

Evaluate the postharvest quality of romaine lettuce grown in a UV-treated hydroponic system

by

Sachin Adhikari

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Approved by:

Major Professor
Dr. Eleni D. Pliakoni

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Abstract

Romaine lettuce, a highly nutritious leafy vegetable widely consumed due to increasing consumer interest in healthy eating. To meet this demand, hydroponic systems, especially deep-water culture (DWC), offer sustainable and efficient alternatives to conventional agriculture because of their rapid growth, high planting density, and energy efficiency. Hydroponically grown lettuce provides superior food safety benefits due to the lower concentration of microorganisms than soil-grown lettuce; however, human-borne pathogen contamination is still possible. Once the hydroponic nutrient solution is contaminated, it spreads rapidly throughout the system and cross-contaminates in the edible parts of the leaves. Ultraviolet (UV) light treatment at the wavelength of 254 nm can provide alternative means for pathogen sterilization in water; however, its effect on produce quality remains unclear. The objective of this study was to investigate the impact of high and low-dose UV-C treated nutrient solutions in a DWC hydroponic system on the harvest and storage quality of romaine lettuce. The quality was evaluated based on the parameters below: leaf length, fresh weight, dry root weight, water loss, SPAD, color, texture, visual quality, respiration rate, macro and micro-nutrients, and Vitamin C. Results suggested that lettuce grown in the nutrient solution that was treated with low-dose UV-C treatment had a significantly longer leaf compared to the non-treated lettuce and significantly higher fresh shoot weight compared to both the high-dose UV-C treated and non-treated lettuce. There were no significant effects on the dry root weight between the treatments. Moreover, lettuce treated with UV-C did not impact water loss, SPAD value, texture, color, and during storage. On the other hand, lettuce grown in a nutrient solution that was treated with UV-C, especially with the high-doses, highlighted significantly better visual quality than non-treated lettuce. Furthermore, lettuce that was grown in the nutrient solution that was treated with low-dose UV-C appeared to have significantly higher Vitamin C levels than lettuce treated with the high-dose of UV-C. This study suggests that application of low-dose UV-C in the nutrient solution of hydroponic grown lettuce could enhance the harvest and storage quality of the crop.

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Chapter 1 - Review of literature

An overview of lettuce production, trends, and nutritional significance in modern agriculture

Lettuce (*Lactuca sativa* L.) is a vegetable grown commercially in moderate climates worldwide (Peng & Simko, 2023). It belongs to the Asteraceae family and is considered one of the most valuable crops compared to other different vegetables grown in the United States (Sapkota et al., 2019). Various lettuce cultivars are available, which can be classified according to the plant and leaf phenotype, such as romaine, iceberg, leaf, Latin, butterhead, stem, and oilseed. Generally, iceberg (*L. sativa* L. var. *capitata* L.), romaine (*L. sativa* L. var. *Longifolia* L.), and leaf (*L. sativa* L. var. *crispa* L.) are the main lettuce cultivars that are found in North America for consumption (Simko et al., 2014). Romaine lettuce is rich in beneficial nutrients and phytochemicals, including antioxidants, fiber, and vitamins (Alemán-Hidalgo et al., 2024). Seeds and stems of lettuce are extracted for edible oil and dried latex (Hassan et al., 2021). Lettuce is one of the top 10 most consumed vegetables in the US (Sandoya et al., 2024), valued at over \$ 2.4 billion annually (Reyes-Chin-Wo et al., 2017). The US holds the second position worldwide as a lettuce producer, just after China (Food and Agriculture Organization of the United Nations, 2021). In the US, iceberg lettuce dominated production until the 1990s, but demand for romaine lettuce in the market changed this dynamic (Sandoya et al., 2024). This change is due to consumer awareness of its higher nutritional value than iceberg lettuce (Mou & Ryder, 2004) and the increased popularity of “Caesar salad” (Sandoya et al., 2024).

California is the largest hub for lettuce production in the US (Sandoya et al., 2024). Most lettuce crops are grown in temperate coastal regions of California, such as the Salinas and Santa Maria valleys, which can be produced year-round (Simko et al., 2014). In the Southwest of the US, such as Yuma, Arizona, and nearby low desert areas produced, most of the winter lettuce and other cool-season vegetables (French et al., 2024). In Yuma, a \$730 million transaction occurred from vegetable crops where lettuce became the primary contributor to the market (French et al., 2024; USDA NASS, 2021). Farmers involved in lettuce cultivation obtained almost one-fifth of the overall \$21.8 billion in sales from US farms through vegetables and melons, with romaine

lettuce generating \$1.54 billion, iceberg lettuce \$1.33 billion, and leaf lettuce \$1.25 billion (USDA, 2023).

Lettuce can be grown as a field crop, in a greenhouse, or in hydroponics and can be grown indoors vertically (Damerum et al., 2020a). In hydroponics, lettuce can be harvested around 20 days after sowing (Kozai, 2018). Lettuce has a short growth cycle that allows for high planting density, quick growth, and lesser resource requirements Bantis et al. (2018) and Zhang et al. (2018). The ideal temperature range for lettuce production is between 17 to 28 °C during the daytime, while the ideal temperature ranges from 3 to 12 °C at night. It is a semi-cool crop susceptible to physiological issues such as tip burn, bolting, and discoloration. It can also develop loose and swollen heads when exposed to higher temperatures. Exposure to lower temperatures will cause slower growth, or even plants can die. The ideal EC (mS/cm) for lettuce production is 1.2 to 1.8, and the perfect pH range is 6.0 to 7.0 (Hardeep Singh; Bruce Dunn, 2017).

Need for hydroponics production

The world is facing serious challenges in the 21st century for feeding the world due to the rapid population growth (Maisonet-Guzman, 2011). The predicted growing population in the world from 2018 to 2050 will be 1.7 billion (Prosekov & Ivanova, 2018), which will reach 9.7 billion in total (United Nations Department of Economic and Social, 2024). Therefore, food production will need to expand by 70% to meet the expected population growth (Hunter et al., 2017). At the same time, there is rapid decline of arable land, soil degradation, and climate change (Wang et al., 2019; Webb et al., 2017). To meet the increasing demand for food, it is necessary to explore alternatives to the agricultural system. These worldwide issues can be addressed by hydroponic farming which has potential to produce crops within limited land and resources (Murali et al., 2011).

Hydroponics is the method of growing plants in nutrient-rich solution without soil. Various chemically inert substrates, including sand, gravel, or water, are used to grow plants with the addition of nutrients (Douglas, 1975; Savvas, 2003). This technique provides control over water, nutrients and light exposure based on the requirements for growth and development of the plants (Resh, 2013). Hydroponically grown crops often have higher yields, improved flavors and

enhanced bioactive compounds than soil-grown crops (Jan et al., 2020). It also offers suitable options for crop production even in unfavorable climates where temperate lettuce, herbs, and other crops, which may not be available due to the climatic limitations (Wattanapreechanon & Sukprasert, 2016). It uses 90% less water for crop production, reduces the need for pesticides, and supports year-round crop production (Vikanksha & Singh, 2023).

There are several factors which contribute to the increasing adaption of hydroponics worldwide. Traditional agriculture faces major problem during crop production due to water scarcity, degraded soil, and climate change (Lipper et al., 2014). Rapidly growing populations worldwide further increase the demand for hydroponics to have efficient and sustainable food production method (Xie, 2019).

The global hydroponic market has increased significantly in the past and is predicted to expand considerably in the coming years. (Ballabh et al., 2022).Recent studies predicted that the market will increase by 20.7% from 2021 to 2028 (Guerrero & Barbieri, 2023) and 12.4% between 2024 and 2030 (Grand View Research, 2024).In 2023, the global hydroponics market was estimated at a value of USD 5 billion (Grand View Research, 2024a), which is expected to reach 9.8 billion by 2028 (Guerrero & Barbieri, 2023). By region, Asia-Pacific dominated the hydroponics market in 2023, which contributed 35% toward the overall revenue due to vast consumption in countries such as China, Australia, and South Korea (Grand View Research 2024). In the European Union, France, Spain, and the Netherlands are the top three hydroponics producers (Ballabh et al., 2022). The United States also increased its dominance in the hydroponic market, was valued approximately at 506.25 million dollars in 2023, which may further rise at a compound annual growth rate (CAGR) of 10.7% between the year 2024 to 2030 (Grand View Research (2024b).

Hydroponics shows promising solutions to address the challenges faced by millions worldwide that were observed in conventional agriculture, such as food security, water scarcity and land limitations (Ballabh et al., 2022; Naresh et al., 2024; Trejo-Téllez & Gómez-Merino, 2012). Hydroponics enable crops to grow more efficiently with the less use of water and land which makes it a viable option for sustainable crop production (Rajaseger et al., 2023). Although hydroponics is adopted mainly in developed countries, it shows high potential in underdeveloped countries to improve food security and reduce the dependency on conventional agriculture (Souza

et al., 2019). Even though hydroponic contributes to addressing global challenges, further research is needed to enhance the efficiency, suitability, and affordability of hydroponic systems for farmers worldwide. Governments, research institutions, and private sectors need to collaborate for investment in research, development and policies to boost hydroponic expansion.

Urban food system and hydroponics

The conventional food production system and distribution practices negatively affect the environment, including biodiversity loss, climate change, freshwater pollution, deforestation, and excess nutrient accumulation (Jaramillo & Destouni, 2015; Lenka et al., 2015). The world is facing rapid population growth and urbanization, which increases various challenges to urban areas, such as land scarcity, inflation of foods, and environmental degradation, which negatively impact the urban food system (Gulyas & Edmondson, 2021). In 2018, 55% of global population was lived in urban areas which is projected to increase to 68% by 2050 (UN DESA, 2018). To solve the problem of food security for long-term sustainability, experts have called for an urban food system (UFS) to be conceptualized more at a localized level (Matacena, 2016). Currently, UFS is highly dependent on industrialized food supply, which has global food sources (Forster et al., 2015; Vieira et al., 2018). Due to the dependence on the global food supply, the urban food system increases high levels of waste and contributes to greenhouse gases through the supply chain (Food, 2015; Goldstein et al., 2016).

Urban agriculture (UA) has emerged to help address food security in densely populated areas such as cities (Jones, 2002). Urban agriculture involves crop production, animal raising, and fish farming within the cities or nearby, including non-food production such as flowers, trees, and pot plants (Weidner et al., 2019). Similarly, it also involves the processing and marketing these products (Yuan et al., 2022). Urban agriculture is done on different scales, such as small commercial farms, community gardens, and individual backyard gardens, including balconies, rooftops, and decks (whyhunger, 2013).

Urban agriculture encourages local food production in cities and sub-urban areas by creating green spaces, such as backyard gardens, and providing families with low-cost options to improve their diets and generate income by selling surplus food (Coelho et al., 2018). According to Jones

(2002), urban agriculture can improve food security by strengthening supply chains, shortening transportation distances, and reducing greenhouse gas (GHG) emissions.

