipated to minimize the use of manpower and the elimination of traditional agricultural practices (Jovicich et al., 2003, Prakash et al., 2020). The growth of plants is faster, and the period needed for cultivation is shorter than in field-grown crops, this is due to the uninterrupted supply of nutrients to the roots which are easily accessible to the plants (Sharma et al., 2018).

Despite the enormous advantages of hydroponic farming, one of its major downsides is the high initial set up cost. The amount needed to acquire training for required technical know-how, cost of resources needed, cost of energy and labour contributes to the higher preliminary investment for this form of farming (Resh, 2013; Boylan, 2020). Hydroponics is crucial in cultivating rapidly growing crops with increased yield, enhanced value, and substantial revenue generation, such as lettuce and other salad greens. (Birkby, 2016). Similarly, it is noteworthy that rising temperatures and an inadequate oxygen supply may reduce crop yields or even complete crop failure. Therefore, ensuring optimal pH, EC (electrical conductivity), and mineral concentration in the nutrient solution is essential to achieve a successful crop growth cycle (Sharma et al., 2018). In a confined hydroponics system, plants share the same nutrient, which could promote the spread of water-borne diseases (Ikeda et al., 2002). Examples are pythium root rot caused by pythium, phytophthora root or stem rot & damping off in seedlings caused by different species of phytophthora and fusarium, a water-borne disease that may also occur in hydroponics farms (Suárez-Cáceres et al., 2021).

2.2. Common hydroponic systems employed by indoor growers.

Recirculation of nutrients and growing medium are the basis for the revised classification of the hydroponic systems. Based on nutrient recirculation these are categorized into two methods, *i.e.*, circulating (closed) or non-recirculating (open) method. The system may also be classified as liquid culture or soilless culture (AlShrouf, 2017; Sharma et al., 2018; Niu & Masabni, 2022).

2.2.1. Ebb and flow system

Through a water pump, nutrient-rich liquid from a reservoir is injected in large quantity into the grow bed, the excess fluid is recycled while some is left in the grow tray at a pre-determined point to ensure a continuous supply of water and nutrient to the plants, the grow tray is flooded at regular intervals to ensure adequate oxygenation of the root zone (El-Kazzaz, 2017; Sharma et al., 2018) (Figure 2.1B).

2.2.2. Deep water culture (DW)

This method is the easiest and most effective way of hydroponics farming (El-Kazzaz et al., 2017), plant roots are suspended in a nutrient-rich solution that is kept aerated and oxygenated. The roots of plants are continuously submerged in water, but to prevent rotting, it is continually supplied with oxygen using air stones. After the initial setup, DW requires minimal technical expertise to maintain and produce faster plant growth than conventional methods and is ideal for cultivating lettuce, strawberries, and herbs. However, the plant growth cycle may be disrupted in case of a power outage causing plant roots to hypoxia (El-Kazzaz & El-kazzaz, 2017; Maluin et al., 2021) (Figure 2.1D).

2.2.3. Drip system

This technique is utilized by both indoor gardeners and commercial growers, making it one of the most popular hydroponic systems in the world. Individual trays or pots are provided with a constant supply of oxygenated nutritional solution through a pump (Maluin et al., 2021). The nutrient solution passes the entire growth medium and the roots before dripping to the bottom of the container. It is regulated by a timer to turn on and off at certain times using gravity (Hughes, 2017), the nutritional solution is drained back into the reservoir through a series of openings and channels (AlShrouf, 2017). A programmed timer is set to be powered on and off at predetermined intervals (Figure 2.1C). This method has been adopted in fabricating the "Green-DNA (GD) hydroponic system" in this study.

2.2.4. Wick system

This describes hydroponics at its most fundamental and elementary level. This mechanism is wholly passive (Aires, 2018), as nutrients are collected in a reservoir and transported to the roots by capillary action. The most common wick is a wool/cotton rope, it requires no investment of time or money to be operational. The primary issue with this method is that plant roots do not receive enough oxygen and the quantity of nutrient solution required for its effectiveness. (Van Patten, 2004; Maluin et al., 2021). This method is adopted in fabricating the "Christmas-tree (CT) hydroponic system", which has been evaluated in this study (Figure 2.1A).

2.2.5. Nutrient film technique (NFT)

The primary components of this system are a submerged pipe and a timer. Plant species, growth medium, and other environmental variables determine how often the plant is flooded with nutrient solution or water using a pre-set timer (Sharma et al., 2018). In NFT, the grow trays are flooded artificially with the nutrient-rich solution and then drained back into the reservoir, thereby recirculating continuously (Morgan, 2021; Maluin et al., 2021). It is an excellent system for growing shallow-rooted crops. (Figure 2.1E).

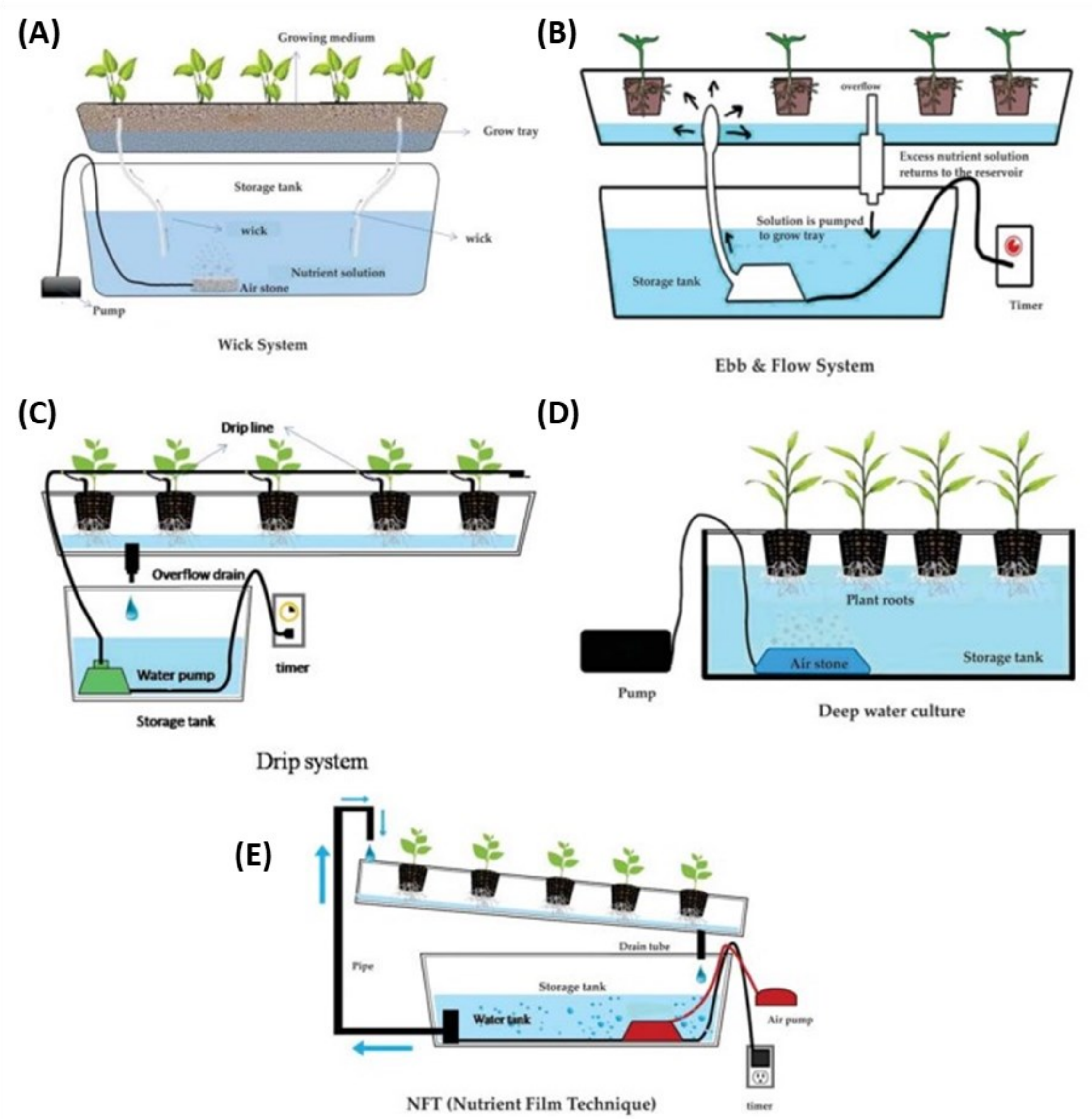

Figure 2.1: Schematic representation of common types of hydroponic systems: A) wick system, B) ebb and flow, C) drip system, D) deep water culture, and E) nutrient film technique (Adapted from Sharma et al., 2018).

2.3. Nutritional composition and health benefit of lettuce

Lettuce (*Lactuca sativa* L.) is a cold-hardy crop belonging to the Asteraceae family. It is a premium leafy vegetable, globally popular for its fast maturation, easy cultivation, and nutritional benefits (Das & Bhattacharjee, 2020). Primarily grown for its leaves, which are consumed raw in salads, water accounts for approximately 95% of its weight which makes it ideal for weight management (Ryder, 2012). Despite its low calorie, lettuce is rich in essential nutrients, it contains significant amounts of vitamins A and K. It is also rich in folate (for DNA synthesis and repair) and iron (for transporting oxygen in the blood) (Kim et al., 2016). Other minerals found in lettuce are potassium, calcium, and magnesium, they support some physiological processes such as muscle function and electrolyte balance (Das & Bhattacharjee, 2020).
Moreover, lettuce contains a variety of bioactive compounds, including phenolics, carotenoids, chlorophyll, and polyphenols (Nicolle et al., 2004). Phenolic compounds, such as flavonoids and phenolic acids, are abundant in lettuce and have been extensively studied for their antioxidant activity. According to Nicolle et al. (2004), these compounds help neutralize free radicals, thereby reducing oxidative stress and the risk of chronic diseases such as cancer and cardiovascular diseases (Turkmen et al., 2006. Carotenoids, another group of bioactive compounds found in lettuce, are potent antioxidants that contribute to the prevention of age-related macular degeneration and other degenerative conditions. It has been shown to aid in detoxification processes by binding to and facilitating the excretion of potential carcinogens from the body (Qu et al., 2005). According to Kim et al., (2016) and Shi et al., (2022), nutritional and health benefits of lettuce vary significantly among lettuce cultivars, based on color, size. and shape. Common cultivars in Canada include romaine, iceberg, and butterhead. Romaine lettuce tends to have higher

vitamin A and C levels than Iceberg lettuce, which is lower in nutrient contents but still contributes to dietary fiber intake.

2.4 Performance of hydroponics systems: effects on the yield and quality of leafy vegetable

Hydroponics may affect the yield and quality of leafy vegetables. Hence, its success is primarily determined by choosing a suitable hydroponic system, planting quality seed or seedlings, environmental conditions, and nutrient solutions (Fallovo, 2009). The nutritional quality of hydroponically produced vegetables may be questioned due to the myth that soilless agriculture implies using chemicals (winter). Nutrient solutions' formulation, application, and absorption enable precise hydroponics management. Various studies have been carried out to evaluate the performance of hydroponics systems on the yield and quality of different crops. A study by Frasetya et al. (2021) evaluated five different hydroponic systems using lettuce as a test crop: the NFT system, Deep film technique System, ebb and flow Systems, aeroponic Systems, and floating raft system. The morphological characteristics of the lettuce plant were affected by the hydroponics treatment. The systems used influenced the fresh and dry shoot and root weight, plant height, and the shoot-root. The NFT system demonstrated an enhanced yield by 6-10% compared to the other four systems (Frasetya et al., 2021). Consequently, with the RFS system, , NFT was suggested, as an effective approach for achieving enhanced growth and yield in lettuce cultivation.

In another study, plant height and leaf length in cucumber were measured to compare the rate of growth in a soil-based and hydroponic system. The plant height was higher in the hydroponic systems compared to soil-based systems, where there was no effect on leaf length (Gashgari et al., 2018). Another study conducted by Majid et al. (2021) accessed the feasibility of hydroponics farming as a viable alternative to soil-based farming. Using three systems: DW, NFT hydroponics system, and soil-based cultivation. It was observed that plants grown in DW system matured faster, produced higher yield, had better quality, and recorded the highest photosynthetic rate, this may be attributed to the abundance water supply in DW which facilitated higher water loss through the stomata. NFT was the most water-efficient technique, cutting down on use by around 64%. The study concluded that the DW and NFT systems performed better than the soil-based system. Similarly, in a study conducted by Goddek (2018), it was shown that lettuce cultivated in an aquaculture-based hydroponic system exhibited superior performance compared to lettuce grown in traditional hydroponic nutrient solutions. The aquaculture-based system resulted in a 7.9% increase in final fresh weight and a 33.2% increase in final dry weight, surpassing the standard hydroponic system.

Another study was conducted to broaden and advance the knowledge of hydroponics farming techniques on lettuce plants in two fabricated hydroponic systems, *i.e*., Continuous-flow solution culture (CFS) and horizontal cylinder type hydroponics (Rotary) and measured each hydroponic system's effectiveness by the minimum number of days required for plant growth (Ghatage et al., 2019). Authors reported that lettuce would fully mature by day 30 in CFS and rotary, which informs their conclusion that the designed systems would grow leafy vegetables faster than the existing ones (Ghatage et al., 2019). A recent study conducted by Thomas et al. (2021) examined three types of systems for lettuce production: soil-based, aggregate hydroponics, and NFT. The physiological parameters (photosynthetic rate, transpiration rate, and stomatal conductance) of lettuce grown using NFT were the highest of all methods. NFT produced the highest yield (260.66 g $plant^{-1}$), while soil cultivation produced the least (123.92 g $plant^{-1}$). Findings from the study suggested that soilless hydroponic systems, particularly NFT, can increase yield by optimizing physiological parameters.

According to various research studies, the growth, yield, and quality of green vegetables cultivated hydroponically are top-notch. For instance, to measure the yield and quality of lettuce and spinach in a circulating NFT, non-circulating NFT, and Open field, Acharya et al. (2021) reported that lettuce and spinach were grown in hydroponic systems, and the results of the circulated NFT and non-circulated systems were compared. Fresh weight, leaf area, and yield were higher in the NFT system than in open-field conditions due to its higher nitrates, phosphorus, and sulphur and, as a result, improved lettuce and spinach quality. Also, the nutritional quality of basil was significantly enhanced in the study reported by Sgherri et al.(2010). They compared the nutritional quality of basil cultivated on the soil to that of basil grown hydroponically (floating system). They reported that basil cultivated in hydroponics had increased antioxidant properties, vitamins, total phenols, and rosmarinic acid levels compared to basil grown on the soil while reducing oxidative stress.

A comparative study by Lei & Engeseth (2021), examines the texture, morphological, and nutritional aspects of hydroponically grown lettuce compared to conventionally soil-cultivated lettuce. Contrary to previous studies, there was no significant difference in plant size, leaf size, and shoot of the lettuce plants grown in hydroponics and soil-based systems. However, hydroponically grown plants had deeper roots, reduced ash, and more moisture. Also, fresh lettuce plants cultivated in soil showed higher levels of bioactive compounds and antioxidants, which may be attributed to the increased moisture content in hydroponically grown lettuce. However, the lettuce's soft texture was modified by lignin accumulation in the plants hydroponically raised. The study concluded that soil-grown and hydroponically grown lettuce are not the same quality (Lei & Engeseth, 2021).

2.5. Effect of light sources on the yield and phytochemical profile of vegetables in hydroponic farming

The growth and development of plants are stimulated mainly by photosynthetic active radiation (PAR), which occurs between 400 and 700 nm in wavelength. Chlorophyll absorbs most light between 625 – 675 nm in the red spectrum and 425 – 475 nm in the blue spectrum; however, not all photons within this range can foster photosynthesis (McCree, 1971; Pinho & Halonen, 2017; Ruangrak & Khummueng, 2019). Light promotes photosynthetic biosynthesis and photomorphogenesis because it is the only source of photosynthetic energy and a vital environmental signal (Walters, 2005; Hu et al., 2007; Matsuda et al., 2007). Demand for natural resources has been reported to be significantly reduced since indoor farming systems use artificial illumination, with a specific potential for lowering water utilized for food production (Graamans et al., 2018).

Indoor farming may take several forms, ranging from greenhouses that rely heavily on sunshine to entirely enclosed facilities that rely heavily on artificial lighting (Pinho & Halonen, 2017). Daily light integral (DLI) in Canada's boreal regions is considered low due to low light distribution and penetration in greenhouses (Bian et al., 2015). In an enclosed space, artificial lighting may be the only option for illumination. Traditionally, plant-growing facilities used low-pressure sodium lamps such as fluorescent lights (FL), high-intensity discharge lamps, incandescent lamps, and high-pressure sodium or metal halide as lighting options in the completely closed facilities (Ruangrak & Khummueng, 2019). Low-intensity lights have been shown to have poor power efficiency, low light emission, a short lifespan, and an unbalanced spectrum (Yanagi et al., 2006), while HPSs have spectral limitations that prevent them from maximizing photosynthesis and ensuring proper plant structure in mass production (Tibbitts et al., 1983). When lights that were designed for human illumination are used to grow plants, the resulting spectra are poor for plant development. Since plant and human light receptors differ so substantially, it is logical that inventions are needed to create a light source adapted to plants (Bula et al., 1991). Today, however, tonnes of spectra are available, particularly in the fluorescent selection, designed for plant cultivation. Although fluorescent tubes are often employed in growth chambers with modest light intensity, their poor power efficiency makes them unsuitable for greenhouses.

Spectrum modulation is best accomplished with light-emitting diodes (LED) due to their high efficiency and minimal energy consumption. LED lights could supplement fluorescent bulbs in a controlled environment because of their higher output and reduced operational costs (Kotiranta, 2013). One of the most significant benefits of LEDs over other light sources is their ability to generate a tailored spectrum. The increased yield, uniformity, and crop quality can be better managed with a spectrum tailored to a specific species or plant family (Pinho et al., 2012). Due to their low cost and high efficiency (Morrow, 2008; Hernandez et al., 2020), LEDs are becoming more popular among indoor growers due to limited sunlight access (Kotiranta, 2013). LEDs may be put near the canopy, enabling multi-tiered growth to minimize water consumption and the cost of electricity (Morrow, 2008; Pinho et al., 2012). LEDs provide a light source with less radiant heat output, making them ideal for indoor growers with little or no natural light (Kotiranta, 2013). Therefore, to maximize production and minimize energy consumption, artificially generated light must deliver wavelengths utilized optimally by plants and satisfy their demands. Plants' responses to light are influenced by its intensity, duration, and periodicity (Pinho & Halonen, 2017). Direct exposure to light is the best to optimize yield at the lowest feasible cost. Unfortunately, in boreal areas, adequate sunlight is only available for a few months yearly to support greenhouse-grown vegetables and herbs (Sutulienė et al., 2022). Hence, there is a need for supplemental or artificial lighting.