Although urban agriculture has several benefits, it faces several challenges as mentioned earlier, especially, limited land space, polluted soil, expensive land costs, and limited water for agriculture (Achard, 2023). Hydroponic technology can overcome this limitation by producing higher yields of crops in limited space, such as apartments, houses, and rooftops (Talib et al., 2018). Hydroponics in urban areas promotes local food production, reduces food milage, and improves access to fresh and nutritious food in urban communities (Rajaseger et al., 2023). Additionally, hydroponics is generally done indoors, which can address soil contamination, unpredictable climate, pests and diseases, water scarcity, etc., that are frequently seen in open-field agriculture (Sardare & Admane, 2013). Hydroponics can shape urban food systems by providing sustainable food production without harming the environment (Velazquez-Gonzalez et al., 2022).

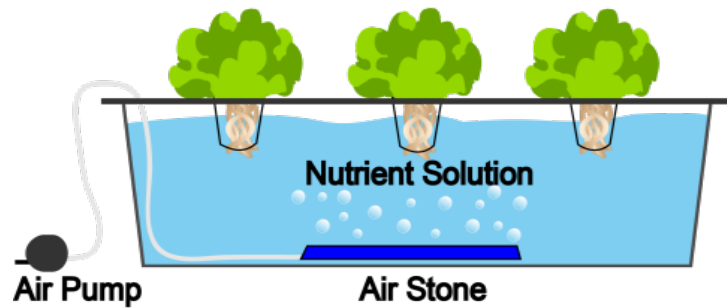
Different types of hydroponics systems

There are various types of hydroponic systems that are classified based on mode of delivery of water, nutrients, and oxygen to plants. Each hydroponic system has some unique benefits and limitations. Hence, understanding the differences between the systems is necessary for selecting the most appropriate method for specific crops and production targets.

Table 1. Types of hydroponics systems with their advantages and disadvantages and plants grown in each system.

Types of Hydroponic system	Description
1. Deepwater culture (DWC)	

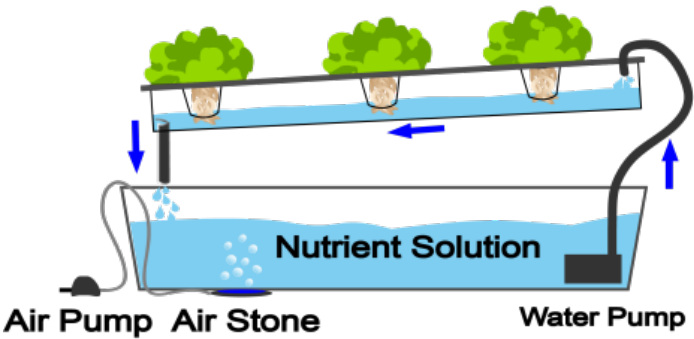
Deep Water Culture (DWC)



Deep water culture is a method where a plant's roots are suspended in the nutrient solution stored in a container, and air is provided directly to the roots with the help of an air stone or diffuser (Aires et al., 2023). It was developed due to the need for improvements in aeration methods for maintaining dissolved oxygen, which consists of a reservoir, air stone, tubing, pump, and floating platform (Hoagland & Arnon, 1938). A floating platform supports plants or pots in a reservoir, with roots immersed in water or nutritional solution and oxygen supplied by an air pump and air stone (Saaïd et al., 2013). It is suitable for most plants but best for big root systems (NoSoilSolutions, 2023). Monitoring oxygen, nutrients, pH, and salt levels is crucial to prevent mold and algae growth in the reservoir (Domingues et al., 2012; Sharma et al., 2018).

Advantage:

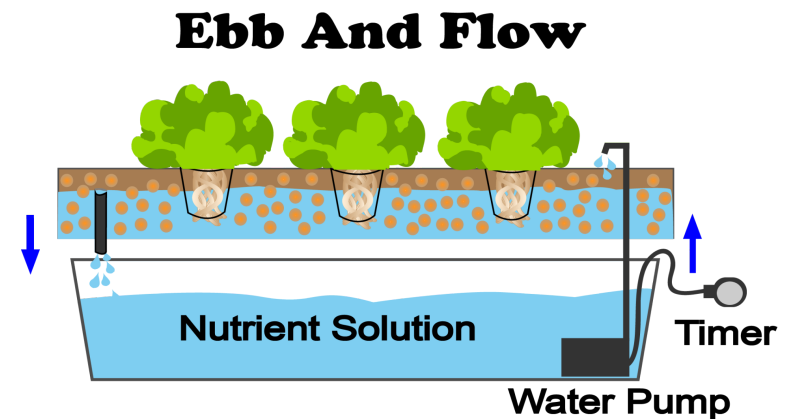
DWC is relatively cheaper to set than other systems, which can be built in different sizes. It can provide depth ranges from 15 to 30 cm. This system keeps nutrient concentrations, temperature, and pH more stable because each plant can access a large amount of nutrient solution. Also, DWC needs less maintenance, and a small DWC system is the best option for small-scale growers (Niu & Masabni, 2022) and ideal for larger fruit-producing plants such as cucumber, etc. (Ballabh et al., 2022).

	<u>Disadvantage:</u> Plants are prone to root diseases, and root mass can grow huge, which can obstruct irrigation cavities, etc. (Grigas et al., 2020). <u>Specific plants:</u> Leafy greens, herbs, and plants with larger roots, such as tomatoes, cucumbers, and peppers (Niu & Masabni, 2022; H. Singh et al., 2019).
2. Nutrient Film Technique (NFT)	Nutrient Film Technique  The nutrient film technique is a popular and widely used hydroponic system. Dr. Alen Cooper developed this hydroponic system in the mid-1960s in England to overcome the problems seen in the ebb and flow system. The nutrient solution is pumped constantly, which flows into channels that can hold different numbers of plants in NFT hydroponic systems (Ballabh et al., 2022; Domingues et al., 2012). When the nutrient solution reaches the end of the channels after passing through the hanging roots of the plants, it is returned to the hydroponic reservoir because of the slight slope of the channels. Grow media is rarely used in NFT hydroponic systems; alternatively, foam net pot inserts are usually utilized to hold the plant in place. <u>Advantage:</u> It is ideal for vertical farming, reduces the need for growing media, and enhanced aeration (McCandless, 2024). There is a constant flow of water in this

	system where the chance of clogging is rare, and the cost of nutrient solution is also low due to the recirculation (Grigas et al., 2020). <u>Disadvantage:</u> NFT is expensive compared to DWC hydroponic system_(Growee, 2025). It is only ideal for plants with little roots, such as leafy greens, because of the size of the channels (Jan et al., 2020; Macwan et al., 2020; NoSoilSolutions, 2023). Additionally, it is sensitive to temperature fluctuations, and system failure risk (Rajaseger et al., 2023). <u>Specific plants:</u> Leafy greens, herbs, strawberries, beans, radish, and cucumber (Rajaseger et al., 2023; Warrington, 2019).
3. Drip system	In this system, water or nutrient solutions are delivered to each plant by using the pump with an electronic timer (Rouphael & Colla, 2005). The drip system

	slowly dispenses nutrients through small nozzles where excess solutions are collected in a reservoir and again recirculated or even allowed to drain out. With this technology, various plant varieties can be grown simultaneously (Jan et al., 2020). The drip system can be divided into two models, i.e., recovery and non-recovery (Saaïd et al., 2013). In the recovery system, water is collected, returned to the reservoir, and then circulated through the system (Schröder & Lieth, 2002). A non-recovery hydroponics drip system allows the used nutrient solution to drain away waste after passing through the crops. So, it is crucial to monitor nutrient solutions or water frequently in the reservoir to ensure the availability of nutrient solutions for plants (Santamaria et al., 2003).
	<u>Advantage:</u> The drip cycle refreshes the growing media by delivering fresh nutrients, water, and oxygen to the plants (Khan et al., 2020; Kumar & Singh, 2023).
	<u>Disadvantage:</u> The major issue in the drip system is the clogging of drip emitters. Additionally, there is waste of nutrient solutions with the non-recovering system (Adelmann, 2023).
	<u>Specific plants:</u> Vegetables, fruits, herbs, and flowering plants (Rajaseger et al., 2023).

4. Ebb and flow system



The ebb and flow system was the first hydroponic system that uses automatic and periodic floods and drains the plant roots with nutrient-rich solutions (Buwalda et al., 1993; Jan et al., 2020). A timer-controlled pump delivers a nutrient solution to the growth tray, which is later drained back into the reservoir for recycling, conserving, and nutrients while reducing negative environmental impacts (Dong et al., 2020).

Advantage:

The ebb and flow system can promote seedling growth and root development. It is a promising method to enhance water use efficiency, prevent waterlogging or drought, and support overall vegetable crop growth (Wang et al., 2022). Ebb and flow systems lower labor costs by removing the need for hand watering and decreasing foliar diseases by keeping the leaves dry (Dong et al., 2020). Despite their advantages, recirculating ebb and flow systems pose a risk of spreading plant pathogens (Sanogo & Moorman, 1993).

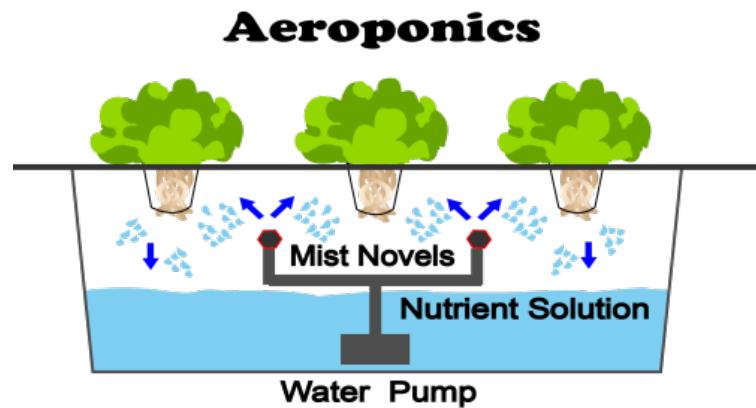
Disadvantage:

Plants are prone to root diseases (Miyake et al., 2014).

Specific plants:

	Lettuce, spinach, tomatoes, cucumbers, peppers, strawberries, radish (Rajaseger et al., 2023).
5. Wick system	The wick system is a hydroponic method that requires no electricity, pumps, or aerators. It is the only type of hydroponic system that may be passive (Ballabh et al., 2022; Shrestha & Dunn, 2017). In most systems, plants are planted in an absorbent grow media such as coco coir, vermiculite, or perlite, with a nylon "wick" leading from the plants to a nutrient reservoir (NoSoilSolutions, 2023). <u>Advantage:</u> According to Ferrarezi & Testezlaf (2016), the wick or passive system is a cost-effective technique that relies on the capillary capacity of plants to absorb nutrients rather than recycling the solution. This technique is best suited for small-scale production (Lee & Lee, 2015a). <u>Disadvantage:</u> This system is not recommended for crops with longer lifecycles (Lee & Lee, 2015a). <u>Specific plants:</u> Leafy greens, herbs, and strawberries (McCandless, 2023).