Various studies have demonstrated the significant effects of light on the yield and quality of hydroponically grown crops; for instance, an experiment conducted by Lin et al. (2013) compared the yield and quality of the lettuce leaves exposed to three distinct light sources: Red, Blue (RB) LED, Red Blue and White (RBW) and FL. The yield of the freshly harvested plants was assessed for its marketable qualities. Their result showed that the marketable qualities of fresh and dry weight of roots and shoots were higher in RBW and FL than in RB. In terms of quality, RB and RBW-treated plants, it is evident that RBW-treated plants had more soluble sugar content and a lesser nitrate concentration, while chlorophyll, carotenoids, and soluble protein had no significant effects among treatments. They argued in their conclusion that lettuce grown under RBW (white) LED lights may benefit from the strategic application of supplemental light quality to increase both nutritional content and yield. In another study, four light sources: red and blue (RB) LEDs, red and blue LEDs with green, fluorescent lamps (RGB), green, fluorescent lamps (GF), and cool-white fluorescent lamps (CWF) were used to investigate light effects on lettuce growth. The authors observed that introducing 24% green light (500 - 600 nm) to the RGB treatment improved plant growth and produced more shoot and root weight than the CWF-grown treatment. Meanwhile, the photosynthetic rate and total chlorophyll content were lower in plants grown in GF system compared to other systems. This could be due to the lower leaf mass per unit area, leading to the lowest reported shoot fresh and dry weight (Kim et al., 2004).

A study by Martineau et al. (2012) was conducted to evaluate LED and HPS supplementary lighting systems for greenhouses; the DLI for HPS and LED lamps were 71.3 mol m^{-2} and 35.8 mol m^{-2}, respectively, even though the LED lamp provided the lesser amount of light for the 4-

week experiment, findings from the study shows that the HPS light treatments produced substantially comparable biomass of shoots to the LED light treatment. The β-carotene, chlorophyll a, chlorophyll b, neoxanthin, lutein, and antheraxanthin content were not significantly altered in lettuce samples. There was a statistically significant change in violaxanthin contents after the light treatments. Regarding energy saving, it was confirmed that LED saved at least 33% more power than its HPS counterpart. Etae et al. (2020) examined how different types of artificial light affected green oak lettuce's development and phytochemical profile. Plants were grown for four weeks using bar-LED, bulb-LED, and fluorescent lamp (FL) lighting. The impact of various artificial light sources on the growth and phytochemical profile of green oak lettuce were reported. The bar-LED light had higher overall yield and quality metrics. Also, the highest phenolic content and antioxidant activities were recorded from plants grown under bar-LED, and chlorophyll a and a+b concentrations were lowest under FL lights. The results in this study suggested that growing green oak lettuce using bar-LED may enhance yield.

2.6. Effect of hydroponics farming method on the sensory evaluation of leafy vegetables

Hydroponic farming methods can influence the sensory qualities of leafy vegetables. This may depend on the plant variety, the growing conditions, nutrient management, harvest time, post-harvest, and storage. Not many studies have compared the effect of different hydroponic systems on the vegetables' sensory qualities but mainly compared hydroponics with the traditional farming method. Hydroponically grown vegetables may have distinct flavors, tastes, textures, and nutritional values. A study by Verruma-Bernardi et al. (2021) observed no visible differences in the sensory evaluation of two varieties of lettuce with six lineages when accessed across all brightness and crunchy texture treatments in an NFT hydroponics system. Similarly, the sensory quality of two tomato cultivars grown in an aquaponic or soil system was comparable. Statistically distinct sensory qualities were discovered through descriptive and objective analyses. It was believed that items produced in aquaponics systems are of equal quality to those grown in soil (Kralik et al., 2023). These results aligned with the study conducted by Manzocco et al. (2011). There was no significant change in the color, texture, or microbial count of the lamb's lettuce from the floating hydroponic system with and without the added 30 mol L^{-1} of silicon compared to the soil- based plots. However, scholars have advised that the hydroponic cultivation method might not be the best for optimal product quality and storage life.

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Chapter 3

Evaluating the performance of small-scale indoor vertical hydroponics systems for lettuce production.

3.1. Abstract

Extreme weather conditions, short growing season with low crop heating units, acidic and stony soils are the major obstacles of crop production in field conditions in Newfoundland and Labrador (NL). Food production in NL is limited to about 10% of the total requirement, with the rest being imported from mainland Canada or other countries, causing substantial economic and environmental burdens to the consumers and the province. Hence, growing vegetables through hydroponics or soil-less methods under controlled environments presents an alternative approach to enhance year-round local food production compared to traditional farming practices. The study herein evaluated two small-scale locally fabricated vertical hydroponic systems: *i)* a Christmas tree-shape design – CT, and *ii)* a Green-DNA-shape design – GD and *iii)* a deep-water culture (DW) system as the control for lettuce production. The experiment was laid out in a completely randomized design with factorial arrangements, and replicated three times, however this experiment was repeated twice under similar controlled environmental conditions. The sensory attributes of the fresh production were also evaluated. Results showed that the DW system produced significantly higher yield, root dry weight, root-shoot ratio, chlorophyll content, and photosynthesis rate than CT and GD systems. The GD system produced significantly higher leaf area and plant height compared to DW and CT. However, both the DW and GD systems showed superior agronomic metrics of lettuce compared to CT, except chlorophyll content, whereas the number of leaves recorded was statistically non-significant in all systems. There was a significant difference in the lettuce yield in different layers in GD and CT systems, most probably due to variation in light intensity and photosynthetic photon flux density. The difference in the yield between the uppermost layer and bottom layer in GD and CT were about 48% and 21%, respectively. The sensory evaluation showed better attributes in CT system owing to bright green leaf color and its visually appealing design whereas, GD system received overall best liking of produce, size, and texture characteristics. Considering the superior agronomic performance and sensory analysis attributes, the GD system could be a promising alternative for indoor leafy vegetable production.

Keywords: Small-scale, indoor, vertical hydroponic systems, light, fabricate, photosynthetic photon flux density.

3.2. Introduction

The concept of vertical farming, introduced by Gilbert Ellis Bailey in 1915, is not a new one. In his book titled "Vertical Farming," Bailey laid the foundation for what has now become an advanced agricultural technique (Al-Kodmany, 2018). Vertical farming involves the strategic arrangement of plants in vertically stacked layers or columns within a rack system. This innovative approach allows for the full utilization of the available cultivation area, significantly reducing land use while maximizing crop yield per unit area (Despommier, 2010; Al-Kodmany, 2018). In vertical farming, plants are cultivated inside constructed indoor facilities, providing a significant protection from the unpredictable weather elements (extreme low temperature, light, and humidity) (Lubna et al., 2022). Generally, crops grown under vertical farming are grown in soilless media or liquid nutrient solution in hydroponic systems. It could be hydroponics, substrate culture, aero-farming (aeroponics), or aquaponics (Savvas et al., 2003; Sharma et al., 2018).

In recent years, hydroponics has emerged as a successful method for growing of vegetables to tackle traditional farming challenges (Both, 2002). This technique utilizes growth media substrates and a liquid nutrient solution, providing all the essential minerals required for plant growth and development (Savvas, 2003). Hydroponics not only ensures efficient resource management and high-quality food production but also optimizes water usage. Nutrients are dissolved in water and delivered directly to the plant roots, promoting maximum yield within the available space (Eigenbrod & Gruda, 2015). The continuous submersion of roots in the nutrient solution enhances plant growth and quality, surpassing that of traditional farming methods (Bugbee, 2003; Hayden, 2006). Hydroponics supports the cultivation of a diverse array of crops, including tomatoes, cucumbers, peppers, and leafy greens such as lettuce (Swain et al., 2021).

Lettuce (*Lactuca sativa* L.), a popular salad vegetable, holds significant agricultural value due to its high economic returns, nutritional benefits, and production capabilities (Kumar et al., 2010; Noumedem et al., 2017). It thrives in cooler climates and is often used as a model plant in hydroponics and light research because of its rapid growth cycle (Frantz et al., 2004; Kim et al., 2004). Meanwhile, one of the primary requirements for a successful hydroponics farming is light. Light is a significant energy source and an integral environmental factor affecting plant growth and development (Zhou et al., 2020). Sunlight is the primary source of energy used by plants during photosynthesis process to generate carbohydrates and sugars (Whitmarsh & Govindjee 1999). Photosynthesis primarily relies on a radiant energy spectrum called photosynthetically active radiation (PAR) (400 – 700 nm) wavelengths. Chlorophyll absorbs most light between 625 and 675 nm in the red spectrum and 425 to 475 nm in the blue spectrum (Pinho & Halonen, 2017). The mechanism by which photosynthesis is driven within this wavelength differs depending on available light sources (McCree, 1971; Ruangrak & Khummueng, 2019).

According to Massa et al. (2008), artificial light sources appeared as an intriguing element in producing the best quality vegetables. For example, spectral quality, light intensity, and energy conversion efficiency are a few factors to be considered before determining light source. Several light sources are being used in greenhouses or controlled environment cultivation facilities, characterized by high energy requirements, fixed spectral output, and high heat generation. However, advanced features of light emitting diode (LED) has changed the narrative around artificial lighting in CEC and greenhouses for improved plant growth and development (Gupta & Agarwal, 2017). LEDs stand out as a superior choice compared to conventional light sources. Their notable benefits stem from their capacity to provide tailored wavelengths for precise plant responses. In addition, LEDs have outstanding energy conversion efficiency, small size, robust design, prolonged lifespan, and low heat emission (Massa et al., 2008). The spectral quality of LED can have a pronounced effect on a crop's anatomy, morphology, nutrient uptake and pathogen resistant (Massa et al., 2008).

Newfoundland and Labrador (NL), Canada's easternmost province, is frequently faced natural disasters like snowstorms, wildfires, floods, rainstorms and droughts, which disrupt agricultural operations and heightens the province's food security challenges (Reza, 2019). These challenges coupled with a short growing season (low heating units or growing degree days), and low soil fertility (low pH, shallow and stony soil), limits field vegetable production (Statistica, 2022), extreme weather (Statistica, 2022). Consequently, local food production is challenged and meets only about 10% of its entire demand, despite government efforts to increase this to at least 20% by 2022 (Food First NL, 2017; GovNL, 2017). For instance, only about 0.2% of the total lettuce consumed in Canada is produced in NL, leading to a limited supply to the consumers in NL.

According to reports, the province had the lowest levels of fruit and vegetables intake and therefore most significant prevalence of diabetes and obesity compared to other Canadian provinces in 2022 (Statistica, 2023). The limited availability of fresh and nutritious vegetables and food cause dependence on the processed and frozen food further limits food choices and hence cause health issues (Food First NL, 2015; Statistica, 2023). Moreso, the heavy reliance on food imports puts a significant economic and environmental burden on the consumers (Reza & Sabau, 2022). It is imperative to explore alternatives to traditional food production methods to address these challenges. Small-scale indoor vertical hydroponics systems offer a promising solution for sustainable local vegetable production (Majid et al., 2021). These systems can ensure a consistent supply of fresh, nutrient-rich vegetables throughout the year, regardless of external weather conditions (Both, 2002). By adopting such systems, NL could enhance its self-sustainability and reduce food insecurity. This study aims to evaluate the efficiency of small-scale vertical hydroponics systems in comparison to conventional hydroponics. Hence, we hypothesised that leafy vegetables grown in the designed small-scale vertical hydroponics system would produce more yield and better sensory attributes than those grown in conventional hydroponic systems. Also, that the variation in light intensity would affect yield in the designed vertical hydroponic systems. To test this hypothesis, experiments were conducted in controlled environment with the following specific objectives:

1. To evaluate the agronomic performance of small-scale vertical hydroponic systems for lettuce production designed for indoor growers.

2. To investigate the impact of light intensity variation on the growth and yield of lettuce cultivated in the vertical hydroponic systems.

3. To assess the sensory attributes of lettuce grown in the hydroponic systems.

3.3. Materials and Methods

3.3.1. Raising of lettuce nursery

Newham lettuce seeds were purchased from High Mowing Organic Seeds (Wolcott, VT, USA) and were seeded in a nursery tray in pre-soaked coco coir (Hydrofarm, CA, USA). These trays were placed in a walk-in growth chamber (Biochambers, MB, Canada) located at Recplex, Grenfell Campus, Memorial University of Newfoundland (MUN), Canada (48° 56' 24.32" N, -57° 55' 55.92" W). The climatic conditions of growth chamber were set up and maintained at 14/10 h day/night, 25/17°C, 65 - 70%, and 400 – 600 ppm for photoperiod, temperature, relative humidity (RH), and carbon dioxide (CO_2) concentration, respectively. Once the seedlings reached the five true leaves stage, they were transplanted into the grow tent in all hydroponic systems (Vivosun ON, CA). In grow tent, photoperiod, temperature, and RH were set up at 16/8 h day/night at 25/17°C, and 75 - 80%, respectively during both crop cycles. A Hobo meter (MX1102A, USA) was installed in the grow tent to continuously monitor the growth conditions throughout the crop cycles, and a digital timer (Noma, ON, CA) was used to monitor the accuracy of the photoperiodicity.

3.3.2. Experimental design

Two small-scale vertical hydroponic systems were designed and fabricated by our research team members to meet the vegetable needs of small-scale indoor growers. The experimental designs comprised of three hydroponic systems: 1) Christmas tree (CT) - a small-scale wick hydroponic design); 2) Green DNA (GD) with a drip hydroponic design); and 3) a deep-water system (DW) as a control. The LED lights (Grow star, ON, CA) were used to supply the lighting in all systems in the grow tent. The LED lamps were hanged horizontally 30 cm above the plant canopy. Both vertical systems (CT and GD) and the DW system were placed in a grow tent for assessing their yield and growth performance (Figure 3.1).

The CT system comprised four vertical layers (layer 1 with a diameter of 0.36 m, layer 2 with a diameter of 0.44 m, layer 3 with a diameter of 0.62 m, and layer 4 with a diameter of 0.68 m), positioned on the right-hand side of the GT (Figure 3.1). It featured 18 numbers of 70 mL plastic grow cups, each equipped with a 3-inch mesh net to contain the coco coir growing medium. The cups were linked through drip tubes to supply and drain nutrient solution. A submersible water pump (Hydrofarm, CA, USA) with a flow rate of 946 L hr^{-1} flow rate was installed in the 34 L nutrient solution storage tank (Sterlite, MA, USA).

The spiral-shaped GD system, comprised of 26 cups; each cup (0.1 m diameter, 0.1 m long) was filled with geotextile fabric material before filling with 400 g coco coir to prevent blocking of the drip tubes, an adjustable flow drip irrigation dripper (Hydrogarden, CO, UK) was affixed to the tubes which in turn was connected to the 34 L nutrient solution storage tank (Sterlite, MA, USA). The dripper pipe was then strategically looped around the system to facilitate nutrient circulation per its intended design. A submersible water pump with a flow rate of 1514 L hr^{-1} flow rate (Hydrofarm CA, USA) was installed in the storage tank. The pump was turned on for 30 min twice a day to facilitate nutrient solution circulation to the plants roots system.

On the other hand, the DW system comprised two rectangular grow containers (14cm long x 41 cm wide) (Homend, GA, USA) with 11 planting holes each. The containers were placed in between the two vertical systems in the grow tent, and side by side on an elevated surface to maintain the same height (30 cm) as the vertical systems; among other materials included were an oxygen pump and bubble stone. The first and second cycles of lettuce crop were grown during the winter season; hence, a heater (ipower Ca, USA) was placed inside the grow tent to increase temperature, and a duct fan (Vivosun, ON, CA) was used to maintain uniform temperature inside the grow tent. This experiment was set up in a completely randomized design in a factorial arrangement with three replications and repeated twice. The vertical hydroponic systems (VHS) comprise of the CT and GD systems. To determine how varying light intensity impacts lettuce yield in the VHS, the mean values of samples from each growth layer were collected and analysed.

Figure 3.1: A pictorial presentation of 45 days old lettuce crop grown in three hydroponic systems in the grow tent; GD = Green DNA (left); DW= Deep water culture (middle) (control); CT = Christmas Tree (right side).

3.3.3. Preparation of nutrient Solution

A commercially available 3-part master blend nutrient kit, consisting of a master blend lettuce formula 8-15-36, Magnesium sulfate ($MgSO_4$) and Calcium nitrate Ca $(NO_3)_2$ (15.5-0-0), a ready-to-mix product (Gecko Grow, AB, CA) was used in this experiment. The nutrient solution was prepared following the product guide to feed the crop plants. The EC and pH of the nutrient solution were monitored daily and maintained between 2.0 - 2.5 mS m^{-1} and 5.8 - 6.5, respectively using EC and pH meters (Bluelab, TA, New Zealand).

3.3.4. Data Collection

Plants were randomly selected and tagged within each hydroponic system. Each system's plants were assigned unique identifiers to ensure accurate and consistent data tracking. The agronomic performance of lettuce was measured 45 days after sowing based on the number of leaves, chlorophyll contents, leaf area (LA), root shoot ratio.(RSR), and plant height while total fresh biomass (yield measured in grams per plant fresh weight (FW)) and root shoot ratio (RSR) were measured same day when plants were harvested. The leaf chlorophyll content was recorded using a handheld chlorophyll meter (SPAD plus-502, Osaka, Japan). For chlorophyll measurements , top three fully expanded leaf were measured at the apex. Plant leaves were counted, and the number of leaves recorded. A portable photosynthesis system (LI-6400 XT, LI-COR Biosciences, NE, USA) was used to measure photosynthesis rate. The system was set up at 21°C, 75%, 400 µmol mol^{-1}, and 700 µmol m^{-2} s^{-1}, respectively for the leaf chamber temperature, air RH, CO_2 concentration, and Photosynthetic photon flux density (PPFD). The photosynthesis rate, stomatal conductance (gs), and transpiration rate (T) were measured from the fully expanded leaf from the top at the harvesting stage of the lettuce. The LA was measured using a portable LA meter (LI-3000C LI-COR Biosciences, NB, USA). The lettuce plants were then separated with knife into root and shoots to ascertain their fresh (g $plant^{-1}$ FW) and dry weights (g $plant^{-1}$ DWT). The roots and shoots were subjected to oven drying at 65°C for 72 h or until a consistent weight was achieved. The final dry weight of the shoot and root was then determined using a weighing scale

(RADWAG, PS 6000/C/2, Poland). The final plant height of lettuce was measured using a measuring tape from the surface of the growth medium to the leaf tip of the longest leaf of each plant at the time of harvesting. The light intensity (PPFD) was measured using a light meter (Dr. Meter CA, USA) both prior to and following the placement of the VHS in the grow tent. This was done to minimize or eradicate any shading affect that may be caused by the VHS (Touliatos, 2016).

The VHS were rotated biweekly to ensure uniform light distribution, and light intensity was measured at plant surfaces in every layer in the VHS. Digital timer was also installed in the grow tent to control day/night illumination. Finally, plant roots and shoots were subjected to oven drying at 65°C for 72 h or until a consistent weight was achieved. The final dry weight (DWT) of the shoot and root was then determined using a weighing scale (RADWAG, PS 6000/C/2, Poland).

3.3.4. Sensory evaluation

A sensory evaluation survey was performed on unharvested lettuce crop in the Functional Foods and Sensory Analyses laboratory at Grenfell Campus, MUN to determine the sensory attributes of lettuce. The sensory evaluation protocol was approved by the Grenfell Campus Research Ethics Board before conducting the sensory analyses. Seventy untrained panelists were randomly recruited from the local population (university students, faculty, and staff) to perform sensory evaluation of the lettuce crop. The age of the panelists was between 18 – 59 years. The lettuce plants from each hydroponics systems were selected and presented to the panelists in a computerized booth (Figure 3.2).

Table 1: Sensory attributes of the lettuce plant and the hydroponic systems recommendation.

Sensory attributes	Characteristics	Mode of determination
Flavor	Aroma/odor	Smell
Appearance	Freshness, spots, wholeness	Visual
Color	Bright green	Visual
Texture	Firmness, tenderness	Touch
Size	Weight and leaf volume	Visual
Overall best	Color, size, shape, and appearance	Visual
Hydroponic systems recommendation	Description and photograph	Visual

The sensory evaluation of each hydroponic system was scored on a hedonic structure scale (Vidal et al., 2020) using the sensory analysis software (SIMs 2000). The lettuce crop plants were assessed by panelists based on leaf color, flavor, texture, size, appearance, and overall liking or based on best performance (Table 3.1).

Figure 3.2: Panelists are conducting sensory evaluation analyses to determine the characteristics of lettuce grown in different hydroponic systems (A), Panelists are answering sensory evaluation questionnaires on lettuce plants (B), and Plants grown in CT, DW and GD systems are displayed for panellists (C).

3.4. Statistical Analysis

A one-way analysis of variance (ANOVA) was used to assess the growth and yield of lettuce cultivated in different hydroponic systems, and two-way ANOVA was employed to assess the effects of light intensity on the yield of lettuce cultivated in the vertical systems. The XLSTAT (2021.3.1) (Addinsoft Software, NY, USA) was employed to run the statistical analyses. Fisher's Least Significant Difference (LSD) at alpha = 0.05 was used to compare the treatment means when a treatment's effects were statistically significant. The Shapiro-Wilk test was employed to check the normality of the data. Sigma Plot 15.0 (Systat Software Inc., CA, USA) and Excel program was used to create the graphical illustrations.

3.5. Results

3.5.1. Lettuce growth parameters

Hydroponic systems had significant ($p<0.05$) effects on the leaf area, chlorophyll content, plant height, and photosynthesis rate (Fig.3.3 (A-D). The GD system produced significantly ($p<0.05$) higher LA (957.4 cm^2 $plant^{-1}$) compared to the lowest (857.2 cm^2 $plant^{-1}$) observed in CT. However, there was no significant difference in LA between GD and DW systems (Fig. 3.3A). The CT system produced higher chlorophyll content (45.1) compared to the lowest (37.7) produced by DW, which was statistically at par with GD. The CT system appears to enhance chlorophyll content in lettuce plant production. The GD had significantly ($p<0.05$) higher plant height (30.2 cm), compared to the least (23.2 cm) recorded in the CT system, although GD and DW were statistically non-significant with each other. Further statistical analyses indicated a higher photosynthesis rate (27.7 µmol m^{-2} s^{-1}) was recorded in the DW system compared to the lowest photosynthesis rate (22.6 µmol m^{-2} s^{-1}) was observed in the GD system (Fig. 3.3C). Hydroponic systems had no significant effects on number of leaves. The observed number of leaves was statistically non-significant across the systems. Overall, the DW and GD systems performed better across the tested growth parameters.

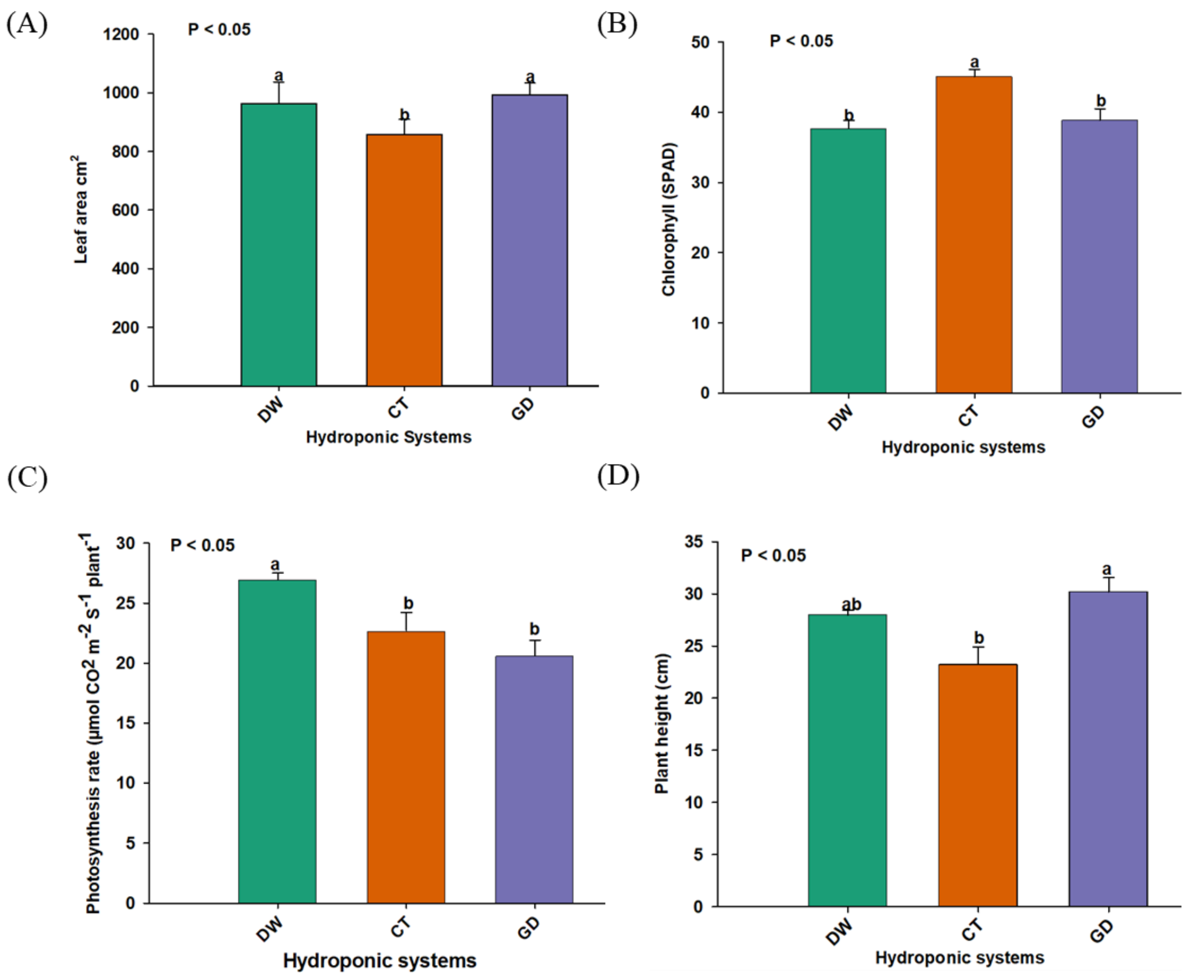

Figure 3.3: The growth performance of lettuce cultivated in different hydroponic systems: (A) leaf area, (B) chlorophyll, (C) photosynthesis rate, and (D) plant height. Vertical bars show the treatment means of three replications with standard error. Significant differences between treatments are indicated by different letters ($p<0.05$, LSD test). DW = Deep water culture (control); CT = Christmas tree; GD = Green-DNA.

3.5.2. Yield and yield components of lettuce.

The lettuce yield, root shoot fresh and dry weight, and the root shoot ratio were significantly ($p<0.05$) influenced by the hydroponic systems (Fig. 3.4 A-C). The DW system produced a significantly higher yield (190.6 g $plant^{-1}$ FW) compared to the lowest yield (130.6 g $plant^{-1}$ FW) observed in the CT system. However, lettuce yield produced by DW and GD was statistically non-significant (Fig. 3.4A). Likewise, the highest root dry weight (RDW) (4.2 g plant^{-1}) was recorded in the DW system, while the lowest (2.1 g plant^{-1}) was observed in the CT system. A significantly higher root shoot ratio (RSR) (19.6%) was recorded in the DW system compared to the lowest (13.8%) recorded in the CT system, though statistically at par with GD (Fig. 3.4 B-C).

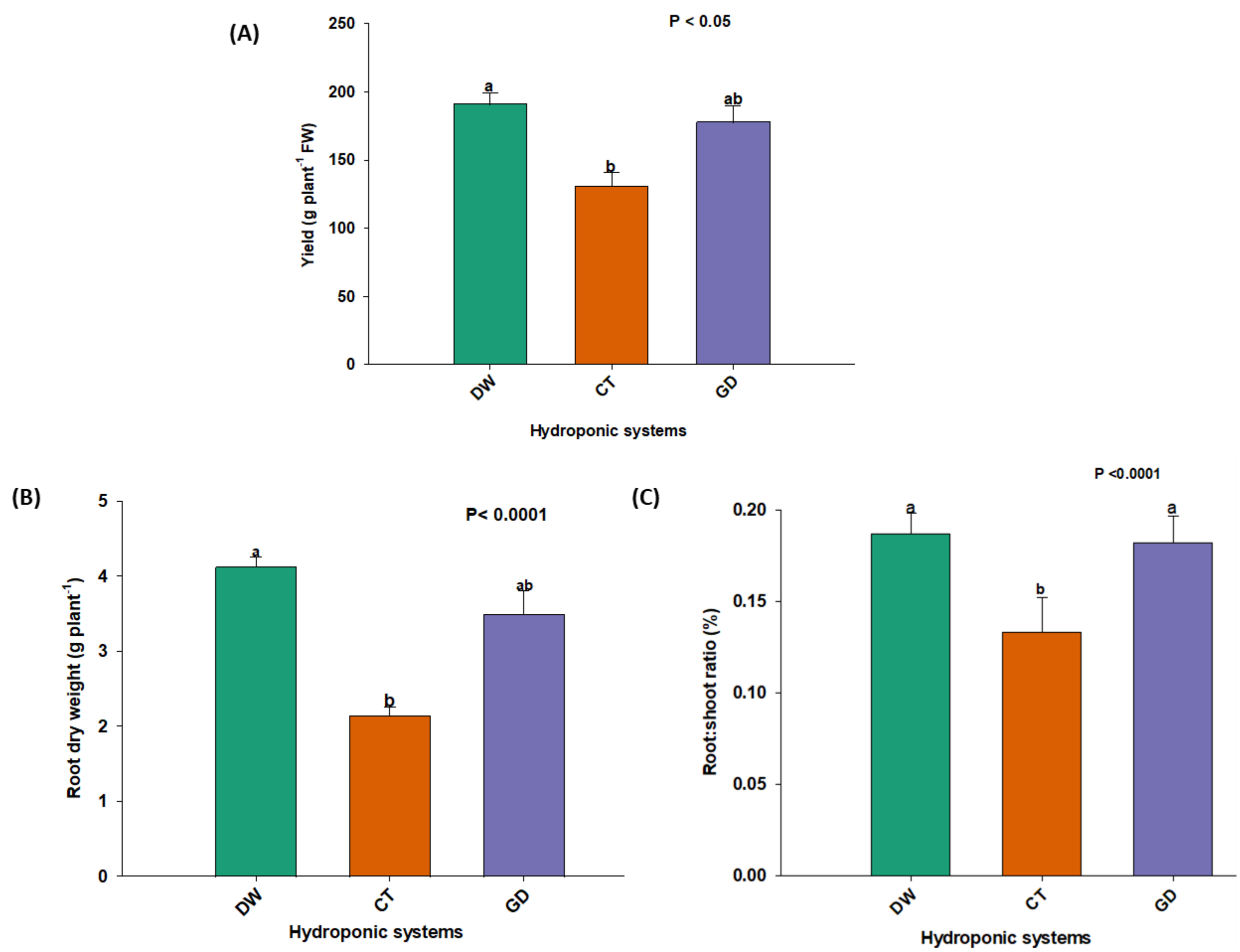

Figure 3.4: The agronomic performance of lettuce grown in different hydroponic systems: (A) yield, (B) root dry weight, and (C) Root: shoot ratio. Vertical bars show the treatment means of three replications with standard error. Significant differences between treatments are indicated by different letters ($p < 0.05$ LSD test); DW= Deep-water culture (Control); CT = Christmas Tree; GD= Green DNA.

3.5.3. Effects of light intensity on the yield of lettuce grown in vertical hydroponic systems

Light intensity (PPFD) had a significant effect ($p<0.05$) on growth layers within the VHS (Table 3.2). PPFD values were statistically the same in all four layers in both the GD and CT systems, except layer three (L3), where a significant difference was detected in the two systems (Fig. 3.6A).

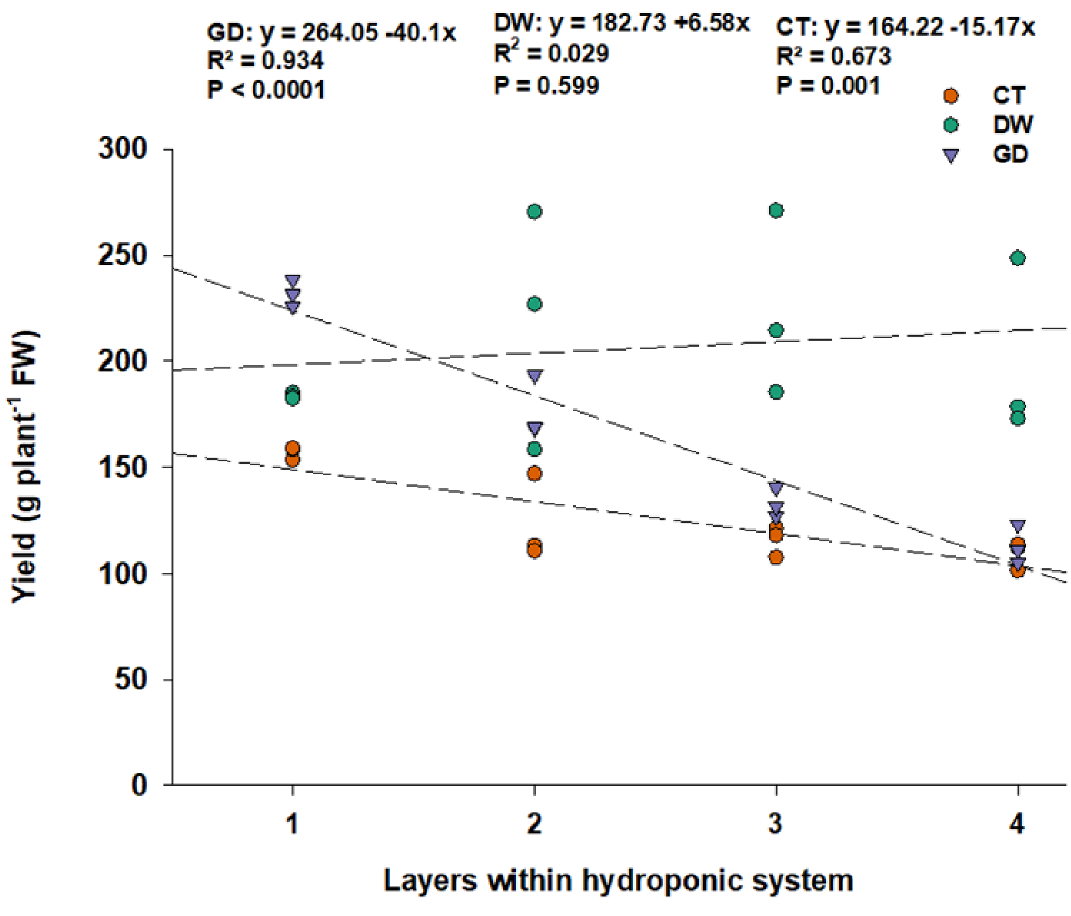

Figure 3.5: Linear regression showing lettuce yield (g plant^{-1} FW) in different layers in all hydroponic systems; the circle with orange color represents CT, Green represents DW, and the purple triangle represents GD. CT = Christmas tree; DW= Deep-water culture GD= Green DNA). p-value showing significance ($p < 0.05$ LSD test); R^2 values and regression equation are reported above the chart.

The VHS showed a significant decline in light intensity as it traversed from L1 to L4. For instance, in the CT system, the PPFD values recorded for L1 and L4 were 647 and 147 µmol m^{-2} s^{-1}, respectively; likewise, 670 and 133 µmol m^{-2} s^{-1} were the L1 and L4 values recorded in the GD system, respectively (Fig. 3.6A).

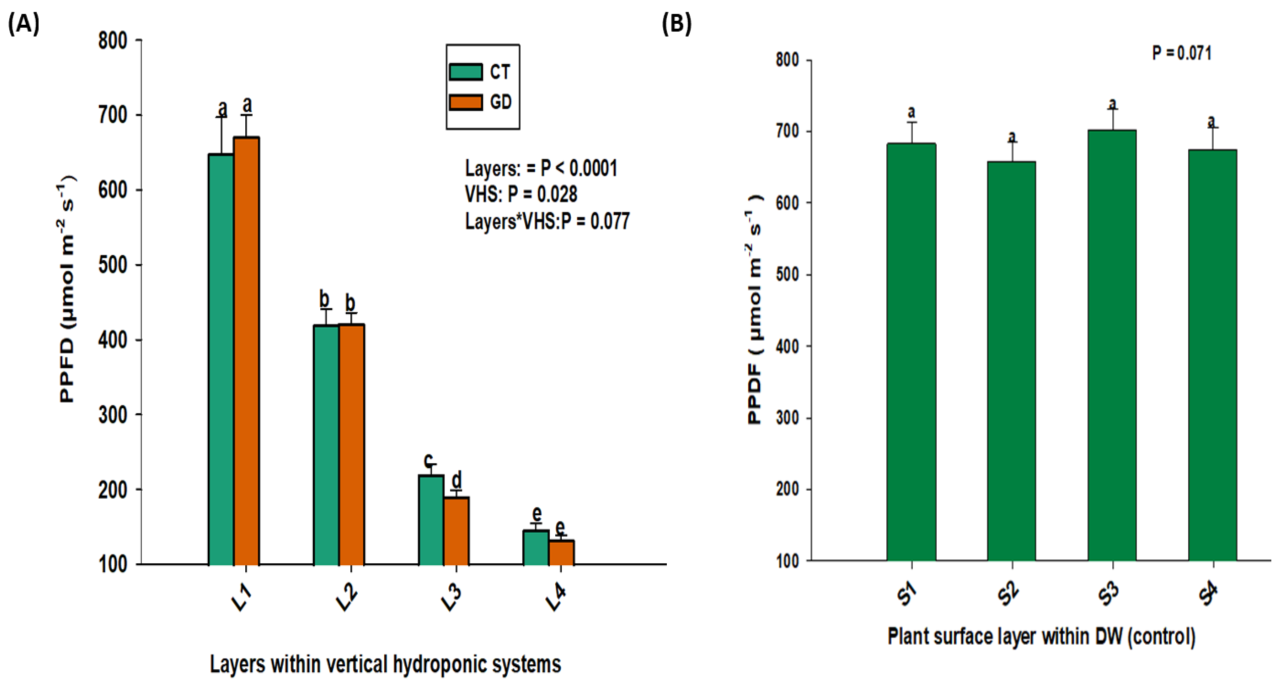

Figure 3.6: (A) Chart showing PPFD within the designed vertical systems versus layers within the vertical hydroponic systems. (B) PPFD within the plant surface in the DW system. Vertical bars are means of three replications ±SE. Bars sharing the same letter do not differ significantly at LSD ≤ 0.05. PPFD = Photosynthetic photon flux density, CT = Christmas Tree; GD= Green DNA, VHS=Vertical hydroponic system.

On the other hand, PPFD had a non-significant effect on lettuce yield across the plant surfaces in the DW system (Fig. 3.6B). Lettuce yield in both vertical systems followed a similar trend, i.e. there was gradual and significant drop in crop yield from L1 > L2 > L3 > L4 in both CT and GD (Fig. 3.5). The difference in yield between L1 and L4 in GD and CT were about 48% and 21%, respectively (Fig. 3.5). The PPFD had significant ($p<0.05$) effects on the lettuce yield grown in the VHSs. The results indicated that yield increased with a rise in PPFD; conversely, a decrease in PPFD resulted in a decrease in plant yield (Figure 3.7).

Table 2: Analysis of variance table showing photosynthetic photon flux density (PPFD) across the layers within the vertical hydroponic systems (VHS).