6. Aeroponics



Aeroponics is a method that grows plants by suspending their root system in a closed chamber, where they are nourished with a fine mist of nutrient-rich solution (Lee & Lee, 2015a; Q. Li et al., 2018). Aeroponics promotes plant growth by providing an oxygen-rich atmosphere with changeable root-zone conditions via a gas delivery system (Kratsch et al., 2006). Aeroponic is essential in plant physiology research but is less commonly used for commercial purposes (S. Lee & Lee, 2015a; Resh, 2022).

Advantage:

Aeroponics can provide sufficient oxygen to plant roots and use nutrients efficiently (Rajaseger et al., 2023). It can produce a high number of mini-tubers in a single generation, allowing for successive harvesting while eliminating field production, lowering costs, and saving time (Buckseth et al., 2016). Aeroponics has shown significant success in seed potato production, especially in the regions like China, Korea, South America, and Africa in recent years (Buckseth et al., 2016; Chiipanthenga et al., 2012; Mateus-Rodriguez et al., 2013; Tierno et al., 2014).

Disadvantage:

This system is expensive for installation and maintenance compared to other system, while timely maintenance is crucial because partial failure in the system can cause damage to plants easily (Lee & Lee, 2015a). Additionally, there is a risk of root drying (Rajaseger et al., 2023).

	<u>Specific plants:</u> Leafy greens, cucumbers, tomatoes, herbs, capsicum, cauliflower, chili, strawberries, potatoes, and flowers (Li et al., 2018; Rajaseger et al., 2023) but this method is generally suited for crops where the roots themselves are harvested product (Li et al., 2018).
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Pictures of different types of hydroponics (NoSoilSolutions, 2023)

Lettuce production in hydroponics

Lettuce is one of the popular leafy vegetables mostly grown in a hydroponic system, where looseleaf, butterhead, and romaine are the common types grown hydroponically (Kaiser, 2016). Hydroponic lettuce holds higher market value than soil-grown lettuce, which can be sold at up to 40% higher prices and significantly reduce waste as its leaves are 99% marketable (Aires, 2018; Barbosa et al., 2015). This could be the reason for the highly profitable and sustainable choice for commercial production.

Hydroponic systems offer significant benefits in yields and resource efficiency compared to soil-grown systems. According to Barbosa et al. (2015), the hydroponic system yields 41 ± 6.1 kg/m² per year, which is 11 times higher than soil-grown lettuce at 3.9 ± 0.21 kg/m² per year. Furthermore, hydroponic lettuce uses water at 20 ± 3.8 L/kg per year, compared to soil-grown lettuce with consumption of 250 ± 25 L/kg per year, which shows 12 times lessen in water usage. Hydroponically grown lettuce not only improves the yield but also offers better quality in term of color, texture, appearance and nutritional content, making it more attractive to consumers (Ballabh et al., 2022; Mehra et al., 2017).

Hydroponics ensure safe lettuce production with consistent growth, which shows uniform and high-quality products (Frasetya et al., 2021; Hopkinson & Harris, 2019). Hydroponically grown lettuce exhibited improved physical characteristics such as longer roots, higher moisture content, reduced ash levels, softer leaves, and firmer midribs, leads to improvements in texture and appearance (Lei & Engeseth, 2021). Similarly, hydroponics offers superior food safety

benefits as it is done in a controlled and soilless environment, and the risk of microbial contamination is significantly lower (Sirsat & Neal, 2013). Hydroponic systems provide further advantages as it has the ability to minimize risks linked with natural disasters such as high-temperature variations, prolonged rainfall, drought, and storms, allowing year-round production (Jenkins et al., 2015).

Food Safety in Hydroponics

Challenges to safe production

In the past few years, fruits and vegetables have played a massive role in foodborne disease outbreaks (Bennett et al., 2018), especially leafy greens, which are usually eaten raw, increase the possibility of transferring foodborne illness compared to cooked vegetables (Uyttendaele et al., 2015). Over the last 10 years, there was also an increment of foodborne illnesses, which became crucial for food safety (Taban & Halkman, 2011). Between 2010 and 2020, there were 66 outbreaks, 2,032 illnesses, 580 hospitalizations, and 15 deaths occurred which were linked with leafy greens contaminated by *Salmonella enterica*, *Listeria monocytogenes*, and *Escherichia coli* strains that produce Shiga toxin (Dorick et al., 2024). In 2020, FDA, CDC, state and local partners investigated a multistate outbreak of *E. coli* O157:H7 linked with leafy greens which causes 40 illnesses and 20 hospitalizations, but they could not figure out which type of leafy greens was responsible (FDA, 2022b). Between 2008 to 2018 in Canada, there were 11 *E. coli* O157:H7 outbreaks linked to leafy greens where seven cases were associated to romaine lettuce, two cases were associated to iceberg lettuce and two cases were associated to other leafy greens (Coulombe et al., 2020). Similarly, there were several other recalls and some outbreaks associated with leafy greens and microgreens in controlled environment agriculture (CEA) caused by pathogens such as *L. monocytogenes*, and *Salmonella* (Topalcengiz et al., 2024).

While several recalls and foodborne outbreaks have been reported in CEA, it increases threats to hydroponics productions. The most common type of bacterial genus found in fresh produce samples that growing in hydroponic farming systems was *Pseudomonas*, while *Proteobacteria*, *Actinobacteria*, *Cyanobacteria*, *Bacteroidetes*, and *Firmicutes* were predominant bacterial phyla (Dong & Feng, 2022). Moreover, various spoilage bacteria and potential human and plant

pathogens, such as *Pseudomonas* and *Clostridium* species, are found during microgreen production in hydroponic farms (Dong & Feng, 2022). Pathogens like *Salmonella* Typhimurium and *Listeria monocytogenes* can live in a hydroponic system throughout lettuce production until harvest (Ilic et al., 2022). They can easily cross-contaminate edible leafy vegetables, resulting in crop loss for the producers. If ignored or unnoticed, it may cause an outbreak that causes illness to consumers, leading to the necessity for further investigation of innovative methods to reduce risks (Ilic et al., 2022). An investigation confirmed that the *Salmonella* Typhimurium outbreak in the summer of 2021 was associated with leafy greens such as baby spinach and lettuce in hydroponics with a controlled environment, but an actual source of contamination is still unknown (FDA, 2022a). It is hypothesized that ineffective water treatment, poor storage of growth media, and insufficient equipment sanitation could be the possible source of contamination (FDA, 2022a). Although CEA physically prevents contaminations from external sources such as stormwater, soil, dust, animals, and improper management, it still has a possibility of microbial contamination (Orozco et al., 2008).

Among the various sources of contamination in hydroponics, water quality is crucial to ensure food safety. Municipal or desalinated tap water is of high quality and has less risk of human pathogen contamination. In contrast, the use of untreated surface water, groundwater, and moderately treated reclaimed water can lead to contamination, which increases the risk to human health (Uyttendaele et al., 2015; Allende & Monaghan, 2015; Gurtler & Gibson, 2022; Park et al., 2012). Therefore, hydroponics businesses should improve water quality, follow rules and regulations, handling procedures, and constant monitoring to protect consumer health (Mario E. Díaz Rivera, 2015).

Potential solutions to enhance food safety issues in hydroponics

Educating the growers with good agricultural practices (GAPS) can empower them to implement effective food safety measures, such as proper sanitation, temperature control, and microbial monitoring (Schmit et al., 2020). Maintaining strict hygiene inside the hydroponic facilities that can significantly reduce pathogen-related risks to a manageable level (Alsanius & Wohanka, 2019; Vallance et al., 2009).

To further enhance microbial safety, there are various methods that can be carried out. Plant growth-promoting bacteria (PGBG) can be used as biocontrol agents which can suppress pathogens by competing with pathogens, producing antibiotics, and stimulating plant defenses (Beneduzi et al., 2012; Compant et al., 2005; Velivelli et al., 2014). Heat treatment can also disinfect microbial contaminations in water by raising temperature levels. This process is generally associated with the denaturation of proteins and enzymes, which are necessary for the microbial survival and lead to cell death (Nastouli et al., 2022). Furthermore, one of the most common methods for water disinfection is the use of chlorine (Rozman et al., 2022). For example, research conducted by Mensah et al. (2024) found that application of SaniDate 12.0 (200 ppm) in nutrient solutions sterilizes *Salmonella* Typhimurium in hydroponic system.

Among various strategies, ultraviolet (UV) radiation is popular method of improving food safety. UV light irradiation at 254 nm effectively disinfect various types of human pathogens present in water (Saguti et al., 2022). Studies have shown that UV radiation decreased *Salmonella enterica* contamination in lettuce (Lippman et al., 2020). In addition, another study found that UV-C can prevent the attachment and growth of *L. monocytogenes* on lettuce leaves, which makes it a potential tool for improving food safety in the fresh produce industry (Kyerere et al., 2021). Research conducted by Lee et al. (2015), observed that application of UV-C dose of 1440 mJ/cm² decreases the growth and development of algae and biofilm in water reservoirs, ultimately expanding the life of hydroponic systems.

Impact of UV treatment on water microorganisms

UV light and its potential benefits for water disinfection

Ultraviolet (UV) lights were designed to mimic sunlight by releasing electromagnetic radiation with wavelengths shorter than visible light but longer than X-rays (Light Tech, 2023). UV light exists between 10 to 400 nm wavelengths and is divided into four types. UV-A (315-400 nm), UV-B (280-315 nm), UV-C (200-280 nm), and VUV (100-200 nm) are the different kinds of UV light that are found in present times. (Chawla et al., 2021; Rajkhowa, 2020; Rangel et al., 2022). Among them, UV-C light is widely known for its germicidal effect on microorganisms and is used for water disinfection (EPA, 2003).

UV radiation is a nonthermal, chemical-free, and cost-effective alternative to thermal treatments and chemical sanitizers (Jeon & Ha, 2018; Kai et al., 2016; G. Li et al., 2017). It is capable of disinfecting bacteria, viruses, and protozoa without changing the chemical composition of water (Lay, 1992). UV radiations help to break down microbial DNA, affect pyrimidines in DNA, and lead to cell death. These effects damage the DNA double helix and interfere with metabolic processes (Goto et al., 2015; Lopez-Malo & Palou, 2005; Yokoyama & Mizutani, 2014). For optimal treatment, UV light is generally emitted at the wavelength of 254 nm using mercury vapor lamps enclosed in quartz sleeves to increase efficiency (Moran, 2018a).

UV light was used in the early 1900s for the first time to disinfect water, but it was later replaced by chlorination due to its lower cost and reliability (Rajkhowa, 2020). UV light gained popularity in the 1990s among drinking water industries when scientists found that *Cryptosporidium* could be inactivated successfully even with extremely low doses (Bukhari et al., 1999; Choi & Choi, 2010; Clancy et al., 2000). In recent years, several commercially available water purifiers combined UV light with filtration and recirculating systems for water purifying (Rajkhowa, 2020). Various pharmaceutical, beverage, electronics, cosmetic, and wastewater treatment industries also use this UV technology (Rajkhowa, 2020). It is essential in addressing global water quality, especially in developing countries and rural regions facing unsafe water problems (Kai et al., 2016).