Source of variation	**df**	**p-values**
VHS	1	0.028
Layers	3	< 0.001
Layers* VHS	3	0.077

$P > 0.05$ is non-significant; $P \leq 0.05$ is significant: and $P < 0.001$ is highly significant

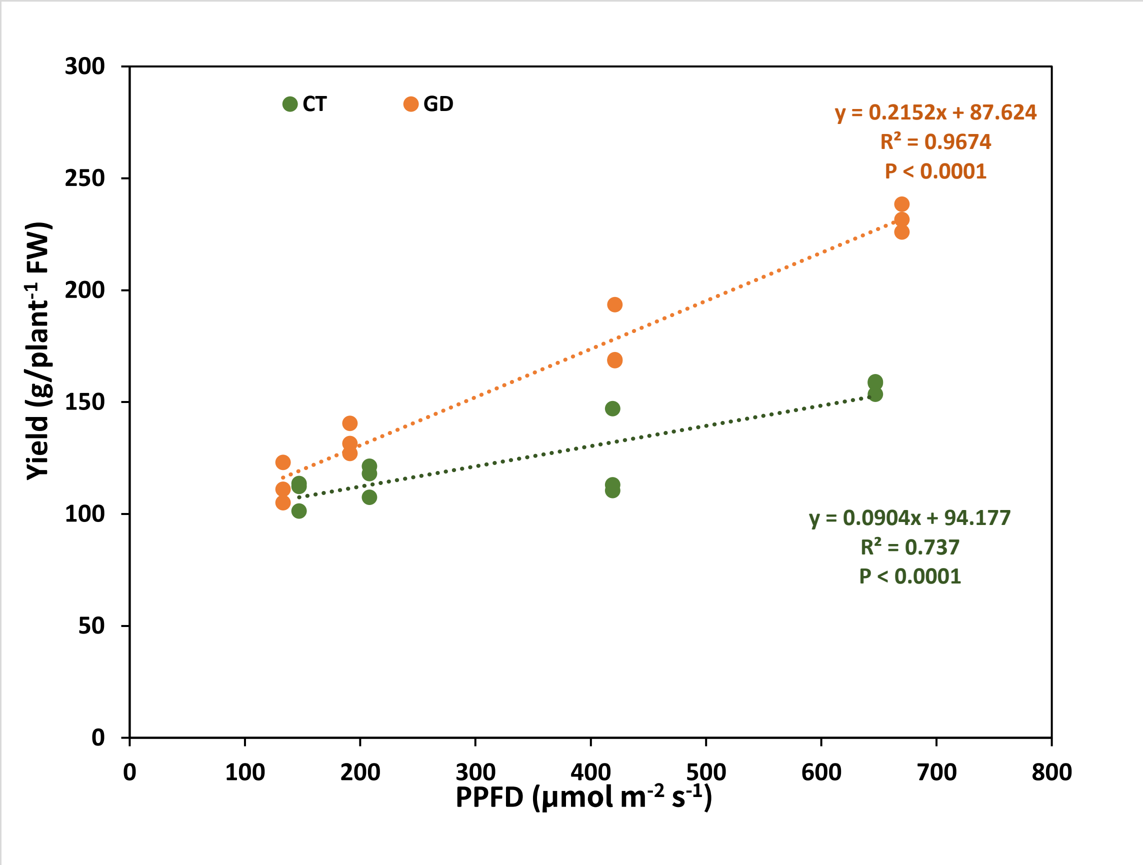

Figure 3.7: The linear regression analysis shows the effect of photosynthetic photon flux density (PPFD) on lettuce yield (g plant^{-1} FW) in CT and GD systems. p-value showing significance ($p < 0.05$ LSD test), R^2 values, and regression equation are reported by each regression line. CT = Christmas tree; GD = Green DNA.

3.5.4 Lettuce sensory evaluation

The panelists recruited for sensory evaluation reported the highest rating of the plants' flavor grown in the GD system. The GD system also received the best ratings based on leaf color and size. In the CT system, lettuce leaf color, hydroponic system recommendation, and overall best were rated higher than GD and DW. Furthermore, panelists preferred having the CT system in their homes over the GD and DW based on its size and aesthetic design (Fig. 3.8). Surprisingly, despite having higher biomass, the results from the DW system revealed that it received the lowest ratings across all sensory characteristics examined.

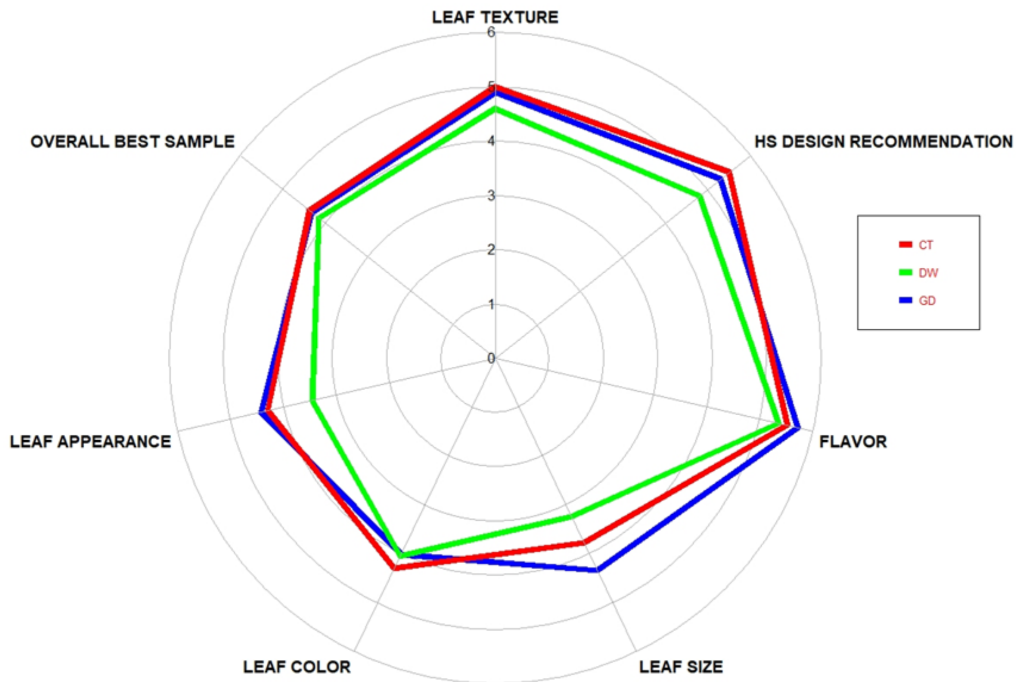

Figure 3.8: The spider web chart shows the sensory attributes (texture, flavor, size, color, appearance, and overall best) of lettuce grown in different hydroponic systems. The scale of preference was 1- 6, indicating the lowest to the highest preference, respectively. DW = Deep-water culture; CT = Christmas tree; GD = Green-DNA. HS = Hydroponic system.

3.6. Discussion

Different hydroponic systems significantly influenced crop growth and yield parameters. In the present study, the DW system produced the highest yield (190.6 g plant^{-1} FW), comparable to GD but lowest in the CT system (Fig. 3.3A). The higher yield in the DW system may be attributed to the constant supply of nutrient-rich water directly to the submerged plant's roots, which ensured a well-aerated root region (Saaid et al., 2013). Nutrient uptake directly depends on nutrient concentration in the solution surrounding the root system. This process may be significantly impacted by several environmental conditions, such as oxygen supply, temperature, light intensity, relative humidity, photoperiod, EC, and pH of the nutrient solution (Bamsey et al., 2012; Domingues et al., 2012). In a recent study conducted by Majid et al. (2021), higher yield was observed in the DW system, which could be attributed to the precise regulation of nutrient solution concentration and the maintenance of an ideal plant growing condition in contrast to the lettuce grown in the NFT and traditional method. A potential factor contributing to the reduced yield in CT could be inadequate uptake of the essential nutrient solution by the root system, which subsequently hindered foliage development and production, ultimately affecting leaf growth and development (Martínez & Garcés, 2010).

The LA is a crucial metric for assessing plant growth and development as it directly relates to photosynthetic capacity, biomass accumulation, and overall plant health (Scott, 2020; Yu et al., 2020). In the current study, hydroponic systems had a significant effect on lettuce LA. Although the highest LA was recorded in the GD system, the DW system's result was similar. The GD system's high LA may be attributed to the nutrient solution's slow, systematic, and uniform application for optimal plant growth (Schwankl et al., 1996; Megersa & Abdulahi, 2015). Lin et al. (2013) observed that a plant with a robust root system produced large leaves, which enhanced the interception of solar radiation and synthesis of photo-assimilates, substantiating the findings of the present study (Fig 3.3A). Also, the findings from Fallovo et al. (2009) substantiate the current study LA increased in floating draft hydroponics because of increased nutrient solution concentration. The results from this study showed that the higher LA, RDW, and RSR (Fig. 3.4 B-C) observed in DW and GD corroborated with the enhanced lettuce yield compared to the CT system.

Photosynthesis rate is another essential parameter for measuring a plant's growth and development. It reflects plants' growth efficiency and provides insights into metabolic activities, productivity, and biomass accumulation (Long et al., 2006). The photosynthesis rate of the lettuce plant significantly ($p<0.05$) influenced the hydroponic systems used in this study. The highest rate in the DW system indicated robust light absorption, a consistent and ample provision of essential mineral nutrients, and favorable environmental circumstances (Muthuri et al., 2009). Bilodeau et al. (2019) observed a strong correlation between plants' yield and photosynthesis rate in a specific environment. The chlorophyll contents in plants indicate the overall health of plants and their performance in agricultural settings (Rorie et al*.,* 2011) and play an essential role in photosynthesis (Wang & Grimm, 2021).

Furthermore, chlorophyll traps and harnesses light energy, which is subsequently transformed into chemical energy to facilitate the growth and development of plants (Alvarenga et al., 2015; Samreen et al., 2017). However, in the present study, higher chlorophyll content was observed in the CT system, where yield was least compared to the GD and DW system (Fig 3.2 B). This may suggest that a higher chlorophyll might not necessarily translate to a higher yield. According to Slattery et al. (2017), an abundance of chlorophyll might result in a decrease in plant productivity, while reducing the amount of chlorophyll can enhance the efficiency of converting absorbed photosynthetically active radiation into biomass, thereby increasing yield by improving light penetration and distribution. The increased level of chlorophyll in the CT system suggests improved efficiency in utilizing light energy for the photosynthetic process.

Light intensity plays a critical role in the growth and development of plants (Mohammed et al., 2021). The possibility of limited light interception or shading effect among different layers in vertical hydroponics systems was anticipated, and hence, optimizing light intensity becomes even more crucial. For example, the findings of the study conducted by Loconsole et al. (2019) observed that manipulating the quality and intensity of light may benefit both the yield and quality of lettuce. Furthermore, Gruda (2005) reported that inadequate or excessive light intensity can affect several aspects of lettuce growth, including leaf nitrate content, shelf life, and the phytochemical profile of the plant. In the present study, light intensity significantly affected the VHS (Table 3.2), i.e., light intensity varied significantly in all growth layers in the VHS (GD and CT) (Fig. 3.5), which led to significant variation in plant yield between layers 1-4 (layer 1 > 2 > 3 > 4). There was a decrease in plant yield with a decrease in light intensity and vice versa. This further explains the lower yield recorded in the lower levels of the vertical systems (Fig. 3.4). However, the total yield from GD and DW were statistically at par (Fig. 3.3A). For instance, L1 received higher light intensity in the GT and CT systems compared to layers 2, 3, and 4. Similar results were reported by Touliatos et al. (2016), who observed that the vertical farming systems exhibited lesser yields compared to the horizontal hydroponic system. Light intensity was uniformly intercepted in the horizontal system (DW), enhancing photo assimilates and the higher yield (Fig. 3.6A). The present study's findings corroborate previous researchers who reported that lettuce yield increases with light intensity (Knight & Mitchell, 1988; Kang et al., 2013). Also, Poorter et al. (2012) reported that light intensity decreases linearly as the distance from the light source increases in controlled environments. Worthy of note is that light intensity employed in this study was above 600 µmol $m^{-2}{\cdot}s^{-1}$ at L1 for the vertical and the DW systems because a decline in light intensity as light travels to the lower layers from L1 to L4 was anticipated, even though the recommended light intensity for indoor hydroponics systems for lettuce plants is between 230 - 290 µmol $m^{-2}\,s^{-1}$ (Kang et al., 2013) and 250 µmol $m^{-2}\,s^{-1}$ (Zhang et al., 2018). This finding is corroborated by a study by Fu et al. (2012), who observed that higher light intensity may lead to enhanced yield, improved plant morphology, shorter growth duration, and better enzymatic antioxidants. In GD and CT systems, 96% and 73% of the variation in plant yield was explained by the variation in light intensity (Fig. 3.5). The regression equation in the VHS further implies that if light intensity is increased by 100 µmol $m^{-2}\,s^{-1}$, there will be a corresponding increase of 87.4g & 94.1g in lettuce yield in the GD and CT system respectively (Fig. 3.5). Also, the regression equation in CT and

GD shows that lettuce yield tends to decrease with the increase in distance from the source or layers (L1 to L4). (Fig. 3.4). According to Gruda (2005), vegetables produced in greenhouse conditions influenced the sensory characteristics of produce in its distinct taste and flavor compared to field conditions. A study conducted by Fontana et al. (2018) compared the sensory properties of lettuce plants grown in three different growing systems. The study observed that vegetables produced hydroponically influenced the sensory characteristics of produce in terms of leaf crispiness, size, consumer preference, and purchase intentions compared to the conventionally and organically grown ones. Results of the present study indicated a wide range of preferences among the panelists who gave the highest rating to the flavor of the plants grown in the GD system (Fig. 3.8), which can be attributed to the intricate nature of human sensory perception and individual preferences (Gonçalves et al., 2014). The GD system type is known for enhancing the marketable yield and quality of plants because of the direct application of the nutrient solution to the root zone (Ayers et al., 1999).

Flavor impacts taste and perception through psychological processes, eventually influencing consumption (Tournier et al., 2009; Raggio & Gámbaro, 2018). The variability in taste preferences can be ascribed to the influence of hereditary variables and prior culinary experiences on taste perception (Lawless & Heymann, 2010). According to Barrett & Co (2010), the acceptance and subsequent consumption of fruit or vegetables may be influenced more by their flavor than by their color or appearance. The GD system-grown plants also had high ratings based on the leaves' appearance and sizes. Previous research has shown that consumers have specific expectations regarding the texture of freshly harvested fruits and vegetables. A non-desirable change in texture or color or an unpalatable taste will likely result in product rejection (Harker et al., 2003; Barrett et al., 2010). In CT, the lettuce leaf's color, preference, and overall liking were rated higher than the GD and DW. Color is a significant parameter in measuring quality and is essential as it may greatly influence acceptance and customer preference (Francis, 1995). Most food approval or rejection is based on visual observation (Ray, 2021). Consumer preference and overall liking for the CT-grown plant may be due to its vibrant color, which was perceived as best in terms of quality. Results from our sensory survey on the production of current experimental designs indicated that panelist would rather have CT systems in their homes or gardens than GD and DW. They may have drawn this conclusion because of the beautiful and aesthetic appearance of the CT system. However, despite its higher biomass, the results from the DW system revealed that it received the lowest ratings across all sensory characteristics examined. This discrepancy could be due to the factors related to marketable qualities and the design of the hydroponic systems. Further studies are required to confirm the efficiency of the vertical systems using improved light quality and sources to minimize the effect of the light intensity on the total fresh biomass/yield of lettuce plants. Embracing inter/intra lighting and vertical grow lamps could enhance photosynthetic activities, ultimately optimizing yield and improving produce quality.

3.7. Conclusion

Indoor vertical farming is an innovative approach that has the potential to enhance local food production at affordable prices and provide access to fresh leafy vegetable production through small-scale hydroponic systems. In this study, the performance of two locally fabricated vertical hydroponics systems, i.e., the Green-DNA (GD) and the Christmas tree (CT), were evaluated with deep water culture (DW) as control. Findings showed that the DW and GD systems produced higher lettuce yields and performed better than the CT systems. Although the DW system demonstrated superior performance in lettuce yield, root dry weight, root-shoot ratio, and photosynthesis rate, it received the lowest acceptance among end users regarding sensory analysis attributes. The CT system produced the best result as the most preferred only in sensory analysis results, and the GD system demonstrated comparable outcomes to the DW system in several parameters, including lettuce yield, root dry weight, root-shoot ratio, leaf area and plant height, and moderately reasonable sensory analysis results. Overall, light intensity showed noticeable variation across different layers in the vertical hydroponic systems, with light penetration diminishing as it reached the lower levels. As a result, lettuce yield decreased as the photosynthetic photon flux density declined in the lower layers. To enhance yield in vertical hydroponic systems, exploring methods for improving light intensity and penetration, such as through inter/intra lighting and vertical light sources, is crucial. Based on the results, the consistent performance of GD system in enhancing lettuce yield and sensory attributes position it as a promising alternative for indoor farming practices. The GD system may be redesigned to portray the aesthetic characteristics of the CT system since it was the most preferred design by the sensory panelists.

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Chapter 4

2. Effect of light emitting diode and fluorescent lamps on the growth, yield, and phytonutrient profile of lettuce plants grown in small-scale vertical hydroponic systems.

4. 1. Abstract

The demand for safer and sustainable food production currently surpasses the supply level, particularly in the boreal regions. Growing leafy vegetables in small vertical hydroponic systems may address the challenges of local food production and ensure year-round harvests, but they are highly dependent on supplementary light sources to maximize production. This study investigates the effects of full-spectrum light-emitting diodes (LED) and fluorescent lamps (FL) on hydroponic systems' growth, yield, and phytonutrients. The experimental treatments were two light sources, i) LED and ii) FL, and three hydroponic systems: 1) Christmas Tree (CT), 2) Green DNA systems, and 3) Deep-water culture system was used as a control. The experimental design was completely randomized, with factorial arrangements repeated twice. Results showed that LED-grown lettuce in the GD system produced significantly higher yield and number of leaves, whereas FL-grown lettuce plants in the CT system produced the lowest yield, chlorophyll content, and number of leaves. Higher antioxidant activity, mineral nutrients, and vitamins (C, D, E riboflavin, folate, and retinol) were recorded in LED-grown lettuce in the GD system compared to the other treatment combinations. Lettuce grown in the DW- LED combination enhanced the phenolic content compared to the lettuce grown in the CT- system under LED and FL. Based on the results, it may be concluded that the GD system with LED arrangements demonstrated superior agronomic performance and phytonutrients of lettuce. However, further research is needed to

optimize the LED spectrum indoors to maximize the yield and quality of lettuce and other leafy vegetables.

Keyword

Hydroponics, full spectrum LED, light sources, leaf area, wick system, drip irrigation, vitamin, phenolic content, antioxidant activity, lettuce.

4.2. Introduction

In boreal regions such as Newfoundland and Labrador (NL), extreme weather conditions, short growing seasons, low crop heating units, and early spring frost significantly restrict the growth and yield of field crops (Osman & Osman, 2013). Additionally, the soils in NL are shallow, stony, and have low pH, resulting in low fertility (Quinlan, 2012; GovNL, 2012). These factors collectively cause a substantial reduction in food production within the province. Consequently, sustainable food production in NL requires addressing these multifaceted challenges through innovative approaches and efficient food production and distribution systems (Capone et al., 2014; Calicioglu et al., 2019).