The use of UV-C light reduces the bacteria counts by over 99% for various pathogens, including *E. coli* and *Staphylococcus albus* (Madhumitha & Muralidharan, 2021; L. Song et al., 2020). Several studies found that UV irradiation can lower overall coliform and aerobic counts (APCs) in hydroponic nutrient solutions (Arthur et al., 2024; D. Li et al., 2019). The inactivation of bacteria depends upon the doses (mJ/cm^2) of UV light, where higher doses show better inactivation (Li et al., 2022). 22 mJ/cm^2 of UV dose can inactivate *Cryptosporidium* and *Giardia* while 186 mJ/cm^2 of UV dose is required for inactivating virus (US EPA, 2006). Saguti et al. (2022) reported that 40 mJ/cm^2 UV dose can inactivate bacteria, parasites, and bacteriophages with single-stranded genomes which may not be enough to inactivate all human pathogenic viruses. Similarly, a higher UV dose of 60 mJ/cm^2 can significantly inactivate the viruses with double-stranded genomes (Saguti et al., 2022). The effectiveness of UV-C light depends upon the damage to microorganisms' cytoplasm and cell membranes. For example, adenoviruses require four times higher doses of UV light than echovirus and poliovirus for effective sterilization (Beck et al., 2017). UV radiation is

essential in sterilizing water and wastewater without producing disinfection by-products (DBPs) or other residues of chemicals. UV light is better and trustable than chlorine and chloramine for water sterilization because it has a broad diversity of inactivation (Afriani & Sulistiyani, 2020). These days, UV treatment is seen as an effective way to reduce the presence of pathogenic microbes in hydroponic systems (Wang et al., 2024).

Challenges faced by UV light during water disinfection

UV light is a promising method for sterilizing harmful pathogens, but it still faces several challenges that affect its efficacy (Usaga, 2022). One of the main issues is water turbidity, which lowers the effectiveness of UV treatment (Jones et al., 2014; Usaga, 2022). Water with higher turbidity absorbs the UV radiation that reacts with other substances and scatters the UV light, ultimately lowering its ability to inactivate microorganisms (Adhikari et al., 2020; Whitby, 2012). The presence of dissolved ions and compounds like manganese or iron in water may interfere with the effectiveness of UV light (Moran, 2018b). The other crucial challenge is variability in the susceptibility of microorganisms towards UV radiation. Research has shown that Gram-positive bacteria, such as *Clavibacter michiganensis*, show more excellent UV light resistance than Gram-negative bacteria (Jones et al., 2014). Viruses like adenovirus, which has Double-stranded DNA (dsDNA), are more resistant to UV radiation compared to single-stranded RNA (ssRNA) and (ssDNA) viruses (Saguti et al., 2022). Natural organic matter (NOM) present in water, such as humic acids, creates a protective environment for microorganisms by shielding them against UV radiation and lowers its effectiveness (Duan & Batchelor, 2014; Vilhunen et al., 2009). Microorganisms, sometimes, can repair and may reverse UV-C induced DNA damage through two mechanisms: photoreactivation (requires light) and dark repair (occurs without light). In photoreactive mechanisms, there is the formation of complex between photoreactive enzymes (PRE) and dimer, and PRE uses light to fix the damaged DNA (Salcedo et al., 2007).

Effects of UV treatments on beneficial bacteria in hydroponic systems

UV-C treatment is gaining popularity as an effective method for disinfecting harmful microorganisms in hydroponics nutrient solutions (de Almeida et al., 2022; Government of

Western Australia, 2022; Perez et al., 2024). Although it is beneficial in inactivating pathogens, it can also eliminate beneficial bacteria (Science in Hydroponics, 2017; W. Zhang & Tu, 2000). For example, when UV light is used in recirculating solution in hydroponics to control the problem of *Pythium* root rot by eliminating the *P. aphanidermatum*, it shows impacts on non-target bacterial populations in the rhizosphere (Zhang & Tu, 2000). The complete removal of beneficial bacteria from the hydroponic system might hamper crop production and can struggle to reach full potential for growth and development in the absence of beneficial bacteria

Beneficial bacteria play a satisfying positive role in the growth of various crops in hydroponics systems by improving nutrient uptake and reduces the dependence on synthetic fertilizers. Plant growth-promoting bacteria improve crop yield and quality in many ways, mainly by boosting the uptake of macronutrients such as nitrogen, phosphorous, and potassium, along with micronutrients like iron, an essential component of chlorophyll (Mu & Chen, 2021). These bacteria live within or near plant roots, which encourage the growth of plants through various processes such as protection from biotic and abiotic stresses, additional phytohormone production, and increasing in the rate of nutrient absorption (Compant et al., 2010; Glick, 2012). Beneficial bacteria help to improve nutrition in many ways, mainly by boosting the uptake of macronutrients such as nitrogen, phosphorous, and potassium, along with micronutrients like iron, an essential component of chlorophyll.

Pseudomonas, *Bacillus*, *Enterobacter*, and *Streptomyces* species are common beneficial bacteria in hydroponic systems that act as biocontrol agents, which show significant benefits against plant pathogens (Lee and Lee, 2015). Still, they are not enough to stop the outbreak of diseases (Khalil & Alsanius, 2009). *Pseudomonas* species fight against various *Pythium* species responsible for root rot in cucumber and tomato. *Bacillus* fights against various pathogens such as *Pythium spp.*, *Cryptococcus coccoides*, *Fusarium oxysporum f. spp.*, and *Rhizoctonia solani* which affect tomato, chrysanthemum, peppers, and lettuce (Chinta et al. 2014; Liu et al. 2007; Renault et al. 2007; Sopher and Sutton 2011; N. Zhang et al. 2011). Also, lactic acid bacteria (LAB) are employed as bio-controlling agents against *Listeria* and *E. coli* O157:H7 contamination on leafy greens at the pre-harvest level (Yin et al., 2023).

As soil-based agriculture system shifted towards indoor soilless agriculture system, many natural microorganisms that benefit plants were lost. (Glick 2012; Hayat et al. 2010; Santoyo et

al. 2016; Vallance J. 2011). These shifts increase the risk and chance of disease outbreaks in indoor production due to the absence of beneficial microorganisms (Vallance J., 2011). To address these issues, the SynCom (synthetic community) technique was developed to replicate the diversity of soil rhizosphere and to establish synthetic microbial communities in soilless controlled environment agriculture (CEA) systems to protect against pathogens (Vallance J., 2011).

Postharvest quality of lettuce

Quality attributes

Quality is the characteristics or features which makes food valuable and beneficial for people to consume (Kader, 1983). Lettuce qualities are determined by several characteristics such as appearance, texture, flavor and nutritional content which are necessary for freshness and minimizing losses for marketability and consumer acceptance (Ahmed et al., 2024; Kader, 2002b). These quality characteristics can be influenced by variety, other preharvest factors, harvest practices and postharvest handling and these quality parameters gives an important indication for shelf life (Damerum et al., 2020).

Appearance

Although product acceptance varies by individual, it generally depends on the freshness and visual appearance during the purchase, characterized by the vibrant colors and leaves free of blemishes. If any damage to leaves, such as mechanical shredding, tearing, and bruising during processing, affects their visual appearance and is instantly rejected by consumers (Rico et al., 2007). Visual quality measurement for romaine lettuce often uses a 5-to-9-point scale introduced by (Kader et al., 1973), which studies firmness, decay, discoloration, wilting, and other unknown defects. There are also various unrelated factors that can significantly alter the visual appearance, from wound issues to microbial contaminations. Chlorophyll degradation can lead to yellowing and a reduction in green color intensity, negatively impacting visual quality (Toivonen & Brummell, 2008). For appearance, color also plays a significant role in food selection, preference, and acceptance, and it could influence test sensitivity, sweetness perception, and general

satisfaction (Clydesdale, 1993). During storage, various biochemical changes occur in lettuce which can change the color may be due to browning and chlorophyll degradation (Ihl et al., 2003; Rico et al., 2007). Light exposure during the storage of lettuce can increase chlorophyll content, which helps to maintain visual quality (Kasim & Kasim, 2017).

Texture

Leaf texture shows the firmness and juiciness of the leaves, which is essential for postharvest quality and consumer preference. Leaf firmness is influenced by leaf anatomy, such as cell wall thickness, cell size, cell adhesion, and turgor pressure (Toivonen & Brummell, 2008). Lettuce is sensitive to water loss because of its high surface area which allows for moisture exchange and leads to the quick dehydration (Wageningen, 2025). If there is excessive water loss during the storage, it can degrade the cell structure of lettuce which ultimately decline the texture quality (Lee & Chandra, 2018). Initial firmness, temperature, and vibration during handling contribute significantly to softening and moisture loss (Shezi et al., 2024; Zhang et al., 2023). However, research has shown that increased calcium levels in plant tissues can help stop the softening process (Kader, 2002b).

Flavor

Flavor is the combination of taste, smell, texture and even temperature of food when it comes to mouth which as it can also be influenced by the appearance of the food (Touzani & Sclafani, 2017). Flavor is an essential aspect of product quality that is ignored compared to factors like appearance, and it tends to degrade before visual signs of spoilage (Damerum et al., 2020). Lettuce contains glucose, contributing to its sweetness and influencing consumer preferences, whereas bitterness harms consumer choice (Chadwick et al., 2016). During shelf life, leaf respiration breaks down sugars and organic acids, which causes degradation in the flavors (Saltveit, 2015).

Nutritional content

Lettuce is popular worldwide for its nutritional benefits which has low calorie, adequate nutrients (Kim et al., 2016). In lettuce, there is approximately 94.3% of water and their macronutrient profile consist of carbohydrates (4.06g/100g), proteins (0.98g /100g), and lipids (300 mg/100g) (USDA-ARS, 2022). Proteins in lettuce serve as enzymes or storage proteins in the cytoplasm, lowering cell osmotic potential. Lettuce consists of concentration of potassium (260 mg/100 g), followed by calcium (28 mg/100 g), phosphorus (23 mg/100 g), and magnesium (12 mg/100 g) and contains trace elements like iron, sodium, zinc, copper, manganese, and selenium are below 1mg per 100 g (USDA-ARS, 2022).

Romaine lettuce also rich in vitamins and antioxidants which contains vitamin A (8710 IU/100 g), followed by beta carotene (5230 µg/100 g), lutein and zeaxanthin (23120 µg/100 g), folate (136 µg/100 g), and vitamin K (102 µg/100 g). Vitamin E (alpha-tocopherol) has a concentration of 0.14 mg per 100 grams in romaine lettuce. These values may differ from others due to the different lettuce varieties and environmental factors (USDA-ARS, 2019).

Lettuce also contains bioactive compounds including polyphenolic substances chicoric (dicafeoyl tartaric acid), chlorogenic acid (caffeoyl quinic acid), anthocyanins, quercetin, and kaempferol derivatives (Damerum et al., 2015; Llorach et al., 2008; Nicolle et al., 2004). These phytonutrients present in lettuce shows health benefits, such as a decreased risk of cancer, obesity, and neurological and cardiovascular illnesses (Cory et al., 2018; Martin, 2013). Phytonutrients help to increase antioxidant activity through cellular stress responses rather than directly acting as antioxidants. For example, some phytonutrients such as quercetin activate the Sestrin 2-AMPK-mTOR signaling pathway during in-vitro studies, leading to the death of colon cancer cells (Bjørklund & Chirumbolo, 2017; Kim et al., 2013). Consuming raw lettuce is better from a nutritional view because boiling has been shown to reduce phytochemicals like chlorogenic acid (Clifford, 2000).

Factors affecting postharvest quality of hydroponically grown lettuce

The postharvest quality of lettuce is influenced by both preharvest and postharvest factors from production to consumption.

Preharvest factors:

Production systems such as hydroponics and soil-grown methods can affect the postharvest quality of lettuce. Hydroponically grown lettuce can be influenced by hydration and structural integrity due to the constant water and nutrient availability, but it is more sensitive to weight loss which decreases the shelf life compared to soil-grown lettuce (Manzocco et al., 2011). This may be due to the higher initial moisture content in the leaves which is later being more prone to moisture loss during storage. However, hydroponic lettuce when harvested with its root, helps to maintain freshness during storage (Suo et al., 2021).

Water quality plays a crucial role in hydroponic system as it can directly impact crop growth, nutrient uptake and overall crop health. Poor water quality is contaminated with microbes which could cross-contaminate to the edible lettuce leaves during production and leads to the spoilage or outbreak of diseases (Dankwa et al., 2019).

Optimization of yield and nutritional quality of lettuce in hydroponic system is possible from nutrient management. Replacing nutrient solution with water before harvest reduces nitrate accumulations in leafy greens which helps to improve the quality of lettuce (Ruangrak et al., 2023). However, nitrogen (N) application in excessive amount leads to higher N accumulation in lettuce which leads to storage disorders and is prone to decay and leads to postharvest decay (Hoque et al., 2010). A study conducted by Resh (2016) found that low level of nitrate (NO_3) application during production can increase soluble sugar and Vitamin C (Guo et al., 2019). Moreover, application of calcium chloride (CaCl_2) known for preventing calcium deficiencies also enhances chlorophyll levels during storage (Perucka et al., 2014). Therefore, balanced nutrient formula is recommended to maintain the yield, nutritional value, extended shelf life by ensuring proper nutrient uptake (Bar-Yosef et al., 2009).

The natural extracts also influence the postharvest quality and shelf life of lettuce. For example, the application of 10^{-6} moles per liter of gibberellic acid (10^{-6} M GA_3) on nutrient

solutions can delay delayed the senescence, reduces the nitrate accumulation, and maintain overall quality in lettuce (Miceli et al., 2019).

Additionally, natural extract such as *Ecklonia maxima* when applied at in nutrient solutions were found to be effective in improving yield, and quality of lettuce at harvest including the improvement in biomass accumulation, leaf expansion, stomatal conductance, water use efficiency and nitrogen use efficiency (Miceli et al., 2021). Genetic factors are also crucial for postharvest and shelf life. Research conducted by Chase et al. (2024) found that genetic markers such as senescence associated genes (SAGs) and transcription factors (e.g. WRKY, NAC, JAZ) linked to leaf morphology can prolonged shelf-life of lettuce. Modification done in the cell wall of lettuce improved texture and reduced water loss, which is essential for extending shelf life. For example, addition of silicon during the growing period enhances the growth and development along with the structure of lettuce cells and lowers the loss of water (Mattiuz et al., 2015; Neves et al., 2020).

Harvesting time is another important factor that can influence the postharvest quality. Harvesting too early or too late can cause suboptimal quality which increases the postharvest loss (Alemu & Oanh, 2024).

Environmental condition such as air temperature impacts affects the growth of hydroponic lettuce during production (Holmes et al., 2019; R. Liu et al., 2020). When temperatures rise above 28 °C, it seems to be stressful which causes bolting and increases the leaf latex and makes them bitter in taste (Holmes et al., 2019; R. Liu et al., 2020). Under the controlled environment conditions, higher light intensity shortly before the harvest boosts carbohydrate and vitamin C production while minimizing cut-edge browning, senescence browning, and off-order in lettuce leaves when stored in ambient packaging (Min et al., 2021).

Postharvest factors:

Low temperature is critical for maintaining postharvest quality of lettuce to reduce respiration (Watada & Qi, 1999). (Kader 2002). High temperature increases the respiration which involves breaking complex molecules like starch, sugars, and organic acids into simpler molecules (CO₂ and H₂O), and produces energy and intermediates essentials for cellular maintenance (Kader, 2002a; Watada & Qi, 1999). Similarly, relative humidity (RH) is also another critical factor for

maintaining postharvest quality during storage. Relative humidity triggers the rate of transpiration by affecting moisture differences between the plant tissue and surrounding air (Saltveit, 2016). Therefore, maintaining optimal relative humidity (95-98%) is necessary to minimize moisture loss and extend the shelf life (Agüero et al., 2011). Transpiration occurs by losing moisture through stomatal openings which causes wilting, leads to the decline in texture, pigment and quality during storage (Agüero et al., 2011; Kramer & Boyer, 1995; Mansfield, 2012).

Using acceptable harvesting tool is crucial to reduce mechanical damage. Harvesting lettuce with sharp-edge blades can reduce physical damage (Peng et al., 2020), while harvesting with blunt blades can increase cellular damage, loss of cell sap and accelerate browning (Bolin et al., 1977).

Ethylene exposure during storage triggers enzymatic discoloration, tissue deterioration, wilting, and senescence, while elevated carbon dioxide (CO₂) levels can lead to brown staining, ultimately reduces the quality and shelf life of lettuce (Damerum, Chapman, and Taylor, 2020).

Microorganism including pathogenic and saprophytic bacteria or fungi are primary contributors for causing postharvest quality loss, as their growth alters lettuce's color, texture, and taste, making it unmarketable (Lugtenberg et al., 2017; Myszka et al., 2017). High temperature favors the growth of bacteria. For example, Shiga toxin-producing strain *E. coli* O157:H7 at 12° C grows more compared to 5° C (Luo, He, and McEvoy 2010). Microbial metabolism increase the respiration rate which leads to the moisture loss, spoilage and quality loss during storage (Simko & Hayes, 2018). Lettuce surface-to-volume ratio, tissue damage, and chemical composition may further influence microbial proliferation (Kramer & Boyer, 1995; Mansfield, 2012).

Storage and handling conditions

Lettuce is highly perishable crop which needs to be maintained at low temperature to reduce respiration during storage for maintaining postharvest quality (Ozturk & Ozturk, 2009; Watada & Qi, 1999). Optimal storage temperatures range for lettuce are recommended between 0 to 5 degrees Celsius; however, retailers keep bagged lettuce in open refrigerator displays on an open shelf at 10 °C to attract consumers (Hall, Jobling, and Rogers, 2013). Therefore, temperature

management is crucial for slowing metabolic reactions and extending shelf life (Kays, 1991; Robinson et al., 1975). However, field temperature can be quickly reduced by vacuum cooling to avoid excessive moisture loss and reduce microbial growth conditions (Rennie et al., 2001).

While low temperatures reduce respiration and microbial growth, high relative humidity may lead to spoilage if hygiene and storage conditions are not well maintained (Lee & Chandra, 2018). Maintaining high relative humidity (98% to 100%) after harvesting is the most successful strategy to stop transpiration, reducing wilting and quality loss (Nascimento Nunes, 2009; Saltveit, 2016). Respiration is a key indicator that gives valuable information on the duration of the commercial life of produce by indicating the metabolic activity of the product's tissue (Damerum, Chapman, and Taylor 2020; Xu, Chen, and Kang 2019). Modified atmosphere packaging (MAP) can effectively reduce the respiration rate (Manolopoulou et al., 2010; Simko et al., 2018). When there is lower oxygen (O_2) concentrations inside MAP can reduce PAL and PPO enzyme activity, preventing cut edge browning in lettuce (Luna et al. 2016). However, the ability of MAP effectiveness varies according to the lettuce cultivars, while some may still experience rapid quick deterioration even using this technology (Leonard et al., 2021; Simko et al., 2018). High levels of vitamin C and phenolics contents in lettuce have been linked to enhanced shelf life, especially when stored under ambient packaging conditions (Mampholo et al., 2019; Min et al., 2021).

The use of innovative methods such as ultraviolet (UV) technology helps in extends shelf life, preserving the postharvest quality, and controlling the diseases. It further helps to boost bioactive compounds such as ascorbic acid, carotenoids, phenolics, etc. and regulates ripening which increases the shelf life, while its effects depend on the plant type, maturity, cultivar, and treatment conditions (Charles et al., 2010; Sonntag et al., 2023). Research reported by Han et al. (2021), found that application of UV-C of the lettuce surface reduces the discoloration and helps in maintaining chlorophyll and ascorbic acid (Han et al., 2021).

Treatment with the combination of ultrasound and ϵ -polylysine (epsilon-polylysine) in harvested lettuce helps prevent microorganisms, improving quality and extending shelf life during storage (Fan et al., 2019). High-throughput phenotyping methods, such as chlorophyll fluorescence sensors and spectral sensors, are used to monitor any changes in color texture and chlorophyll content caused by enzymatic discoloration (Simko et al., 2015; Wang et al., 2022). Plant-derived

natural extracts have been evaluated for their effectiveness in lowering enzymatic discoloration (Xylia et al., 2021). Washing lettuce with chlorine and other sanitizer during postharvest handling helps to decrease microbial contamination, but it has limited long-term benefits and raises concerns about harmful byproducts (Allende & Monaghan, 2015; Gil et al., 2009). Dipping of harvested lettuce in amino acids like L-cysteine enhances the appearance and texture and prevents browning and odor (Pace et al., 2014).

Research objectives

Lettuce, particularly romaine, is the most popular cultivated for hydroponic systems due to its rapid growth, high planting density, and low energy requirements. This growing method is affiliated well with the increasing demand for healthy, convenient options like bagged salads. Lettuce is a widely consumed and economically important leafy vegetable valued at over \$2.7 billion in 2018 only in the US. While hydroponic systems offer the advantage of year-round fresh produce and minimizes several contamination risks associated with traditional agriculture (like soil and animal contact), they are not entirely free from pathogen contaminations. An outbreak of *Salmonella* Typhimurium in 2021 summer, which is associated with the consumption of packaged leafy greens from Controlled Environment Agriculture (CEA) indoor hydroponics, resulted in 31 illnesses and four hospitalizations, demonstrating the potential for devastating consequences when contamination does occur. Hydroponic use recirculate nutrient solutions, increases the risk of contamination throughout the system and contamination can occur through water, growing media, or human handling remains. Once introduced, pathogens can readily proliferate in the system's favorable environment. UV light treatment of the water is a promising method, as it successfully eliminates pathogens without leaving any harmful residues in the nutrient solutions. To our knowledge, no research has been conducted on how the UV treatment of hydroponic nutrient solutions impacts the crops' postharvest quality and storage potential. This study aims to address this knowledge gap by investigating the effects of UV-treated nutrient solutions on hydroponically grown romaine lettuce. Specifically, we propose the following objectives:

1. Assess the impact of UV-treated nutrient solutions on romaine lettuce growth and nutrient content by evaluating crop yield and analyzing macro- and micronutrient levels in lettuce grown in DWC hydroponic systems with UV-treated nutrient solutions.
2. Determine the effects of UV-treated nutrient solution on harvest and postharvest quality and storage potential of romaine lettuce grown on the DWC hydroponic system by measuring key quality parameters, including leaf length, fresh weight, dry root weight, weight loss, visual quality, color, texture, Soil Plant Analysis Development (SPAD) value, respiration rate, and Vitamin C.