One innovative approach is Controlled Environment Agriculture (CEA), an advanced and innovative hydroponic farming method. It allows plant cultivation in a controlled environment to tackle issues associated with traditional farming practices (Mattson, 2024). By providing optimal growing conditions, CEA enables year-round harvests and eliminates the risk of crop loss (Ajayambikadevi, 1995). This system involves cultivating plants inside enclosed structures such as vertical farms, greenhouses, and growth chambers. Vertical farms are specialized indoor agriculture that capitalizes on vertical layouts by arranging crops on multiple levels or cultivating them on vertical surfaces (Despommier, 2010).

A core technique used in CEA is hydroponics, which employs liquid fertilizer solutions instead of traditional soil-based systems (Savvas, 2003). Hydroponics offers numerous benefits, including high water and nutrient use efficiency, soil-transmitted diseases and pest prevention, reduced physical labor requirements, multiple crop cycles, and significantly higher yields than traditional soil-based systems (Jan et al., 2020). However, success in indoor hydroponic farming depends on numerous factors, such as the nutrient solution, pH and EC levels, choice of growing media, light, and other prevailing environmental conditions (Sarkar & Majumder, 2017; Srivani et al., 2019).

Among these factors, light intensity and quality are particularly crucial. Light sources and intensity significantly impact hydroponically grown lettuce's growth, productivity, and quality (Li & Kubota, 2009). The minimum suggested light intensity for human comfort in a residential environment is estimated at 7 mol m^{-2} s^{-1} when using cool white fluorescent lamps (FL) (Paz et al., 2019). In contrast, standard residential lamps provide a daily output of only about 0.6 mol m^{-2} d^{-1} if operated continuously for twenty-four hours. Therefore, supplementing lights is vital to support indoor vegetable production in residential environments (Paz et al., 2019). Ensuring consistent year-round production and optimizing the yield and quality of crops requires adequate light energy, achieved through prolonged photoperiods and appropriate light sources (Ohashi-Kaneko et al., 2007; Appolloni et al., 2021).

Typical light sources used in CEA include fluorescent lamps (FL), incandescent lamps, and LEDs (Zissis, 2013). Full spectrum light-emitting diodes (LEDs), which emit all wavelengths from ultraviolet (UV) to visible to infrared (IR) within the photosynthetic active radiation range (380 - 780 nm), are particularly noteworthy (Massa et al., 2008; Ahmed et al., 2020) (Figure 4.1). Designed to mimic natural sunlight, full-spectrum LEDs offer balanced lighting and are wellsuited for plant growth and development in CEA, owing to their wide range of wavelengths (Dutta & Liotta, 2017; Yap et al., 2021; Ding et al., 2021).

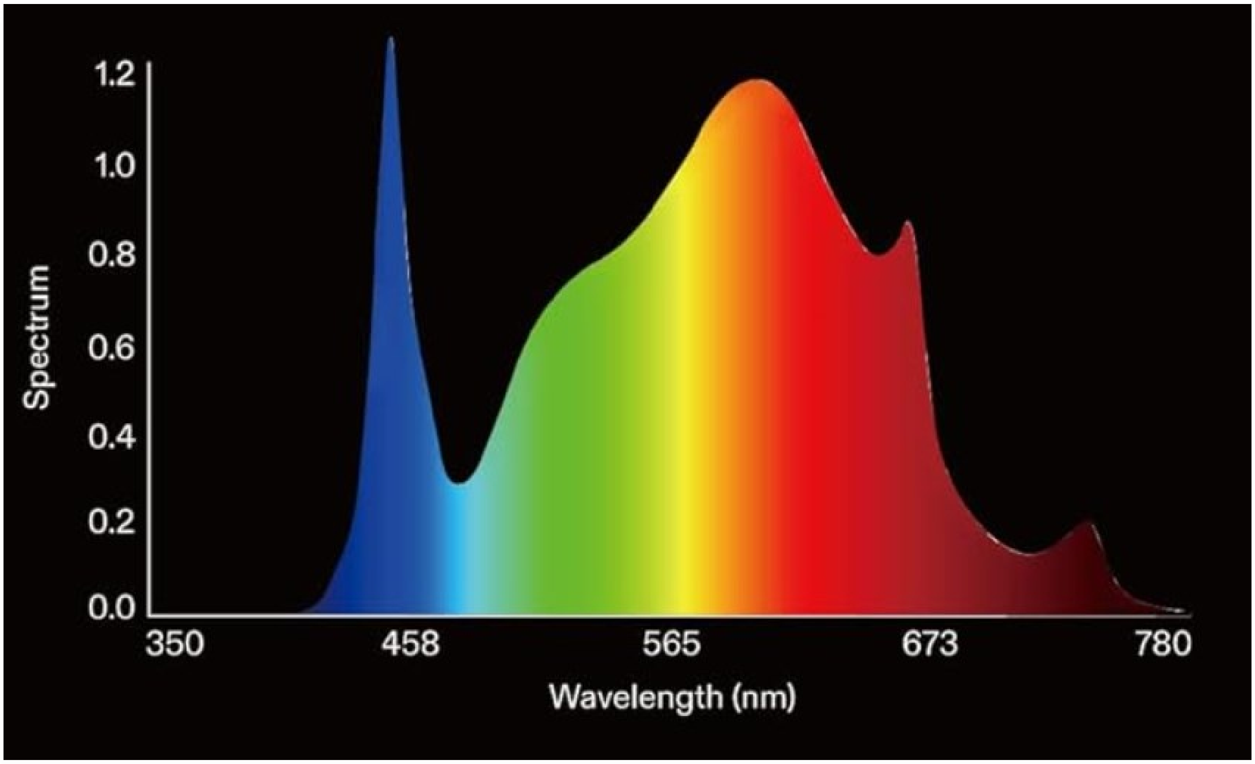

Figure 4.1: Typical spectral power distribution of full spectrum LED (380 nm -780 nm) (Adapted from: Vivosun, 2024).

On the other hand, FLs are low-pressure mercury vapor discharge lamps that emit visible light through the fluorescence of a phosphor coating. Daylight bulbs, which generate light over the entire optical spectrum and include some ultraviolet light, also aim to mimic natural sunshine, although none replicate it precisely (Veitch & McColl, 1994; Gupta & Agarwal, 2017). While FL lights enhance the photosynthetic photon flux density (PPFD) to provide optimal conditions for plant physiological processes, they may encompass non-essential wavelengths of inferior quality, resulting in diminished efficiency in promoting optimal plant development (Kim et al., 2004a).

For instance, adequate light is needed to promote photosynthesis, growth, and development of plants (Zhu et al., 2008). Artificial or supplementary light sources have emerged as critical factors in growing high-quality vegetables in a controlled environment (Massa et al., 2008), affecting photosynthesis, nutrient uptake, and hormone regulation (Ouzounis et al., 2015; Pinho & Halonen, 2017). Currently, a wide array of spectra, especially in the fluorescence and LED range, are readily accessible for plant growth (Seiler et al., 2017). Due to the poor power efficiency of FL lights, LED lights emerge as the most appropriate light source for achieving spectrum modulation, owing to their exceptional efficiency and low energy usage (Kotiranta, 2013). Light quality, influenced by light sources, can potentially enhance the accumulation of vital nutrients and antioxidants, thereby improving nutritional composition (Li & Kubota, 2009).

Several studies have explored the effects of light sources on hydroponically grown lettuce. For example, Lin et al. (2013) analyzed lettuce leaf yield and quality under three light sources: Red blue – RB-LED, Red blue and white- RBW-LED, and FL. They found higher yields in RBW-LED and FL, suggesting that supplemental light sources could increase lettuce's nutritional quality and yield. Similarly, Camejo et al. (2020) examined the impact of different light sources—LEDs (W, RB) and FL—on the growth and health properties of two lettuce varieties, *Batavia lettony,* and *Batavia diablotin*. Results showed that LED illumination, particularly RB lights, positively affected growth parameters in *B. diablotin* plants compared to FL lights. Changes in light intensity also affected leaf texture and the accumulation of bioactive compounds differently in the two varieties. Etae et al. (2020) also studied the effect of three light sources on green oak lettuce's growth and phytochemical contents. They reported that bar-LED light (with a 1:1:1 ratio of blue 460 nm: red 630 nm: red 660 nm) provided better quality in terms of PAR and yield photon flux density, resulting in higher shoot and root mass compared to plants grown under FL (380 - 700 nm) lights. Bar-LED lighting also led to higher levels of total phenolic content and antioxidant activities in the lettuce plants.

In a greenhouse study, Martineau et al. (2012) evaluated LED and high-pressure sodium (HPS) supplementary lighting systems for Boston lettuce (Lactuca sativa var. capitata) production. Despite the lesser moles of light produced by LED (35.8 mol m–2) compared to HPS (71.3 mol m–2), LED produced comparable shoot biomass and nutritional content. Furthermore, Li et al. (2012) reported the effects of LED (blue, blue + red, and red), FL, and natural sunlight on non-heading Chinese cabbage (*Brassica campestris L.)* seedlings' growth and nutritional contents. Low-intensity red LEDs (100% R, peak at 660 nm) produced the highest dry matter weights for shoots and roots, while blue LEDs (100% B, peak at 460 nm) resulted in higher chlorophyll and vitamin C levels. The study concluded that LED light sources are more efficient in enhancing produce's vegetative and reproductive development. However, traditional LEDs can only tailor their spectral composition to specific wavelengths. A broadband-spectrum light is crucial to support plant growth as an artificial light source in an indoor environment. Hence, the full-spectrum LED is employed in this study to replicate the diverse wavelengths found in sunlight, providing plants with the necessary light energy for photosynthesis and other physiological processes essential for growth and development.

Therefore, to further investigate the effect of full spectrum LED and FL lights on the growth, yield, and quality of lettuce in different indoor small-scale vertical hydroponic systems (VHS), we hypothesized that LED light would enhance the growth, yield, and phytochemical profile of lettuce in the designed vertical hydroponic systems. To test this hypothesis, an experiment was conducted twice in a grow tent in a controlled environment with the following specific objectives:

1. To determine the effects of full spectrum LED and FL light sources on the growth and yield of lettuce plants grown under different vertical hydroponic systems.
2. To assess the effect of full spectrum LED and FL sources on the phytonutrient profile of the lettuce grown in the vertical hydroponic system.

4.3. Materials and methods

Lettuce seeds (*Lactuca sativa L*. cv. 'new ham') were purchased from High Mowing Organic Seeds (Wolcott, VT, USA), were planted in nursery trays with pre-soaked coco coir (Hydrofarm, CA, USA) and placed in a walk-in growth chamber (Biochambers, MB, Canada). The crop growing conditions of the growth chamber were set and maintained at 16/8 h day/night, 25/17°C, 75 - 80 %, and 400 - 600 ppm of photoperiod, temperature, relative humidity (RH), and carbon dioxide (CO_2) concentration respectively at the nursery stage. After two weeks, the lettuce seedlings were transferred to the hydroponic system in a grow tent (Vivosun, ON, CA) in the Recplex building, Grenfell Campus Memorial University. Photoperiod, temperature, and RH were set up and maintained at 16/8 h day/night, 25/17°C, and 75 - 80 % during both crop cycles (Zandvakili et al., 2017). The Hobo meter (MX1102A, MA, USA) was installed in the grow tent to monitor the growing conditions throughout the crop cycles, and the digital timer (Noma, ON, CA) was used to monitor the accuracy of the photo periodicity.

4.3.1. Establishment of the experiment

The experimental treatments were comprised of a) hydroponic systems and b) light sources (Table 4.1). The two vertical hydroponics systems (VHS) were designed and fabricated locally and designated as Christmas Tree (CT), a small-scale wick hydroponic system design; Green-DNA (GD), a drip hydroponic system design; and a commercially available deep-water culture system

(DW - as control). Off-the-shelf LED and FL lights were used as light sources *i)* 1000W LED 2x2 ft full spectrum (white, blue, red, and IR (3000K, 5000K, 660nm and IR 760nm) (380 - 780nm) from Vivosun, ON, Canada and *ii)* daylight 6500K FL T5 (8 tubes each) (Durolux, ON, Canada).

Table 4.1. Hydroponic systems and light sources used in this study.

Light Sources	Hydroponic systems	Treatment ID
LED	Deep-water culture (Control)	DW x LED
	Christmas tree	CT x LED
	Green-DNA	GD x LED
FLUORESCENT	Deep-water Culture (Control)	DW x FL
	Christmas Tree	CT x FL
	Green-DNA	GD x FL

The LED light panels were adjusted to get PPFD within the same range as the FL lights. The average PPFD measured at the plant canopy for LED at 320 ± 20 µmol m^{-2} s^{-1} and FL at 305 ± 11 µmol m^{-2} s^{-1}. The hydroponic systems in the grow tent were set up so that light panels were horizontally suspended 30 - 40 cm above the plant canopy in the grow tent (Figure 4.2). The experiment was set up in a completely randomized design in a factorial arrangement with three replications. In this study, only data from the first layer of the vertical systems were considered for a comparative analysis with the DW system to mitigate any bias stemming from variations in the light intensity within the lower layers.

Figure 4.2: A pictorial presentation of a 45-day-old lettuce crop grown in three hydroponic systems in the grow tent under two different light sources. A) lettuce grown with LED, B) lettuce grown with fluorescent lights (FL), GD = Green DNA (left); DW= Deep water culture (middle) (control); CT = Christmas Tree (right side).

The CT system setup consists of four separate layers, each holding 18 plastic grow cups with a capacity of 70 mL. Each cup has a 3-inch mesh net to hold the coconut coir, which acts as the growth medium. The 34 L tank (Sterlite, USA) stored the nutrient solution, which was then circulated by a submersible pump (Hydrofarm, CA, USA) operating at a 946 L hr^{-1} flow rate. On the other hand, the GD system had two distinct spiral layers, which held 26 cups in total. Geotextile fabric was placed in each cup (10 cm in height and 10 cm in diameter) before being filled with coco coir to prevent blockage of the drip lines. An adjustable irrigation dripper (Hydrogarden, CO, UK) was affixed to a tube connected to the nutrient solution storage tank (Sterlite, USA). The drip pipe was strategically looped around the system to facilitate the nutrient solution's circulation. A submersible water pump with a flow rate of 1514 L hr^{-1} flow rate (Hydrofarm, CA, USA) was installed in the storage tank. The pump was turned on twice daily for 30 min to allow the flow of nutrient solution to the root zone.

Additionally, there were two 10 L DW hydroponics growing containers (Homend GA, USA) (14cm long x 41 cm wide). Each container featured 11 planting holes, an oxygen pump, and a bubble stone. The containers were placed side by side at the center of the growth tent on an elevated surface to maintain the same height as the vertical system. Since the first and second cycles of the lettuce crop were grown in the winter, to maintain an optimum temperature inside the grow tent, a heater (iPOWER CA, USA) along with a duct fan (Vivosun ON, CA) was installed for uniform air circulation. The vertical systems were rotated bi-weekly to minimize the impact of light intensity on the lower layers of the vertical system.

4.3.2. Nutrient solution preparation

An off-the-shelf 3-portion master blends nutrient kit consisting of master blend lettuce formula 8-15-36 (N-P-K), magnesium sulfate ($MgSO_4$), and calcium nitrate $Ca(NO_3)_2$ (15.5-0-0), a ready-to-mix product (Gecko Grow, AB, CA) was used in this experiment. Electrical conductivity (EC) and pH of nutrient solution were continuously monitored and maintained at 2.0 - 2.5 ($mS\ m^{-1}$) and 5.8 - 6.5, respectively, using standard procedure. The EC and pH levels in the nutrient solution were monitored daily using an EC/pH meter (Bluelab, Newzealand).

4.3.3 Measurement of plant growth parameters

The agronomic performance of lettuce was evaluated 45 days after sowing, considering the number of leaves, chlorophyll content, leaf area (LA), and plant height. The chlorophyll content of the top three lettuce leaves was measured at the apex with a handheld chlorophyll meter (SPAD-502, Minolta Co. Ltd., Osaka, Japan). Plant leaves were manually counted, and the number was recorded. The LA of lettuce was measured using a portable LA meter (LI-3000C LI-COR Biosciences, NB, USA). Plant height was measured using a measuring tape from the surface of the growth medium to the leaf tip of the longest leaf of each plant at the time of harvesting. The PPFD is measured using a light meter (Dr. Meter, CA, USA). At harvest, the lettuce plants were cut with a knife into root and shoots to ascertain their fresh (g $plant^{-1}$ FW) and dry weights (g $plant^{-1}$ DWT). The roots and shoots were put in a paper bag, followed by oven drying at 65°C for 72 hr or until a consistent weight was achieved. The final dry weight of the shoot and root was then determined and recorded using a digital weighing scale (RADWAG, PS 6000/C/2, RA, Poland).

For the phytonutrient analyses of lettuce plants, freshly harvested plant samples were labeled appropriately, stored in a clean zip lock bag, and kept in the -20°C freezer. Plant tissue samples were freeze-dried (Labanco, MI, USA) and stored in 50 mL centrifuge vials in the -20°C freezer until analyzed.

4.4. Nutritional composition of plant tissues

4.4.1 Water and fat-soluble vitamins

The protocol for vitamin extraction was adopted from Santos et al. (2012). Briefly, a 25 mg freeze-dried lettuce sample was extracted with 1.6 mL of 10 mM ammonium acetate/methanol 70:30 (v/v) containing 0.01% BHT. Standard solutions (50 µL of 1 mg mL^{-1} hippuric acid as internal standard) were added, and samples were shaken for 15 min and then placed in an ultrasound bath for 15 min. Then, samples were centrifuged at 12,000×g for 15 min, and the supernatant was withdrawn and filtered through a Mini-Uniprep, then injected into a high-performance liquid chromatography-mass spectrometry (HPLC-MS/MS) system to determine water-soluble vitamins (WSV) against the corresponding standard curves. The solid residue from the first extraction was re-extracted with 1.2 mL of ethyl acetate for 15 min in the ultrasonic bath. Finally, the samples were centrifuged (12,000×g, 15 min), and the supernatant was filtered through a Mini-Uniprep and then injected into an HPLC-DAD-MS/MS for fat-soluble vitamins (FSV) analysis against the corresponding standard curves. All samples were run with four replications.

4.4.1.1. Measurement of water-soluble vitamins (WSV) content

Stock solutions of each vitamin (1 mg mL^{-1}) were prepared on ice and in low light: Vitamin B1, B3, B5, B6 (3 forms), and vitamin C were dissolved in methanol. Vitamins B2, B7, B9, B10, and Bx were dissolved in 0.1 M NaOH solution. All solutions were prepared in amber glass vials. A stock mixture solution (0.1 mg mL^{-1}) was made using these individual solutions, and a calibration curve was generated by a serial dilution of the stock solution (10-500 ppb) calibration range. UHPLC-MS/MS method was utilized for the quantification of water-soluble vitamins (WSV), using Acclaim C18 reverse column (4.6 × 150 mm, particle size: 5 µm, pore diameter: 120 Å; Thermo Fisher Scientific, ON, Canada). The LC mobile used Solvent A, which consisted of 10 mM of ammonium formate and 0.1% formic acid in deionized distilled water, while solvent B consisted of 100% acetonitrile. Chromatographic separation was performed at 35°C (column oven temperature) with a flow rate of 0.4 mL min^{-1}, and 10 µL of the extract was injected into the system. The mobile gradient was used in a 22 min method as below: equilibrium at 10% solvent B for 3 mins, then increased to 100% solvent B over 14 min gradient and back to the start condition of 10% solvent B for 5 min. The Orbitrap mass spectrometer ESI ion source was operating in positive ion mode. The optimized parameters used were a sheath gas flow rate of 40, an auxiliary gas flow rate of 15; an ion spray voltage of 3.80 kV, capillary temperature of 300°C, Tube lens:100 V, capillary voltage of 35 V, mass range of 50-1000 m/z; full scan mode at a resolution of 60,000 m/z; top-5 data-dependent MS/MS at a resolution of 30,000 m/z; and collision energy of 35 (arbitrary unit); acquisition time 22 min; isolation window: 1.5 m/z; automatic gain control target: 0.250. The mass spectrometer was externally calibrated to 1 ppm using an ESI-positive calibration solution (Thermo Scientific, MO, USA).