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Chapter 2 - Evaluate the postharvest quality of romaine lettuce grown in a UV-treated hydroponic system

Introduction

Hydroponics is a method of growing plants in a nutrient solution without soil (Jones Jr, 1982; Spehia et al., 2018). It has become a more crucial alternative for plant production due to higher yield, shorter lifecycle, no soil contamination, easy nutrient management, and positive consumer acceptance (Gonnella et al., 2002; Nicola et al., 2004; Ohse et al., 2001; Petropoulos et al., 2016). The most grown leafy vegetable in the hydroponic system is lettuce which includes looseleaf, butterhead, and romaine (Kaiser, 2016). The US lettuce market was worth over \$2.7 billion in 2018 (USDA NASS, 2018), where romaine lettuce alone holds nearly 43.2 percent of total sales (Hirsch, 2019). Romaine lettuce became popular as Americans searched for healthy and nutritious food due to its superior nutritional profile, higher levels of Vitamins and folate, and crisp texture and versatility when used in foods (Hirsch, 2019). Hydroponically grown lettuce offers food safety benefits because studies have shown significantly lower concentrations of microorganisms than soil-grown lettuce (Sirsat & Neal, 2013). Although controlled environment agriculture (CEA) such as greenhouses, hydroponics, plant factories etc., physically prevents crops from external sources such as stormwater, soil-borne pathogens, dust, animals, etc., microbial contamination is still possible (Orozco et al., 2008).

Between 2010 and 2020, there were total 66 outbreaks which were linked with leafy greens resulted in 2,032 illnesses, 580 hospitalizations, and 15 deaths occurs due to the contamination by *Salmonella enterica*, *Listeria monocytogenes*, and *Escherichia coli* strains that produce Shiga toxin (Dorick et al., 2024). Back in 2020, FDA, CDC, state and local partners investigated a multistate outbreak of *E. coli* O157:H7 linked with leafy greens which causes 40 illnesses and 20 hospitalizations, but they could not figure out which type of leafy greens was responsible (FDA, 2022b). Similarly, several recalls and some outbreaks has been reported associated with leafy

greens and microgreens in controlled environment agriculture (CEA) caused by pathogens such as *L. monocytogenes*, *Salmonella* (Topalcengiz et al., 2024).

Pathogens like *Salmonella* Typhimurium and *Listeria monocytogenes* can live in a hydroponic nutrient solution throughout lettuce production until harvest, where they can easily cross-contaminate edible leafy vegetables, resulting in outbreaks of diseases along with crop loss for the producers (Ilic et al., 2022). In the summer of 2021, there was an outbreak of *Salmonella* Typhimurium in the hydroponics under controlled environment agriculture (CEA) from Bright Farms, which grew various leafy greens, including romaine lettuce in a hydroponic system, though the actual source of contamination was unknown (FDA, 2022). In hydroponics, there are various sources of contamination, including water, reusable growth media, equipment, etc., used in systems (Saldinger et al., 2023). Water is one source that can transfer human-borne pathogens to the production system. The nutrient solutions present in the hydroponic system provide a favorable environment to human pathogens, which will spread quickly and contaminate the hydroponically grown crop (Saldinger et al., 2023).

The presence of harmful microorganisms in hydroponic systems not only poses food safety risks but also increases the chance of quality deterioration. Spoilage microorganisms such as *Pseudomonas* species produce lytic enzymes and lipopeptide, which will break down cellulose, hemicellulose, and pectin and weaken the cell walls and accelerate deterioration (Federico et al., 2015; Lagaert et al., 2009). Quality loss usually occurs due to the enzymatic activity or the growth of bacteria and fungi, quickly reducing the quality and making the product unmarketable (Cocetta et al., 2021). Once lettuce is contaminated with spoilage microorganisms, its quality may decrease during storage and lead to a significant decline in shelf life (Huang et al., 2018). After the contamination, microorganisms are difficult to control and disinfect during storage, which further leads to quality deterioration, including sensory quality such as appearance, texture, and freshness (Sun et al., 2022). When lettuce loses its quality, its market value reduces, creates challenges for the preserving freshness and quality in hydroponic lettuce production (Suo et al., 2021).

Ultraviolet light (UV-C) is gaining popularity in disinfect the harmful pathogens present in the hydroponic nutrient solutions that could prevent outbreaks of diseases. UV light exists between 10 to 400 nm wavelengths and is divided into four types: UV-A (315-400 nm), UV-B (280-315 nm), UV-C (200-280 nm), and vacuum UV (VUV, 100-200 nm) that are found in present

times (Chawla et al., 2021; Rajkhowa, 2020; Rangel et al., 2022). Among them, UV-C light is widely known for its germicidal effect on microorganisms and is used for water disinfection (EPA, 2003). For example, Kim et al. (2020) found that UV-C lights completely disinfect *Escherichia coli* (*E. coli*), *Pseudomonas cichorii* (*P. cichorii*), and *Fusarium oxysporum* (*F. oxysporum*) when treated in hydroponic nutrient solutions. UV light with a wavelength of 254 nm has the ability to disinfect bacteria and viruses in water (Lehtola et al., 2003; Timmermann et al., 2015). It damages the DNA double helix of microorganisms that disrupts bacterial metabolic processes, which fails to multiply and ultimately death of cells (Goto et al., 2015; Lopez-Malo & Palou, 2005; Yokoyama & Mizutani, 2014). Research done by Corrêa et al. (2024), found higher inactivation of *E. coli*, with a reduction of 4.2 and 5.2 log CFU at 20.37 mJ/cm² and 489.02 mJ/cm² in circulating nutrient solutions.

While UV-C treatment has the ability to effectively disinfect all harmful microorganisms in hydroponics nutrient solutions (de Almeida et al., 2022; Government of Western Australia, 2022; Perez et al., 2024), it also eliminates beneficial bacteria (Science in Hydroponics, 2017; Zhang & Tu, 2000), known for playing a crucial role in plant health. Beneficial bacteria such as *Pseudomonas*, *Bacillus*, *Enterobacter*, and *Streptomyces* not only promote plant growth but also contribute to postharvest stability by suppressing spoilage microorganisms (Lee & Lee, 2015a). Plant growth-promoting bacteria show beneficial impacts, such as enhancing the growth and development of crops, protecting against biotic and abiotic stresses, additional phytohormone production, and increasing the rate of nutrient absorption (Compant et al., 2010; Glick, 2012). Oliveira et al. (2022) found that inoculating beneficial bacteria such as *A. brasilense* and *T. harzianum* improved the yield and reduced the leaf nitrate content in hydroponic arugula. As beneficial bacteria help plants in nutrient uptake, calcium absorption by hydroponic lettuce prevents tip burn (İkiz et al., 2024). *Trichoderma* spp. increased the weight and the concentration of Vitamin C in red lettuce (Stojanović et al., 2020). Plant growth-promoting rhizobacteria (PGPR) in floating water culture increases the plant weight, number of leaves, leaf area, leaf dry matter, yield, and chlorophyll content in lettuce (Ikiz et al., 2024). Without these beneficial bacteria, lettuce might experience reduced growth, lower postharvest stability, and increased susceptibility to spoilage.

Although UV-C treatment is a common practice for microbial disinfection in hydroponic system, its effects on the plant growth and postharvest quality of produce specifically remain

lettuce are largely unknown. This research attempts to address this knowledge gap by investigating the impact of UV-C treatment of nutrient solutions on romaine lettuce growing hydroponic on plant growth and postharvest quality. More specifically our objectives were to:

Assess the impact of UV-treated nutrient solutions on romaine lettuce growth and nutrient content by evaluating crop yield and analyzing macro- and micronutrient levels in lettuce grown in DWC hydroponic systems with UV-treated nutrient solutions.

Determine the effects of UV-treated nutrient solution on harvest and postharvest quality and storage potential of romaine lettuce grown on the DWC hydroponic system by measuring key quality parameters, including leaf length, fresh weight, dry root weight, weight loss, visual quality, color, texture, Soil Plant Analysis Development (SPAD) value, respiration rate, and Vitamin C.

Materials and Methods

Plant materials and growing conditions

This experiment was conducted at the Postharvest Physiology Laboratory of Kansas State University, Olathe, Kansas. Deep-water culture (DWC) hydroponic system (Model No. 100025-BLK- Version B, Aerogarden, available on Amazon) was used in the experiment, where each tower contains two systems, and each system has two containers (Figure 2). In each tower, one of the systems was positioned at a lower side, and another was placed vertically, which consisted of four containers per tower. In total, 18 containers were used, with each container having four rock wool cubes inside the basket for seed germination.

Lettuce (“Sparx” cultivar, Johnny’s Selected seeds) was grown under environmental conditions with a temperature of 21 °C and 60% relative humidity (RH). Artificial lights were set to a 13-hour photoperiod at a height of 49 cm from the surface of the hydroponic container, with a target daily light integral (DLI) of 12 mol/m²/day. Eight liters of deionized (DI) water was added to each container, and the pump attached inside the container was operated on the manufacturers default setting irrigating for five minutes followed by 25-minute off interval. Seeds were sown in pre-moistened rockwool cubes, with 2-3 seeds per cube, which was thinned after the emergence of true leaves later, and only one seedling was retained in each rockwool cube. After seed

germination, electrical conductivity was maintained between 1 and 1.2 mS/cm to prevent stress for underdeveloped roots and pH between 5.7 and 5.9 until the emergence of true leaves. After the emergence of true leaves, the seedling was thinned, and only one seedling was retained in each rock wool cube. EC was then adjusted to 1.6 – 2.0 mS/cm, which supports faster growth, while pH was maintained between 5.7 and 5.9 throughout the growing period as recommended (Yang et al., 2024).

To regulate nutrient levels, fertilizers such as Hydro-grow leafy and calcium nitrate were applied in equal amounts in the ratio of 1:1 to maintain EC levels. Additionally, 1% of sulfuric acid (H_2SO_4) was used to lower pH, while 1% of potassium hydroxide (KOH) was used to increase pH level as needed. Finally, lettuce was harvested when it reached commercial maturity, i.e., 6 weeks after direct seeding in Rockwool cubes.