4.4.1.2. Measurement of fat-soluble vitamins (FSV) content

Standard curves of FSV mixture (A, A acetate, D2, D3, E, K1, K2, and β-carotene) with concentrations in the calibration range 3 - 100 ppm were made and run with all plant samples. The filtered FSV extractions were analyzed by UHPLC-PDA-MS/MS method using Acclaim Polar Advantage II (PA2) column (4.6 mm × 150 mm, particle size: 5 μm, pore diameter: 120 Å; Thermo Fisher Scientific, ON, Canada) was used for the analysis. The mobile system was used as follows: Solvent A consisted of 10 mM ammonium acetate in methanol containing 0.1% acetic acid, while Solvent B consisted of MTBE: methanol 80:20 (v/v), 10 mM of ammonium acetate, and 0.1% acetic acid. The separation was performed at 35°C column compartment temperature, 0.4 mL min^{-1} flow rate, and 10 µL extract injection into the system. The Orbitrap MS was operated in the positive APCI ion mode to determine the fat-soluble vitamins. The following optimized parameters were used for the Orbitrap mass spectrometer: sheath gas flow rate: 40; ion spray voltage: 4 kV; an auxiliary gas flow rate: 15; tube lens: 30 V; mass range: 100-1000 m/z; capillary temperature: 300°C; capillary voltage: 30.0 V; full scan mode at a resolution of 60,000 m/z; top-5 data-dependent MS/MS at a resolution of 30,000 m/z; and collision energy of 35 (arbitrary unit); injection time of 15 min; isolation window: 1.5 m/z; automatic gain control target: 0.250. The mass spectrometer system was externally calibrated to 1 ppm using APCI positive calibration solution (Thermo Scientific, MO, USA).

4.4.2. Minerals content analyses

4.4.2.1. Digestion and extraction of mineral elements

The mineral content of the lettuce plant was determined following the method of Ali et al. (2019). Briefly, 0.1 g of each freeze-dried lettuce sample was mixed with 9 mL concentrated trace-metal grade nitric acid (HNO_3) (70%), and 3 mL of hydrogen peroxide (H_2O) 30% was added in the digestion tubes. Each sample was digested using the Microwave Multiwave 5000 Digestion System (Anton Paar Canada Inc., QC, Canada). Samples were digested in two stages: 20 min ramp to 200°C for 3 min at 1500 W (stage one) and 10 min at 200 °C for 15 min at 1600 W. The digestion tubes were cooled at room temperature, and samples were filtered into 50 mL sterile plastic tubes and stored at 4°C. Before analysis, samples were diluted with deionized distilled water as needed and stabilized at 3% nitric acid.

4.4.2.2. Measurement of mineral elements profile by ICP-MS

The mineral content was analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS; Thermo Scientific iCAP Q ICP-MS). A standard calibration curve ranging from 1 - 400 μL^{-1} was prepared using IV-ICPMS-71, a standard mixture (InorganicTM Ventures, Inc; Christiansburg, VA 24073, USA). Aliquots of the digests were diluted with 3% nitric acids and spiked with Rhodium103 (final concentration = 10 ppb) as the internal standard for ICP-MS analysis. The ICP-MS analysis was conducted using the following parameters: an auxiliary gas flow of 0.79 mL min^{-1}nebulizer gas flow of 1.01 mL min^{-1}, plasma gas flow of 14 mL min^{-1}, RF power of 1548 W, detector mode KED and a dwell time of 0.01s using Argon gas at a purity of 99.99%. All samples were run with four replications for analysis.

4.4.3. Total Antioxidant activity (TAA) and total phenolic content (TPC)

The estimation of total antioxidant activity (TAA) was conducted using ABTS (2,2-azinobis (3-ethylbenzothiazoline-6-sulfonic acid)) and FRAP (ferric reducing antioxidant power) assays.

The plant leaf extract preparation procedure outlined by Cano et al. (2010) was used with some modifications. In brief, 5 mL of HPLC grade 0.7% acidified ethanol was mixed with 1 g of freeze-dried powder plant samples. The mix was incubated away for 10 min at room temperature. Then, the mix was centrifuged at 5000 x g for 10 min. The supernatant was carefully collected into 2 mL plastic microtubes without unsettling the pellet and was used to calculate the lipophilic antioxidant activity (LAA) and lipophilic phenolic content (LPC) without further dilution. The pellets were re-suspended in 50 mM sodium phosphate buffer (pH = 7.5), vortexed, centrifuged, and the aqueous supernatant pooled as described by Manful et al. (2020). Lipophilic antioxidant activity (LAA) and hydrophilic phenolic content (HAA) were determined using the above supernatant. The extracts were stored in darkness at – 20°C.

4.4.3.1. Antioxidant activity using the ABTS assay.

The HAA and LAA were extracted using Arnao et al.'s (2001) procedures with slight modifications. For HAA, 160 µL of 25 mM of ABTS [2,2’-azinobis-(3-ethylbenzothiazoline-6-sulfonate)] stock solution, 480 µL of 125 µMol H_2O_2, and 200 µL of 1 mg mL^{-1} HRP (Horseradish peroxidase) in 1160 µL of 50mM sodium phosphate buffer (pH = 7.5) were mixed in a total volume of 2 mL, reaction mixture takes about 10 min to stabilize, After stabilizing, with starting absorbance from 1.0 in a Cytation imaging microplate reader (BioTek Instruments, Inc., Winooski, VT, USA) change to ABTS sample protocol, plate 1 was read. Out for 10 min to add samples and standard, absorbance read 2 is collected after 10 min delay. For the LAA, a reaction mixture containing 160 µL of 25 mM of ABTS, 480 µL of 125 µMol H2O2, and 1000 µL of 1 mg mL^{-1} HRP in 360 µL of 0.7% acidified ethanol (95 % v/v) in a total volume of 2 mL was prepared. Contrary to HAA, the reaction mixture was ready for immediate use, the absorbance read 1 was around 0.7, the plate was out for 10 min to add standards and samples, and absorbance read 2 was collected after 10 min delay. A standard Trolox (1 mM) stock solution in deionized water was serially diluted to prepare the working standards. The summation of the HAA and LAA values determined the values for the TAA. The results were expressed as µM Trolox equivalents/g of the dry plant sample.

4.4.3.2. Ferric reducing antioxidant power assay (FRAP).

The TAA of the lettuce leaf samples was measured using the ferric reducing antioxidant power (FRAP) developed by Benzie & Strain (1996) and modified by Manful et al. (2020). FRAP was freshly made by mixing 25 mL of sodium acetate buffer (pH = 3.6; molarity = 300 mM), 2.5 mL of TPTZ (2,4,6-tripyridyl-s-triazine; Molarity:10 mM), and 2.5 mL of $FeCl_3 \cdot 6H_2O$ solution (ferric (III) chloride hexahydrate; Molarity: 20 mM). After mixing, the solution was heated in an oven at 37°C for 15 min before use. Then, 20 µL of each standard or sample was reacted with 180 µL of freshly made FRAP solution in a 96-well microplate. The resulting mixture was subjected to incubation for 30 mins, and the absorbance was measured at a wavelength of 593nm using the Cytation Imaging microplate reader (Agilent, CA, USA). The TAA extracts' values were determined by summing the LAA and HAA antioxidant activity values based on a Trolox standard curve (0.0 - 3.5 mM). The results for the plant extracts were expressed in µmol Trolox equivalent /g (TE/g) extract (dry weight).

4.4.4. Total phenolics assay

The total phenolic content (TPC) in lettuce leaves was determined using the Folin–Ciocalteu method, developed by Cano et al. (2003), with minimal changes. In summary, a working solution diluted 10–fold was prepared by combining 5 mL of Folin–Ciocalteu reagent with 45 mL of distilled water. To analyze hydrophilic (HPC) or lipophilic (LPC) sample extracts, 25 µL of the appropriate sample extract were combined with 125 µL of a 10-fold Folin–Ciocalteu working solution and 50 µL of either sodium phosphate buffer (pH:7.5; Molarity:50 mM) or 0.7% acidified ethanol, depending on the type of extract. The resulting solutions were kept in darkness and incubated for 30 min. The absorbance was then measured at a wavelength of 755 nm using a cytation imaging microplate reader (Agilent, CA, USA). The total phenolic content in the sample extracts was quantified using a standard curve derived from a 1 mg mL^{-1} solution of Quercetin. The results were reported in milligrams of Quercetin equivalent per gram of dry weight (. TPC was quantified by summing the values of HPC and LPC.

4.5. Statistical analysis

A two-way analysis of variance (ANOVA) was done to determine the effects of LED and FL lights on the growth, yield, and phytonutrients of lettuce, and the XLSTAT (2023.2.0) (Addinsoft Software, NY, USA) software was employed to run ANOVA. Fisher's Least Significant Difference (LSD) at alpha = 0.05 was used to compare the treatment means when a treatment's effects were statistically significant. Prior to data analysis, the normality of the data set was checked using the Shapiro-Wilkes test. Figures were prepared using the SigmaPlot 15.0 software program (Systat Software Inc., CA, USA).

4.6. Results

4.6.1. Lettuce growth (g $plant^{-1}$ FW)

The hydroponic systems (HS), light sources (LS), and their interaction (HS x LS) had a significant ($p<0.001$) effect on the chlorophyll content (SPAD) of the lettuce plant (Fig. 4.3A). The SPAD-502 meter was used for the rapid, accurate, non-destructive measurement of leaf chlorophyll concentrations. HS and LS had a non-significant effect ($p<0.05$) on plant height. Results showed that the DW system under LED (DWL) exhibited higher chlorophyll content (58.7 SPAD) in lettuce leaves, followed by the CT system under the LED light (CTL), while the lowest (45.7 SPAD) was recorded in the CT system under the FL light (CTF). However, chlorophyll content in lettuce leaves among different treatments ranges from 45.1 to 58.7 (SPAD). Statistical analysis showed that HS had significant effects ($p < 0.001$) on LA of lettuce. Data presented in Fig. 4.3D indicated that the maximum LA (1086.34 cm^2) was recorded in the DW system, followed by the GD, and the lowest (722.84 cm^2) was observed in the CT system. Statistical analysis showed a non-significant effect ($p = 0.611$) of LS and the HS × LS ($p = 0.475$) on the LA of lettuce (Fig. 4.3D). Furthermore, the interaction between HS × LS had significant ($p<0.05$) effects on the plant height of lettuce (Fig. 4.3C). Maximum plant height (24.5 cm) was observed in the CT system under LED light, while the lowest (19.94 cm) plant height was observed in the lettuce plants grown in the DW system under the LED light. HS and HS x LS had significant effects ($p<0.05$) on the number of leaves of lettuce (Fig. 4.3B). The lettuce plant grown in the GD system under LED light produced a significantly higher number of lettuce leaves (39), followed by the lettuce plants in the GD system under FL light, while the lowest (24) was observed in the CT system under FL light. Meanwhile, LS had no significant effect ($p = 0.094$) on the number of lettuce leaves produced by the HS.

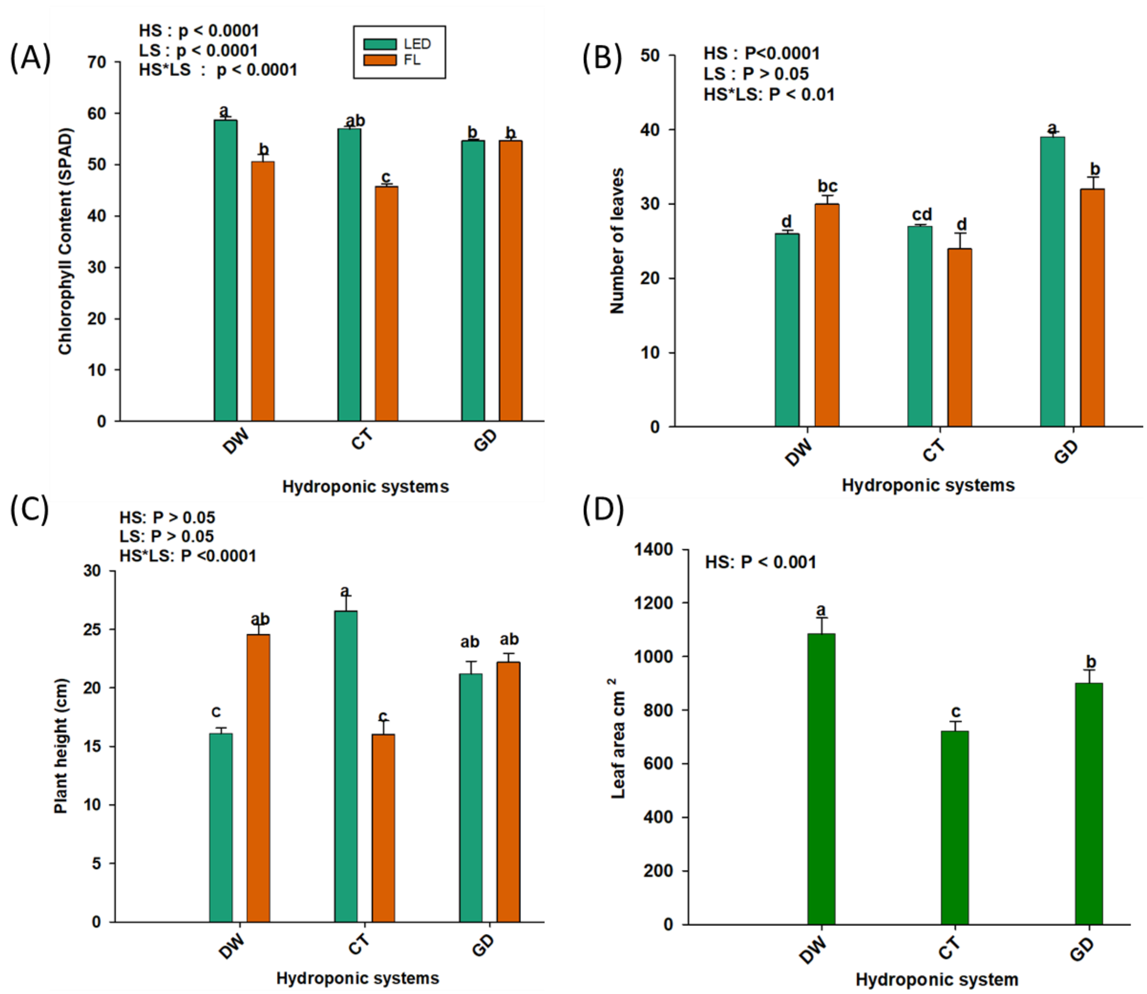

Figure 4.3: Interactive effects of hydroponic systems (HS) and light sources (LS) on the growth performance of the lettuce crops: (A) chlorophyll content, (B) number of leaves, (C) plant height, and the effect of hydroponic systems on leaf area (D). Vertical bars show the treatment means of three replications with standard error. Significant differences between treatments are indicated by different letters ($p < 0.05$, LSD test); DW = Deep-water culture (control); CT = Christmas Tree; GD = Green DNA; HS = Hydroponic systems; LS = Light sources; HS x LS = interaction between hydroponic systems and light sources.

4.6.2. Lettuce yield

Results indicated that HS, LS, and their interaction (HS × LS) had significant ($p<0.001$) effects on lettuce yield. The lettuce grown in the GD system under the LED lights produced a higher yield (233 g plant^{-1} FW), followed by the DW system under the LED lights, while the lowest yield (48 g plant^{-1} FW) was observed in the CT system under LED light. Lettuce plants grown under the

LED light showed superior agronomic performance by producing a 90% higher yield than the FL light, while the GD system performed better with 39% and 63% higher yield in the DW and CT systems, respectively (Fig. 4.4).

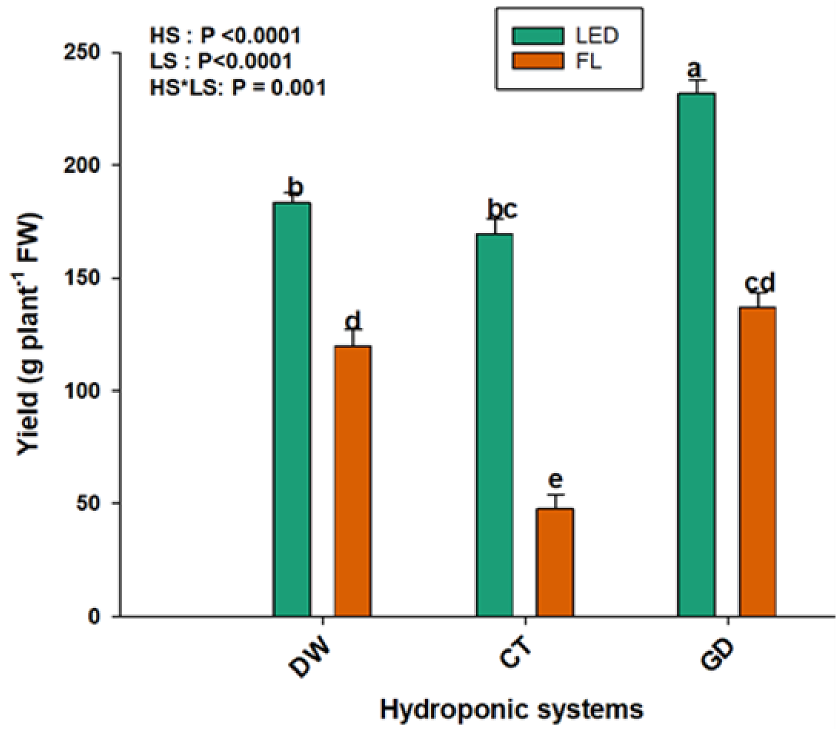

Figure 4.4: The effects of light emitting diode (LED) and fluorescent lights (FL) on lettuce yield grown in different hydroponic systems under a controlled environment. Vertical bars show the treatment means of three replications with standard error. Significant differences among treatments are indicated by different letters on bars ($p< 0.05$, LSD test); DW= Deep-water culture (control); CT = Christmas Tree; GD = Green DNA; HS = Hydroponic systems; LS = Light sources; HS xLS = interaction between hydroponic systems and light sources.

4.6.3. Total antioxidants and total phenolics

Data presented in Table 4.2. showed that HS and the interaction between HS × LS had significant ($p<0.001$) effects on the total antioxidants of lettuce leaves using the FRAP method. The lettuce plants in the GD system with LED lights produced significantly ($p<0.005$) higher total antioxidants (32.63 µmol g^{-1} DWT), followed by the GD system with the FL lights. The lettuce plants grown in the CT system exposed to LED lights exhibited the lowest (23.93 µmol g^{-1} DWT) total antioxidant concentration (Table 4.2). The ABTS method was consistent with our observation of the antioxidant activity in the FRAP method. HS, LS, and their interaction (HS x LS) had a significant ($p<0.05$) effect on the TAA of the lettuce plants. It showed that the GD system under the LED light produced significantly higher (24.35 µmol g^{-1} DWT) total antioxidants compared to the GD system exposed to FL lights, whereas the lowest (16.97µmol g^{-1} DWT) total antioxidants were observed in the CT system with FL lights. However, LED lights produced 92% higher TAA in lettuce plants than FL lights. Statistical analysis indicated that HS, LS, and their interaction (HS x LS) significantly influenced TPC in lettuce leaves. The data presented in Table 4.2 indicated that the maximum TPC (8.30 mg g^{-1} DWT) was observed in the DW system with the LED lights, followed by the CT system with LED lights, while the lowest (3.18 mg g^{-1} DWT) TPC was reported in the CT system with the LED lights. Overall, TPC in LED lights surpassed the FL lights by 21%, as indicated in Table 4.2.