UV-C treatment of hydroponic nutrient solution

UV treatments were performed on day 7 for the first time, followed by treatments every 14 days for the second and third time using a Minipure MIN-1 UV chamber (Atlantic Ultraviolet Corporation, Hauppauge, NY) connected to a peristaltic pump (model: P12A/Y35, Across International, Sparks, NV) to deliver different treatment doses. UV-C light at a wavelength of 254 nm was used for the treatments. In our study, a nutrient solution flow rate of six liters per minute (6 L/min) was considered as the low-dose UV-C treatment with estimated dose delivered at 10.91 mJ /cm² which has ability to reduce the *E. coli* 25922 by 1.46 log CFUs/ml (Unpublished data, Moore, M., Kansas State University, Olathe), while a flow rate reduced to three liters per minute (3 L/min) was considered the high-dose UV-C treatment with estimated dose delivered at 21.83 mJ /cm² which has ability to reduce the *E. coli* 25922 by 1.36 log CFUs/ml (Unpublished data, Moore, M., Kansas State University, Olathe. Before each treatment, the UV-C chamber was preheated for 2 minutes to ensure stable and effective UV-C exposure before the nutrient solution passed. The UV-C power was turned off while the treated nutrient solution was recirculated into the hydroponic container. In the Minipure MIN-1 UV chamber, a flow rate of 1 gallon per minute (3.785 liter/min) is equal to 30 mJ/cm² in 99.9% clear water as recommended (Fresh Water Systems, 2025). The low-dose UV-C and high-dose UV-C are calculated as 18.93 mJ /cm² and 37.85 mJ /cm² respectively for clear water. When UV-C was applied in nutrient solutions, in our study, there was an average transmittance of 57.61% (vary according to studies). Estimated UV-C

dose delivered = UV-C dose in clear water x (Transmittance of nutrient solution / Transmittance of clear water) equation (1)

where,

Estimated UV-C dose delivered = Adjusted UV-C dose actually received by the nutrient solutions

UV-C dose in clear water = Dose applied in clear water conditions

Transmittance of nutrient solutions = Percentage of UV light transmitted through nutrient solution

Transmittance of clear water = Percentage of UV light transmitted through clear water.

Experimental design

Due to a limited growing space, a randomized complete block design was employed. The experiment had three replications, and the growing cycle (or time) was the blocking factor. In each of the three replicate growing cycles, 72 lettuce heads were grown. The experimental unit was four lettuce heads.

Harvest and postharvest storage

Each treatment (control, low-dose UV-C, high-dose UV-C) and exit day had four lettuces for analysis. The harvested lettuce was packaged in 16" x 11" x 5" perforated plastic sleeves (Harris seeds) and closed manually with a stapler. The packages were placed on plastic trays in a Forma Environmental Chamber (Thermo Fisher Scientific) at 4 °C with 90% relative humidity and stored for up to seven days. Postharvest quality was evaluated on four heads per replication (replicated through time) per treatment and four exit days: harvesting day (D0), day 3 (D3), day 5 (D5), and day 7 (D7).

Postharvest and storage quality measurement

Growth and yield:

Leaf length: The length of the longest leaf of each head was measured from the base to the tip with the help of a ruler. Four lettuces per treatment were measured only on harvest day (D0).

Fresh weight: The fresh weight of lettuce was recorded immediately after the harvest with a digital weighing balance (Sartorius Lab Instruments & Co. KG, Göttingen, Germany) with an accuracy of ± 0.01 g, and all measurements were recorded to the nearest hundred of a gram. Fresh weight was measured on harvest day for all the treatment groups and exit days. The total fresh weight of each four heads of lettuce was recorded, and the average fresh weight per lettuce (g/lettuce head) was then calculated by dividing the total weight by four.

Dry root weight: For each trial, the total weight of three roots per treatment was measured, and the average weight per root (g/root) was calculated. Fresh roots were kept on a paper towel to absorb the water and then dried in the oven (Precision™, Thermo Fisher Scientific, Waltham, MA, USA) at 60 °C. It was taken out after 3 days after being thoroughly dried.

Postharvest quality:

Weight loss: Weight loss was measured over a seven-day storage period in a Forma Environmental Chamber (Thermo Fisher Scientific) at 4°C and 90% relative humidity. It was calculated by comparing the total weight of the four lettuces per treatment from each exit day (Day 3, Day 5, Day 7) to their initial weight recorded on day 0. The differences in weight measurements were used to determine the final weight loss, which was expressed as percentage weight loss described by Bourne (1976): $\text{Weight loss (\%)} = [(Iw - Fw)/Iw] \times 100\%$, where Iw represents the initial weight (D0), and Fw represents the final weight (weight on measurement day).

Texture: The texture was evaluated by determining the deformation force (Newtons) with a texture analyzer TA-58, TA.XT.plus (Texture Technologies Corp., Scarsdale, NY, USA) using a TA-91 Kramer Shear Cell (Texture Technologies Corp., Scarsdale, NY, USA) equipped with five blades. The midrib of four outer leaves from the same lettuce head was removed, and the leaves were arranged in stacked layers for measurement. The force used to cut through the stacked leaves was measured as peak force, a similar method conducted by Prakash et al. (2000). In each trial, four lettuce heads per treatment were measured for each exit day (Day 0, Day 3, Day 5, Day 7).

Visual quality: The visual quality of romaine lettuce was evaluated non-destructively each day throughout the storage period. Four lettuces per treatment per trial were separated to study visual

quality. The visual quality of romaine lettuce was assessed using the scale by Jeff Brecht, with scores from 9 to 1 (excellent to very poor) (

Table 2). The score above the predetermined threshold of 5 was considered commercially marketable (Belisle et al., 2021).

Color: Color was measured on day 0 and day 3, day 5 and day 7. Color was determined based on four lettuces per treatment and four measurements per lettuce. Two outer leaves of each head and two measurements were taken that were diametrically opposed to the leaf axis according to methods done by (Batziakas, 2019). Color measurements were made using an A5 Chroma-Meter (Minolta CR-400; Minolta Co. Ltd., Osaka, Japan). The instrument was calibrated with the Minolta calibration standard white reflector plate before sampling lettuce leaves. L*, a*, and b* readings were transformed to those of the L, a, b color space and finally to hue angle and chroma according to Setser (1984) and as recommended by McGuire (2019). Hue angle was expressed on a 360° color wheel where 0° and 360° represents red, 90° represents yellow, 180° represents green, and 270° represents blue. Chroma indicates color purity or saturation (high values are more vivid) (McGuire, 2019).

Soil plant analysis development (SPAD) value: SPAD value measures chlorophyll content on the leaves. A chlorophyll meter (SPAD-502 Plus, KONICA MINOLTA, Inc., Japan) was used for the non-destructive measurement of chlorophyll content. Four SPAD readings from four outer leaves of the four lettuces per treatment were measured from each exit day (Day 0, Day 3, Day 5, Day 7). In each trial, the average value of four lettuce from a single tray per treatment was recorded for each exit day.

Respiration rate: A closed system was used to determine the respiration rate (mL CO₂ /kg-hr) described by Biale (1981). Measurements were taken on the day of harvest by a gas analyzer (Dansensor checkMate 3, Ametek MOCON, Denmark). Each sample was sealed inside the 5-liter closed jar for one hour before the measurements were taken on harvest day. Three lettuce heads per replication per treatment were measured. The respiration rate was calculated using the equation: Respiration rate = (Void Volume x %CO₂ produced) / (tissue weight x time), where void volume (container) was measured in mL, CO₂ produced is the difference between final and initial CO₂ concentration, tissue weight was measured in kg, and time was measured in hours.

Nutritional quality:

Macro and micro-nutrient content: On the harvest days, three lettuces per treatment per replication were collected individually and dried in an oven (Precision™, Thermo Fisher Scientific, Waltham, MA, USA) at 60 °C for three days until thoroughly dried. The dried samples were ground and passed through a 2mm sieve to prepare the sample for nutrient analysis. After the samples were ready, we sent them to the Soil Testing Laboratory, K-State, Manhattan, for analysis. A LECO TruSpec CN Carbon /Nitrogen analyzer reports total levels (organic and inorganic) of Carbon (C) and Nitrogen (N) on a weight percent basis, according to the TruSpec CN instrument method (LECO Corporation, St. Joseph, MI, 2005). For phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg), Zinc (Zn), iron (Fe), copper (Cu), manganese (Mn) and sulfate (SO₄), analysis is done from Perchloric digestion method by an Inductively Coupled Plasma (ICP) Spectrometer, Model 5800 ICP OES Agilent Technologies (Giesecking et al., 1935). Macro-nutrients such as nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg), and Sulfate-sulfur (SO₄-S) were expressed in percentage (%), and micro-nutrients such as copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) analyzed in ppm which are then expressed in ug/g DW (1ppm = ug/g DW).

Vitamin C content: Lettuce samples were obtained from the hydroponic experiment as described previously. Each treatment consisted of four lettuce heads, were cut with a knife into small pieces and homogenized. For each treatment, three samples were prepared by taking 2g each of homogenized lettuce and mixed with 20 mL of an acid mixture (2 N glacial acetic acid and 6% meta-phosphoric acid) using a benchtop homogenizer (POLYTRON PT 1600 E, Kinematica Inc., Bohemia, NY, USA) and stored at -20°C. A stock solution of ascorbic acid (1 mg/mL) was prepared by dissolving L-ascorbic acid (≥ 99.0 % assay, Fisher Scientific, Hampton, NH, USA) in the same acid mixture, and six standards (2.5 - 40 µg/mL) were prepared. Ascorbic acid (AA) content was determined spectrophotometrically using a modified method from Terada et al. (1978). On the analysis day, extracts were thawed and centrifuged at 12,000 xg for 20 min at 4°C using a Prism™ R Refrigerated Microcentrifuge (Labnet International, Edison, NJ, USA). After centrifugation, the extract was moved to a new microcentrifuge tube and centrifuged again for

clarification. For ascorbic acid (AA) analysis, 1mL of clarified extract was oxidized to dehydroascorbic acid (DHAA) with 0.2% 2,6-dichloroindophenol (2,6-DCIP) and incubated for 1 hour. Excess 2,6-DCIP was removed with 2% thiourea, followed by the addition of 2% 2,4-dinitrophenylhydrazine (2,4-DNPH) solution. Samples and standards were incubated for 3 hours at 60 °C (Heratherm™ Convection Oven, ThermoFisher Scientific Inc., Asheville, NC, US). Samples and standards were cooled in an ice bath, and 90% sulfuric acid was added, turning to a red-colored solution. The absorbance was measured at 540 nm using a Synergy H1 plate reader (BioTek Instruments, Inc. Winooski, VT, USA), and AA content was quantified using a calibration curve and expressed in milligrams per 100 grams fresh weight (mg/100 g FW).