Table 4.2: Analysis of variance and treatments means comparison showing the effects of light sources (LS), hydroponic systems (HS), and their interaction (LS x HS) on total antioxidant activity and total phenolic content of lettuce leaves.

Source of variation	**TPC (mg QE/g DWT)**	**TAA FRAP (µmol Trolox/g DWT)**	**TAA ABTS (µmol/g DWT)**
Hydroponics systems (HS)			
GD	4.71±0.15c	15.40±1.89c	20.7±0.86b
CT	5.59±0.32b	26.67±2.89b	18.05±0.14c
DW	6.24±0.49a	28.41±0.09a	23.41±1.12a
Light sources (LS)			
LED	19.77±0.25a	28.31±1.62a	7.26 ± 2.02a
FL	15.71±0.49b	27.98±1.37a	3.77 ±1.16 b
Hydroponic systems x Light sources			
DW x LED	8.30±0.11 a	29.30±0.55c	21.44±0.13c
CT x LED	7.24±0.02b	23.93±0.82 f	19.46±0.36d
GD x LED	6.24±1.33c	32.63±0.13 a	24.35±0.19a
DW x FL	4.19±0.87d	27.21±0.35 d	19.25±0.48d
CT x FL	3.94±0.13 e	25.11±0.88 e	16.97±0.18e
GD x FL	3.18±0.05 f	31.76±0.25 b	23.11±0.32b
Significance			
Hydroponic systems	***	***	***
Light Sources	***	NS	***
Hydroponic systems x Light sources (HS x LS)	***	***	***

DW = Deep water culture (control), CT = Christmas Tree, GD = Green-DNA, LED = Light Emitting Diodes, FL= Fluorescent lamps, *** highly significant ($P<0.001$), NS = Not significant, Values represent means ± standard error (n=3 for hydroponic systems, n=2 for light sources, and n=6 for HS x LS sources). Means in the same column with different letters indicate significant differences (LSD test; two-way ANOVA, at ($P<0.001$).

4.6.4. Vitamins

4.6.4.1. Water-soluble vitamins

Results indicated that HS, LS, and their interaction (HS × LS) had significant effects on vitamin C, niacin, and riboflavin. However, findings indicate a non-significant effect of LS and HS x LS on folate concentration in lettuce (Fig. 4.5A-D). The GD system with LED lights resulted in higher vitamin C (9.7 mg g^{-1} DWT), followed by the DW system with LED lights. The lowest concentration (5.18 mg g^{-1} DWT) was observed in the CT system with FL lights (Fig. 4.5A). Higher (29 µg g^{-1} DWT) riboflavin concentration in lettuce was observed in the GD system produced under LED lights, followed by the FL lights grown lettuce in the GD system, and the lowest (12 µg g^{-1} DWT) was observed in the CT system with FL lights.

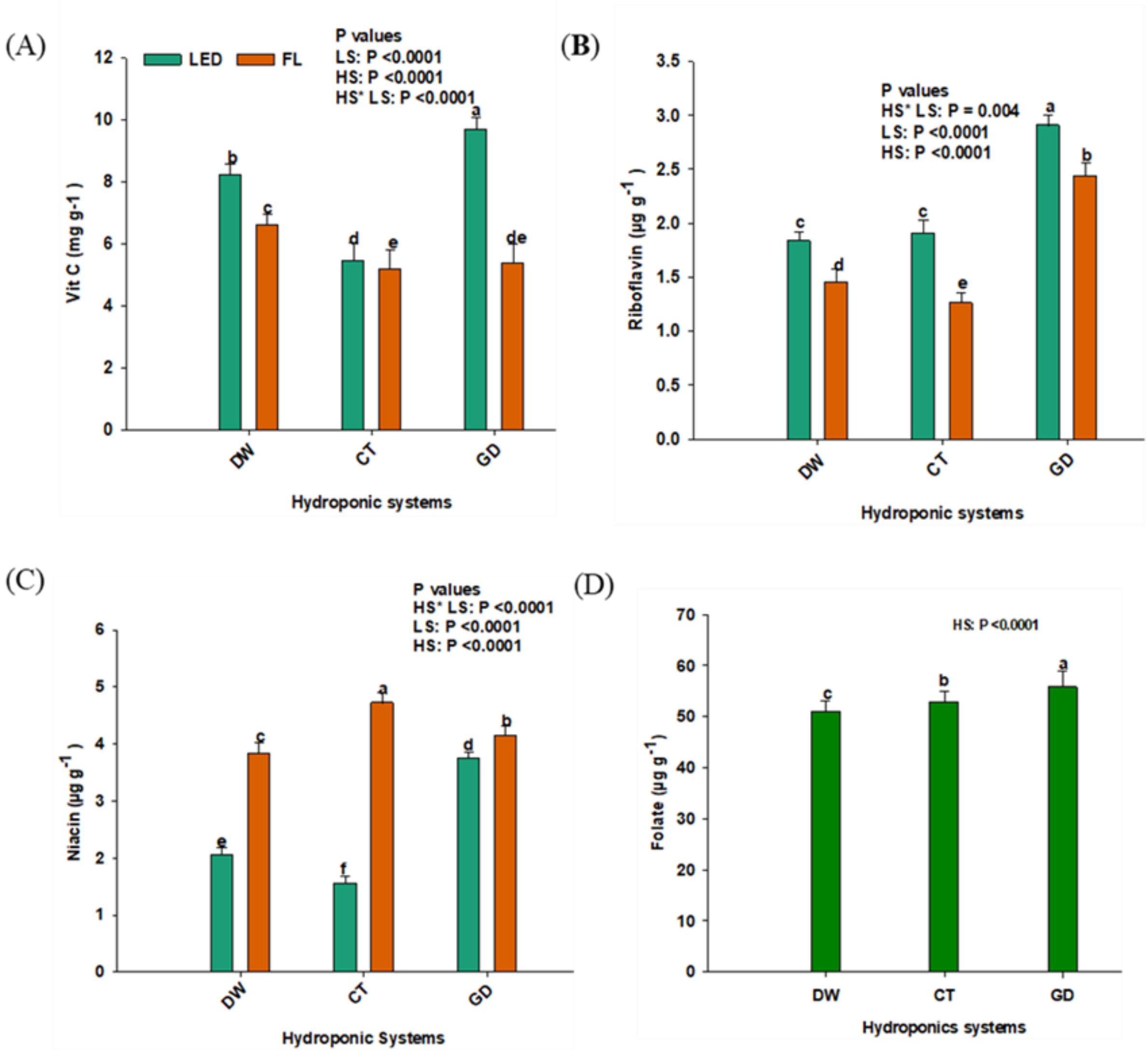

Figure 4.5: Interactive effects of hydroponic systems and light sources (HS x LS) on (A) vitamin C, (B) riboflavin, (C) niacin, and (D) folate concentration of lettuce grown in hydroponic systems. Vertical bars are means of three replications ±SE. Bars with different letters indicate significant differences ($P \leq 0.05$; LSD). DW = Deep-water culture (control); CT = Christmas Tree; GD = Green-DNA; HS = Hydroponic systems; LS = Light sources; HS x LS = interaction between hydroponic systems and light source.

The riboflavin concentration of lettuce grown in the CT and DW system with the FL lights indicated a statistically non-significant result (Fig. 4.5B). Overall, LED lights enhanced the riboflavin concentration of lettuce grown in all three hydroponic systems compared to FL. Lettuce grown in the CT system with FL light produced a higher (4.7 $\mu g\ g^{-1}$ DWT) concentration of niacin, and the lowest (1.6 µg g^{-1} DWT) was observed in the CT system with LED lights (Figure 4.5C). On the other hand, HS had significant ($p<0.05$) effects on folate concentrations, while LS and the interaction between (HS x LS) had a non-significant effect on folate concentration in lettuce (Fig. 4.5D). Folate concentration was higher (65.7 µg g^{-1} DWT) in GD, followed by CT, and the lowest (44.03 µg g^{-1} DWT) was observed in the DW system (Fig. 4.5D).

4.6.4.2. Fat-soluble vitamins

The results showed that HS, LS, and their interaction (HS × LS) had a significant effect ($p<0.001$) on the concentrations of vitamin E in lettuce plants. LS had a non-significant effect on phytonadione, while the interaction between HS and LS had no significant effects on phytonadione and vitamin E concentrations (Fig. 4.6A-B). Phytonadione concentration was higher (5.81 mg g^{-1} DWT) in lettuce grown in the DW system with LED lights, and the lowest (2.42 mg g^{-1} DWT) was observed in the CT system with LED lights (Fig. 4.6A). Also, vitamin E concentration was significantly ($p<0.001$) higher (30.1 mg g^{-1} DWT) in lettuce grown in the DW system with LED light compared to the lettuce plants grown in the GD system under the LED lights, while the lowest (8.0 mg g^{-1} DWT) was recorded in lettuce grown in CT system with FL light. Overall, LED-grown lettuce plants produced 3x higher vitamin E than lettuce grown under FL light (Fig. 4.6B).

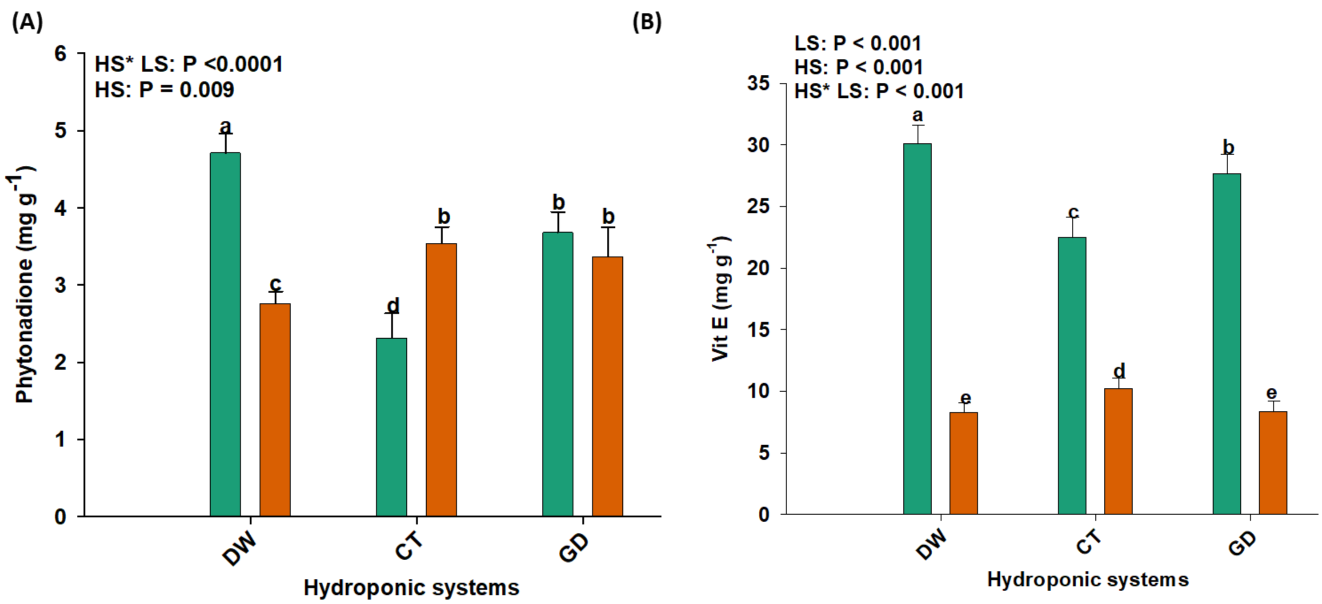

Figure 4.6: Interactive effects of light sources (LS) and hydroponic systems (HS) on (A) Phytonadione, (B) vitamin E concentration of lettuce. Vertical bars are means of three replications ±SE. Bars with different letters indicate significant differences at ($P \leq 0.05$; LSD). DW = Deep-water culture (control); CT = Christmas Tree; GD_= Green-DNA; HS = Hydroponic systems; LS = Light sources; HS x LS = interaction between hydroponic systems and light sources.

Retinol concentration was approximately 100% higher (0.11 mg g^{-1} DWT) in the GD system,compared to the CT system. The lettuce plants grown under FL light produced 66% more retinol concentration than lettuce grown under LED lights. (Fig. 4.7A). Also, vitamin D concentration was significantly higher (0.41 mg g^{-1} DWT) in the GD system, while the lowest (0.27 mg g^{-1} DWT) was observed in the CT system. Exposure of lettuce plants to LED lights triggered 42% increase in vitamin D concentration compared to FL lights (Fig. 4.7B).

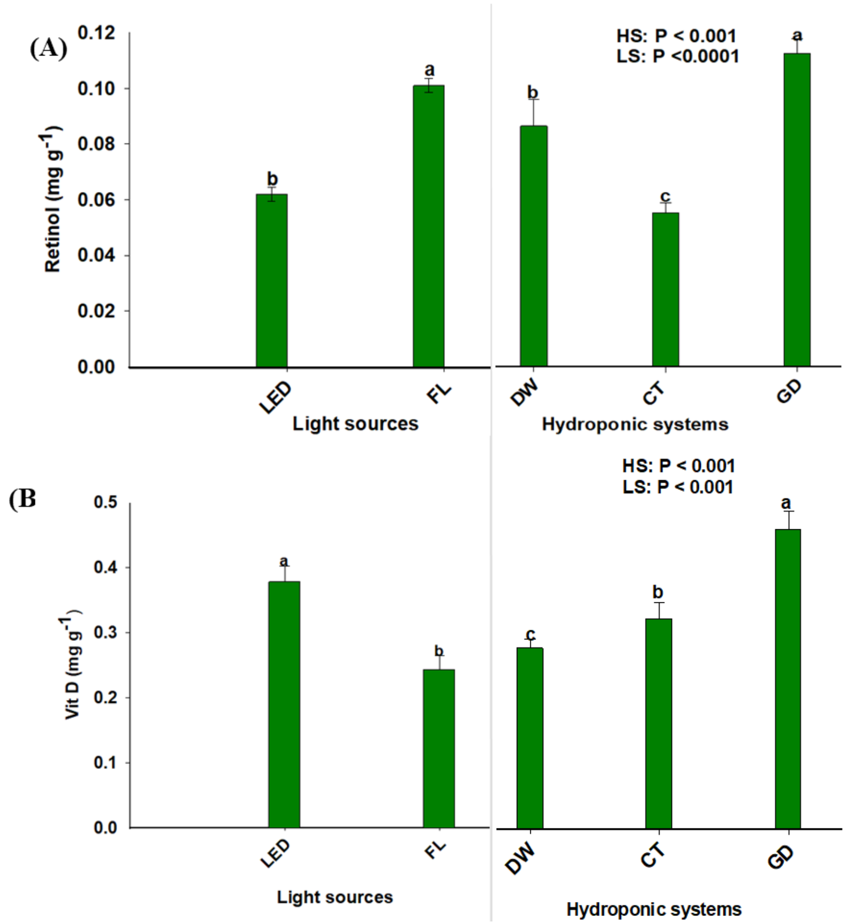

Figure 4.7: Effects of light sources (LS) on retinol concentration (A) and vitamin D concentration (B) of lettuce grown in different hydroponic systems. Vertical bars are means of three replications ±SE. Bars with different letters indicate significant differences at (LSD; P ≤ 0.05). DW = Deep–water culture (control); CT = Christmas Tree; GD = Green-DNA; HS = Hydroponic systems; LS = Light sources.

4.6.5. Mineral Concentration

Data shown in Table 4.3 indicated that HS, LS, and their interaction (HS x LS) had significant ($p<0.001$) effects on the mineral concentration of lettuce. The HS, LS, and its interactive effects had significant effects on calcium (Ca), potassium (K), magnesium (Mg), zinc (Zn), boron (B), iron (Fe), and manganese (Mn) as shown in Table 4.3.

Table 4.3: Analysis of variance and comparison of treatments means showing the effect of light emitting diodes (LED) and fluorescent light (FL) sources on the mineral element concentration of lettuce grown in different hydroponic systems.

Source of variation	Calcium (mg g^{-1})	Potassium (mg g^{-1})	Magnesium (mg g^{-1})	Zinc (µg g^{-1})	Boron (µg g^{-1})	Iron (µg g^{-1})	Manganese (µg g^{-1})
Hydroponics system (HS)							
GD	25.6±2.36a	235.82±13.11a	87.59±3.12b	11.23±1.8a	13.91±0.11c	28.56± 3.26a	4.91±1.12a
CT	23.86±1.91b	158.55±12.89b	85.96±1.88c	8.11±0.43b	20.39±0.60a	26.67 ± 2.89 b	2.64±0.88b
DW	17.85±1.82c	116.91±10.89c	95.39±3.86a	6.87±0.6c	19.37± 0.62b	15.40 ± 1.89 b	1.74±0.86c
Light sources (LS)							
LED	27.28±3.16a	178.28±5.62a	96.87±2.02a	7.83±0.98b	18.76±1.53a	25.11 ± 1.62 a	3.56±0.06a
FL	17.4±2.64b	162.98±7.37b	87.79±1.42b	9.64±0.68a	17.01±1.63b	21.98 ± 1.37 b	2.04±0.03b
HS x LS							
DWxLED	19.67±1.04d	88.23±2.55f	96.8±1.20a	3.25±0.15e	18.09 ±0.26c	28.66 ± 0.65 b	3.56±0.19b
CTxLED	33.03±1.71a	191.17±1.82c	78.5±0.86c	5.78±0.58d	21.65±0.33b	34.45 ± 0.82 a	1.79±0.06d
GDxLED	29.16±1.44b	254.57±3.13a	96.2±4.69a	7.98±0.68c	25.56±0.38a	28.45 ± 0.19 b	4.41±0.19a
DWxFL	10.56±2.74e	145.58±3.35d	92.6±2.88b	10.49±0.57b	16.36±0.45d	18.39 ± 0.20cz	1.33±0.33f
CTxFL	14.41±1.43f	125.44±4.88e	74.2±4.46d	10.44±0.76b	14.34±0.61f	18.88 ± 0.34 c	1.56±0.16c
GDxFL	15.70±0.91c	216.87±7.65b	96.6±2.32a	14.48±0.51a	14.56±0.22e	12.42 ± 0.55 d	2.19±0.32e
Significance							
HS	***	***	***	***	***	***	***
LS	***	***	***	***	***	***	***
HS x LS	***	***	***	***	***	***	***

*** represents significant differences at alpha 0.001, respectively. The values presented are means ± SE (n = 12 for HS and LS and n = 6 for HS x LS). Different letters within each column indicate significant differences among hydroponic systems, light sources, or their interaction according to Fisher's Least Significant test (two-way ANOVA, p = 0.05). DW = Deep–water culture (control); CT = Christmas Tree; GD = Green-DNA; HS = Hydroponic systems; LS = Light sources; HS x LS = Interaction between hydroponic systems and light.

The CT system with LED lights showed the highest Ca concentration (33.03 mg g^{-1} DWT), followed by the GD system with LED lights, and the lowest Ca concentration (10.56 mg g^{-1} DWT) was observed in the DW system with FL lights. Maximum (254.57 mg g^{-1} DWT) K concentration was reported in lettuce plants grown in the GD system under LED lights, followed by the GD system under the FL lights, while the lowest (88.23mg g^{-1} DWT) was observed in the DW system with LED lights. Lettuce plants grown with LEDs produced about 9% higher K concentration than in FL lights. The concentration of Mg was higher (96.8 mg g^{-1} DWT) in the lettuce grown in DW with LEDs, then statistically at par in the GD system with both LED and FL lights, while the lowest (78.5 mg g^{-1} dwt) concentration of Mg was reported in CT system with LED lights. LED lights produced a 10% higher Mg concentration than FL lights.

Interestingly, the maximum (14.48 µg g^{-1} DWT) Zn concentration was reported in lettuce plants grown in GD with FL lights, followed by the DW with FL light treatments, statistically the same as CT with the FL light treatment, while the lowest (3.25 µg g^{-1} DWT) was reported in the GD system with LED lights. The concentration of B was higher (25.56 µg g^{-1} DWT) in the GD system with LED lights treatment, followed by the CT with LED lights, and the lower (14.34 µg g^{-1} DWT) concentration was observed in the CT system with FL lights. Lettuce plants exposed to LED lights showed an increased B concentration compared to those treated with FL lights. Also, the CT system with LED indicated the highest Fe concentration of 34.45 µg g^{-1} DWT, followed by the DW system with LED treatment, while the GD system with FL had the lowest Fe concentration of 12.42 µg g^{-1} DWT. Plants subjected to LED lights exhibited a roughly 14% rise in Fe concentration compared to those subjected to FL lights. Finally, the concentration of Mn was higher (4.41 µg g^{-1} DWT) in the GD system with LED lights, followed by the DW system with LED light treatment, while the lowest (1.33 µg g^{-1} DWT) Mn concentration was observed in the DW system with FL lights.

4.7. Discussion

Plant growth is a vital biological activity that forms the basis for both environmental and agricultural productivity, which can be influenced by growing conditions and systems. However, artificial light sources have the potential to influence yield, the accumulation of vital nutrients and antioxidant content in hydroponically cultivated leafy vegetables in an indoor environment (Ohashi-Kaneko et al., 2007; Li & Kubota, 2009; Singh et al., 2019). Since leafy vegetables are grown for their leaves and sometimes stems, the growth rate is often measured by the yield, i.e., the shoot (Buxbaum et al., 2020). The LED lights enhance the growth and yield of lettuce. For instance, a study conducted by Lin et al. (2013) investigated the effects of light sources (RB LED, RBW LED, and FL) and observed that RBW LED lights showed higher yield and growth performances than those treated with FL lights, the FL's lower growth, and yield was attributed to lower light quality which may have affected light penetration to the plant's canopy which in turn led to a reduction in yield and market value because of the plant sizes. In another study, LED lights were described as a sustainable option for indoor farming as they increased yield by 1.6 times compared to the FL (Pennisi et al., 2019). In the present study, the lettuce plants grown in the GD system under LED lights produced a higher yield and number of leaves, whereas the FL lights in the CT system resulted in lower yield and lesser number of leaves of lettuce crop. This superior yield performance in the LED-treated plants may be attributed to the full spectrum, i.e., the higher luminous efficiency of PAR supplied by the LED lights. Although far-red LED (700 - 760 nm) is absorbed in small quantities, combined with visible lights in the (400 - 700nm), it may enhance photosystem II efficiency, increasing the photosynthetic rate to improve yield (Jin et al., 2021). Previous studies conducted by Choi et al. (2013) and Etae et al. (2020) evaluated light sources (LED, FL, and external electrode FL and LED bars) and observed higher growth and yield of lettuce that were cultivated under LED lights compared to the lettuce grown under FL lights. LEDs' outstanding performances may be attributed to their tailor-made spectrum, definite wavelength, and efficient energy distribution, enabling them to supply the plant's specific light energy requirement for photosynthesis (Schulze et al., 2014; Mitchell & Sheibani, 2020). The color spectral produced by the lighting source also influenced biomass accumulation. Another way to measure the success of hydroponic systems efficacy is by looking at how well plants are growing in them (Lennard & Leonard, 2006). This study showed that lettuce yield under the tested HS showed that GD > DW > CT (Fig. 4.3), i.e., varying HS used, influenced growth and yield parameters. However, the impact on plant nutritional status was minimally affected, suggesting that all three systems can be effective (Schmautz et al., 2016). The LA can serve as an accurate measure of light interception (Koester et al., 2014) necessary for photosynthesis and other biological mechanism (Man et al., 2015; Rayburn & Griggs, 2020), which are crucial determinants of plant productivity (Weraduwage et al., 2015). In the present study, the LA of lettuce grown in the hydroponic systems was pronounced (Fig. 4.2D). Higher LA was noticed in the DW system, which might be due to their constant access to nutrient-rich solutions, while the lower LA in the CT system may be directly related to the poor yield, which is further accompanied by fewer leaves and dwarf plants. This could be due to the wick's inability to distribute sufficient nutrients evenly through capillary actions (Junejo et al., 2022). The impact of light sources on chlorophyll content can be used to assess crops' nitrogen (N) status and, subsequently, their overall health (Rorie et al., 2011; Shin et al., 2013). Findings from this study showed that both HS and LS and their interaction significantly influenced the chlorophyll content of lettuce. Higher chlorophyll content was found in the DW system under LED and lowest in the CT system under FL lights. This is corroborated by a study conducted by Shin et al. (2013), who reported that the impact of light sources on lettuce leaf's chlorophyll (SPAD) value was examined using four different LEDs and FL light treatment as a control. The researchers found that SPAD values were higher in R, B, and RB LED lights compared to the FL lights, suggesting that the higher SPAD values are due to the LED light illumination in the treatments. The lower chlorophyll levels observed in the CT system, particularly under FL illumination, could be due to the passive delivery of nutrients to plants to the root zone, which inhibits the regular supply of essential elements needed for chlorophyll synthesis (Shrestha & Dunn 2010). LS can enhance lettuce's phytonutrient profile and nutrient content by affecting the absorption and accumulation of various macro and micronutrients. In a study by Choi et al. (2013), the LS employed in the research affected the phytochemical contents of lettuce plants. The white LED treatment enhanced total phenolic and flavonoid content. Research conducted by Rouphael et al. (2018) and Lei et al. (2018) suggested that some phytonutrients, including carotenoids, anthocyanins, and phenolic compounds, can be enhanced in lettuce with the use of specific LED light treatments. Findings from this study indicated that the interaction between LS and HS significantly influenced the total antioxidant and total phenolic properties of lettuce plants (Table 2). The TAA and TPC (ABTS and FRAP) were higher in lettuce crops grown under LED lights in the GD and DW systems. These findings align with Vitalie et al. (2022) work, which examined three light source variations for tomato cultivation that enhanced polyphenol and antioxidant concentrations. According to their findings, RB LEDs were more effective in stimulating the synthesis of health-enhancing compounds compared to RBG LEDs, attributable to the presence of cryptochromes responding to blue light, which may be suppressed by the presence of green light in the RGB spectrum and FL lights. Conversely, FL light failed to augment antioxidant or phenolic properties due to its high concentration of green wavelengths, which does not contribute to its synthesis. According to a greenhouse study by Samuolienė et al. (2012), supplementing lighting with LEDs can enhance baby lettuce's antioxidant properties, adding that its advantages are mostly pronounced at higher wavelengths (Ouzounis et al., 2015; Negrao et al., 2020; Bhatla & Lal, 2023). Another study by Wu et al. (2007) stated that the expression of β-carotene and antioxidant activity in pea seedlings increased significantly under R and B LED lights. Moreover, Lu et al. (2016) found that 24-hour LED lighting significantly augments the concentration of phenolic compounds in lettuce. The increased antioxidants and phenolic contents enhanced by LED lights could be related to the activation of light receptors and signaling pathways that regulate gene expression associated with various physiological processes and phenolic compound biosynthesis, leading to increased accumulation of these bioactive compounds (Zhang et al., 2019). Moreover, the observed increase in TPC and TAA in the hydroponic systems can be credited to the continual exposure of lettuce plants to nutrient solutions in both the GD and DW systems (Aires, 2018). Lettuce is widely known and grown because of its rich nutrient composition. For instance, it is a major source of vital vitamins K, A, and C (available in plants as ascorbic acids), folates, and iron and may be beta-carotene depending on the cultivar and production method (Das & Bhattacharjee, 2020). Previous studies have shown that light sources, quality, and spectra may influence lettuce's phytochemical and nutritive concentration. LED lighting allows gardeners to control the light quality and intensity, which impacts photosynthetic and transpiration rates, resulting in plant nutrient buildup (Tang et al., 2009).

The findings of the present study indicated that lettuce plants grown under LED lights supported a higher concentration of the WSVs (Fig. 4.5A-B, 4.6A-B) and FSVs (Fig. 4.4), except niacin, where FL had a higher concentration. The GD system promoted higher vitamin C, riboflavin, and folate concentrations in lettuce grown under LED lights. This may be attributed to the broader wavelength in LED light that allows uniform light distribution and the high proportion of B and R lights, which may have enhanced the vitamin C content (Bian et al., 2018). In another report, LEDs supplemented at higher wavelengths boosted baby lettuce vitamin C concentration and antioxidant capabilities (Samuolienė et al., 2012). Also, lettuce plants cultivated under exclusive exposure to blue LED light exhibited the highest concentration of vitamin C in comparison to the greenhouse condition (control) (Amoozgar et al., 2017). On the contrary, a study conducted by Xiaoli et al. (2014) using different light sources reported that a mix of B LED and FL (FLB) sources resulted in a significantly lower vitamin C, with no significant impact on the other light treatments, indicating that FL light might not be great for influencing vitamin concentration. In an exclusive FL lights research, Ohashi-Kaneko et al. (2007) investigated light qualities on lettuce plants grown under R, B, RB, and white (W) FL. Lettuce grown under B and RB light had more vitamin C than plants grown solely under white FL. Studies that compared the hydroponic method of crop production with the conventional methods reported that hydroponic production may influence nutritional qualities in leafy vegetables. For instance, hydroponic cultivation improved the levels of vitamins C and E, improving the antioxidant capacity and total phenols in basil (Sgherri et al., 2020). In the current study, the FSV concentration in the lettuce plant had vitamin E > phytonadione > vitamin D > retinol (Fig. 4.5 & 4.6). Lettuce contains essential minerals, from macro to microelements, that help maintain a healthy life. For instance, it contains N, a key component of amino acid found in protein, essential for growth and development in humans, K to help maintain proper fluid balance in the body by acting as an electrolyte, and Ca for structural support and strength. Other mineral elements include phosphorus (P), Mg, Fe, Zn, Mn, and B in varying quantities depending on several factors (Shi et al., 2022). High light intensity was reported to promote the accumulation of P, K, Ca, Mg, and Zn in lettuce, resulting in higher biomass weight. In the present study, the light sources influenced mineral composition concentration in lettuce plants. Generally, both the macro (Ca, K, Mg) and micro (B, Fe, Mn) element concentrations detected were significantly enhanced by the LED lights compared to lettuce grown in FL light, which had higher levels of Zn. FL light influenced the increased concentration of Zn by 57% compared to LED. The higher level of R and B light irradiation in the LED light wavelength may have been responsible for this enhancement (Nguyen et al.,2020). LEDs improve the mineral content in lettuce by providing an optimal light spectrum for the plant's growth and development. It can directly enhance the mineral content of the plant by facilitating the activation of enzymes related to mineral uptake at the appropriate spectrum (Li & Kubota, 2009). The outcome of the present study is in agreement with a study conducted by Shin et al. (2013), who reported that lettuce plants cultivated under LED light had higher levels of N, Ca, Mg, Mn, and Fe as compared to those under FL lights which had increased P and Mn concentrations. The enhanced concentration was more pronounced in the lettuce plants grown under R, B, and R+B LEDs. Another study conducted by Pinho et al. (2017), where five different light treatments (Four different LED ratios and 1 HPS) were investigated, reported that all macronutrients reported (N, P, K, Ca, Mg, & S) were influenced by LEDs which enhanced the nutrients uptake while the HPS had the lowest uptake. However, B uptake was significantly higher for the HPS-treated plants than the other light treatments. In addition, findings from Amoozgar et al. (2017) indicated that lettuce plants grown under R LED had an increasing effect on the concentration of K, Fe, Zn, Cu, and Mn, while Mg contents were enhanced by B+R and W LED treatments compared to the typical greenhouse-grown plants. Information regarding the impact of different hydroponic systems on the mineral elements concentration of lettuce is limited.

4.8. Conclusion

Results from this experiment indicated that lettuce plants grown with the Green-DNA (GD) system under light emitting diodes (LED) light had superior yield and higher leaf numbers compared to lettuce plants grown under the fluorescent (FL) in the Christmas tree (CT) system, which had the lowest yield, chlorophyll content, and number of leaves. The deep-water culture

(DW) system outperformed other systems through improved chlorophyll content and leaf area, whereas the lettuce grown with the CT system under the FL light had the lowest yield, chlorophyll content, and number of leaves. The GD system with LED lights promoted higher antioxidant activity, enhanced significant mineral element concentrations, and increased vitamins (C, D, E riboflavin, folate, and retinol). Meanwhile, the DW system enhanced the phenolic content of the lettuce plant in LED compared to the CT system under both LED and FL. Based on the findings, the study concludes that the lettuce grown with the GD system under the LED light produced better plant yield, growth, and quality results than the other treatments. Hence, it is suggested as a potentially ideal small-scale hydroponics system for maximum yield and robust quality for lettuce production. Further research is proposed to study the effect of vertical light sources on the yield and quality of vertical hydroponic systems under household conditions.

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Chapter 5

5.1. General Summary and Conclusions

The objectives of the present studies were:

1. To evaluate the agronomic performance of different small-scale hydroponic systems (HS) for lettuce production designed for indoor growers.

2. To investigate the impact of light intensity variation on the lettuce yield cultivated in the vertical hydroponic systems (VHS).

3. To assess the sensory attributes of lettuce grown in vertical hydroponic systems compared to the commercially available deep-water culture system (DW).

4. To determine the effects of full-spectrum light emitting diodes (LED) and fluorescent light (FL) sources on the growth and yield of lettuce plants grown under different vertical hydroponics systems.

5. To access the effect of full spectrum LED and FL sources on the phytonutrient profile of the lettuce grown in the vertical hydroponic system.

Chapter 3 evaluated the agronomic performance of two locally fabricated vertical hydroponics systems, *i.e.*, the green-DNA (GD) and the Christmas tree (CT). The commercially available DW system was used as control. Lettuce seedlings were established in the growth chamber before being transplanted into the hydroponic systems in the grow tent. Agronomic parameters such as fresh and dry weight, leaf area, chlorophyll content, plant height, and photosynthesis rate were measured to evaluate the performances of the hydroponics systems. Also, sensory analysis was conducted to determine the sensory attributes of lettuce grown and test the acceptability of the three different hydroponic systems. Findings from the study demonstrated that hydroponic systems significantly influenced lettuce yield and growth parameters. The GD system showed higher leaf area (LA) and plant height (PH) compared to the CT system, while the CT system promoted better chlorophyll synthesis. The DW system produced the highest yield, root dry weight, root-shoot ratio, and photosynthesis rates, while the CT system had the lowest values for most parameters. Light intensity is critical in plant growth, with varying levels observed across hydroponic systems and layers. The VHS exhibited significant variation in light intensity, influencing plant yield, with higher levels correlating with increased yield. Notably, the DW system yielded uniformly due to consistent light interception. In the sensory evaluation analysis, panelists preferred the flavor, leaf appearance, and size of the GD system-grown lettuce. The CT system received higher ratings for leaf color and overall preference. However, despite its higher biomass, the results from the DW system revealed that it received the lowest ratings across all sensory characteristics examined. This discrepancy could be due to the factors related to marketable qualities and the design of the hydroponic systems. The DW and GD systems performed better in yield and growth parameters, while the CT system was preferred for its visually appealing design and leaf color. Given the findings outlined above, the consistent performance of the GD system in improving lettuce yield and enhancing sensory attributes presents it as a highly promising alternative for indoor farming practices. Overall, the study highlighted the importance of optimizing hydroponic systems and light quality to maximize lettuce yield and quality. Further research is needed to explore improved lighting strategies and hydroponic system designs to enhance photosynthetic activities and yield.

Chapter 4 focused on assessing the impact of light sources on the growth, yield, and phytonutrient composition of lettuce; two varying light sources, full spectrum LED and FL, and two VHS (GD and CT systems) and the DW system as control. This study evaluated the effect of HS and light sources on the growth and yield of lettuce plants by measuring their agronomic parameters. Findings from this study indicated that lettuce plants grown with the GD system under

LED light had superior yield and higher leaf numbers compared to lettuce plants grown under the FL lights in the CT system, which had the lowest yield, chlorophyll content, and number of leaves. The DW system performed better than other systems through improved chlorophyll content and leaf area, whereas the lettuce grown with the CT system under the FL light had the lowest yield, chlorophyll content, and number of leaves. Also, some plant tissue analyses such as vitamins, total antioxidants, total phenolics, and mineral concentrations were conducted to determine the phytonutrient composition of the lettuce plant using various methods, including HPLC-MS/MS, ICP-MS, and spectrophotometry. The potential of full-spectrum LED lights to enhance lettuce growth and yield was examined, drawing on previous research to support current findings. For instance, Lin et al. (2013) demonstrated that LED lights, particularly the RBW LED variant, surpassed fluorescent (FL) lights' yield and growth performance, attributed to their superior light quality and penetration capabilities. Similarly, Pennisi et al. (2019) advocated for LED lights as a sustainable alternative, showcasing a significant increase in yield compared to FL lights. Research by Choi et al. (2013) and Etae et al. (2020) also corroborated the benefits of LED lights, attributing their success to a tailored spectrum and efficient energy distribution. LEDs' precise wavelength and efficient energy distribution allow them to meet plants' specific light energy requirements for photosynthesis, resulting in enhanced biomass accumulation. In the current study, the GD system with LED lights promoted higher antioxidant activity, enhanced significant mineral element concentrations, and increased vitamins (C, D, E riboflavin, folate, and retinol). Meanwhile, the DW system enhanced the phenolic content of the lettuce plant in LED compared to the CT system under both LED and FL. This superiority of LED-grown plants can be attributed to the full wavelength spectrum and higher luminous efficiency of photosynthetically active radiation (PAR) supplied by LED lights. Therefore, the lettuce grown with the GD system under the LED light produced better plant growth, yield, and enhanced the phytonutrient composition compared to the other treatments.

Additionally. this study provided strong evidence that full-spectrum LED light can be used as a reliable light source to enhance the growth, yield, and phytonutrients of hydroponically grown vegetables in an indoor environment. Overall, the study highlights the significant role of LED lights in enhancing lettuce growth, yield, and nutritional quality in hydroponic systems. By providing tailored light spectra and efficient energy distribution, LED lights offer a sustainable solution for indoor farming, with implications for improving food security and nutritional outcomes.

5.2. Recommendations

There are limitations to the outcome of this study since it was not tested in the household condition for which it was initially designed. Therefore, further is recommended:

1. To evaluate the performance of the VHS for the cultivation of leafy vegetables in a household condition

2. To maximize yield in VHS, introduce inter/intra lighting to lower levels of the vertical system to enhance light penetration and improve photosynthetic activities and plant quality.

3. To provide a vertical lighting source to plants grown in the VHS rather than horizontal lighting to optimize yield.

4. To improve the VHS's design and fabrication method to increase market acceptability.

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