Statistical analysis:

All statistical analysis was performed using the statistical analysis software JMP (v17.2, JMP, SAS Co. Ltd., USA) and R Studio (Version 2024.12.0+467 by Posit Software, PBC) from Mac. For most response variables collected, a mixed model effect was used where the UV treatment and storage days were fixed factors, and the blocking factor (growing cycles) was a random factor. Leaf length, harvest fresh shoot weight, harvest dry root weight, and water content were modeled using a one-way mixed model because storage was not considered. Tukey's honestly significant difference (HSD) test was used for all mean separation

Results:

Growth and yield

In leaf length parameter, there were significant differences among the treatments ($p < 0.05$). The lettuce leaves that were grown in a nutrient solution treated with low-dose UV-C treatment (21.77 cm) were significantly higher than the control (20.37 cm), while the high-dose UV-C treatment was not significantly different from either the control or low-dose UV-C treatment (21.38 cm) (Figure 3). In fresh shoot weight parameter, there were significant differences in fresh shoot weight at harvest among the UV treatments ($p < 0.0001$). The low-dose UV-C treatment resulted in significantly higher fresh weight (108.51 grams/lettuce head) than both the high-dose UV-C treatment (99.3 grams/lettuce) and control (89.97 grams/lettuce). The lettuce that was grown

in a nutrient solution that was treated with high-dose UV-C also had significantly higher fresh shoot weight compared to the control (Figure 4). In case of dry root weight, there were no significant differences among the treatments in the dry root weight. The average dry root weight of the lettuce grown in a nutrient solution treated with high-dose UV-C was 0.7 g/root, the highest among the treatments. The average dry root weight of lettuce that was grown in a nutrient solution that was treated with low dose UV-C was 0.69 g/root, and the control group showed an average weight of 0.64g/root, which was the lowest compared to other groups (Figure 5).

Postharvest and storage quality

There were no significant differences among the lettuce heads that were grown in the different treatments and the interaction between treatments and days in weight loss. However, lettuce loss significantly over the storage days ($p < 0.05$) (Table 3). Similarly, in texture, there were no significant differences among the lettuce heads that were grown in the different treatments or in the interaction between treatments and days. However, lettuce texture decreases significantly over the storage days ($p < 0.01$) (Table 3). In visual quality, there were significant differences observed among the treatments in lettuce visual quality ($p < 0.001$). Additionally, lettuce visual quality significantly decreases over time ($p < 0.0001$) (Table 3). However, no significant interaction was found between treatments and days. Lettuce heads that were grown in the different treatments had no significant differences from day 0 (D0) to day 5 (D5) across the storage period. However, significant differences were observed on day 6 (D6) and day 7 (D7). On D6, the lettuce that was grown in a nutrient solution that was treated with high-dose UV-C showed the highest visual quality score (6.63), which was significantly higher than the lettuce that was grown in non-treated in a nutrient solution (5.75) ($p < 0.01$), while the low-dose UV-C treatment did not differ significantly from either group. A similar pattern was observed on D7, where lettuce that was grown in a nutrient solution treated with-high-dose UV-C maintained significantly higher than non-treated lettuce (5.13) ($p < 0.05$). There were no significant differences recorded among the treatments and the interaction between treatments and days for lightness (L^*). However, storage days had a significant effect on L^* values ($p < 0.01$) (Table 3). For the red-green tones (a^*), there were also no significant differences among the lettuce heads that were grown in the different treatments and the interaction between treatments and days. However, storage days had a significant effect on a^* ($p < 0.05$) (Table 3). Similarly, chroma (c^*) also follows the same pattern

where there were no significant differences among the treatments and the interaction between treatments and days. However, storage days had a significant effect on c^* ($p < 0.001$) (Table 3). There were no significant effects of treatments and the interaction between treatment and day interaction in SPAD value. However, the SPAD value showed a significant decrease over the storage period ($p < 0.01$) (Table 3). Similarly, there were no significant differences were observed in respiration rates among the lettuce heads that were grown in the different treatments on the harvest day. The average respiration rate of the control group (120.23 mL /kg h) was the highest among the treatments, followed by high-dose UV-C (77.19 mL /kg-h) and low-dose UV-C (62.89 mL /kg-h) (Figure 13).

Nutritional Quality:

The macro-nutrient contents (nitrogen, phosphorous, and potassium) of lettuce showed no significant differences among the treatments (Table 5). Similarly, micro-nutrient contents (calcium, magnesium, sulfate-sulfur, copper, iron, manganese, zinc) were also not significantly affected by any of those treatments (Table 6). In Vitamin C content, there were significant differences among treatments ($p < 0.05$) and storage days ($p < 0.0001$). However, there was no significant interaction between treatments and storage days (Table 3). The Vitamin C content of lettuce was significantly affected by UV-C treatments on the day of harvest and after three days of storage (D3). At D0, the lettuce that was grown in non-treated in a nutrient solution that was treated with low-dose UV-C had the highest Vitamin C content (22.67 mg/100 g FW), which was significantly higher than the lettuce that was grown in a nutrient solution that was treated with high-dose UV-C (17.95 mg/100 g FW) ($p < 0.05$) but not significantly different from the control (20.29 mg/100 g FW). The lettuce that was grown in a nutrient solution treated with high-dose UV has the lowest Vitamin C content compared to other groups on day 0. On D3, significant differences were observed between the treatments. The lettuce that was grown in a nutrient solution treated with low-dose UV-C treatment maintained the highest Vitamin content (18.8 mg/100 g FW), which was significantly higher than the Vit C content from the lettuce that was grown in a nutrient solution treated with high-dose UV-C (14.02 mg/100 g FW) and the non-treated lettuce (13.96 mg/100 g FW) ($p < 0.05$). However, there were no differences between the control and high-dose UV-C treatment. On D5 and D7, no significant differences were observed among the treatments.

Discussion

Growth and yield

In our study, there were significant differences in leaf length and fresh shoot weight between lettuce grown in UV-C treated solutions and lettuce grown in nutrient solutions without the treatment of UV-C. The low-dose UV-C treatment significantly increased the leaf length in lettuce compared to the non-treated lettuce ($p < 0.05$). High-dose UV increased the leaf length more than non-treated lettuce, but it was not statistically significant compared to the non-treated lettuce and lettuce treated with low-dose UV-C. Like leaf length, the fresh shoot weight of lettuce that was grown in low-dose UV-C significantly resulted in higher length than the fresh shoot weight of the lettuce that was grown in high-dose UV-C and control nutrient solution. All three treatment groups in fresh shoot weight are significantly different from each other as non-treated lettuce resulted in the lowest weight. This result suggests that low-dose UV-C treatment may act as a mild stressor that enhances plant growth, whereas high-dose treatment may induce stress that suppresses plant growth. Our research findings are like those of Schwartzkopf (1987), who observed a slight increase in plant growth with low-intensity UV radiation bulb, although their findings were not statistically significant. Research conducted by Premuzic et al. (2007) supports our findings because disinfection of harmful microorganisms with chlorine in hydroponic nutrient solutions enhances the fresh weight of lettuce. In our study, no differences were found in dry root weight, indicating that the root development in lettuce was unaffected by UV-C application. Our findings differ from those of Perez et al. (2024), who observed root development (in length and size) in crispy lettuce through UV-C treatment in nutrient solutions. This difference from our results might be due to lettuce variety, UV exposure time and the photoperiod as their study used crispy lettuce (cultivar: 'Veneranda'), constant UV-C treatment, and a longer exposure period of 20 hours per day, while in our study, we used romaine lettuce (cultivar: 'Sparx'), three treatments during growth cycle, and provided 13 hours of light each day. According to Kang et al. (2013), a longer photoperiod can enhance the growth of lettuce, which may have influenced the observed differences in root development.

Postharvest and storage quality

Weight loss is one of the important indicators for determining the freshness and overall quality of lettuce (Charles et al., 2018). Our study found no significant effect of lettuce that was grown in a nutrient solution that was treated with UV-C on weight loss. However, we observed a 12% cumulative weight loss across all treatments by day 7 when stored at 4 °C and 90% RH. Research reported by Agüero et al. (2011) observed that butterhead lettuce (*L. sativa* cv. Lores) when grown in soil under the cover had 18% weight loss at the end of storage (day 5) stored at 0-2 °C with 70-72% RH and when stored at 0-2 °C with 95-98% RH, there was only 4-5% of weight loss. These differences in weight loss may be due to variations in production methods, cultivar, and storage conditions that affect moisture retention during storage (Agüero et al., 2011; Manzocco et al., 2011). Water loss occurs over the storage because of natural processes like transpiration and respiration, which causes water loss, reduces firmness, and ultimately leads to wilting (Chitarra, 2005).

Texture is one of the key quality attributes in lettuce which can influence consumer perceptions of freshness, crispiness, and crunchiness (Fillion & Kilcast, 2002). Our study didn't find significant effects of UV-C treatment on the texture because UV-C treatment is primarily used for pathogen sterilization in nutrient solutions and might not directly impact plant cell structure. Measurement of texture can be difficult due to its inherent variability, which may be the reason for the lack of significant differences in the study (Toole et al., 2000). These results suggest that regardless of doses, UV-C treatments do not negatively affect the lettuce texture, which supports their potential to use without compromising texture quality. However, we observed a significant decline in lettuce texture during storage, a common issue due to water loss and cell wall degradation (Lee & Chandra, 2018).

Visual quality significantly influences the marketability of lettuce (Martínez-Ispizua et al., 2022), where consumers often reject lettuce heads with brown spots (Oliveira et al., 2013). Although the visual quality decreased during storage across all treatments ($p < 0.0001$), lettuce grown in nutrient solution treated with high-dose UV significantly preserved visual quality compared to the non-treated lettuce on days 6 and 7. These results suggest that lettuce that was grown in a nutrient solution treated with high-dose UV-C maintain its visual quality during storage, may be due to the disinfection of microbial contamination in nutrient solutions. High-dose

UV-C exposure may induces strong stress that might be helpful in suppressing microbial growth effectively in nutrient solutions (Corrêa et al., 2024) and eliminate the possibility of cross-contamination of pathogenic and saprophytic bacteria, including fungi which are primary contributors to postharvest quality loss, as their growth alters color and texture (Lugtenberg et al., 2017; Myszka et al., 2017).

Color is one of the important attributes affecting consumer perception of quality, as it significantly impacts food choice and acceptability and can even affect taste perception (Clydesdale, 1993). In our study, UV-C application to the nutrient solution did not significantly affect lettuce leaves lightness (L^*), red-green (a^*), and chroma (c^*) or in their interaction between treatment and days. This suggests that different doses of UV-C exposure in the hydroponic nutrient solution do not directly affect the color attributes of lettuce leaves. While we observed significant color variations over the storage period, these changes were independent of the UV-C treatment. During storage, enzymes such as polyphenol (PPO) and peroxidase (POD) are linked with browning, which reduces color changes (Chen & Fan, 2021). To the best of our knowledge, no previous studies have investigated the effects of UV-C treatment of hydroponic nutrient solution on postharvest quality, including color.

In our study, there were no effect on chlorophyll content of lettuce grown in UV-C treated nutrient solutions, while significant decline in SPAD value was observed over the storage days, possibly due to leaf senescence (Tanaka & Ito, 2025). During senescence, the degradation of chlorophyll facilitates the recovery and recycling of essential nutrients like nitrogen, which results in the yellowing of leaves (Kuai et al., 2017). Our findings differed from those of Perez et al. (2024), who observed that chlorophyll a (Chl a) was significantly higher in the UV-C treated group with 20 h photoperiod compared to a group having the same photoperiod with no UV-C. These findings suggested UV-C treated nutrient solutions along with 20 hours photoperiod could increase chlorophyll content. It differed from our results, which may be due to the methodology used in the experiment. Perez et al. (2024) used soil-grown 37-day-old lettuce seedlings and then transplanted hydroponics system where nutrient solutions were treated with UV-C constantly. However, in our study, treatment of nutrient solution was treated only three times during whole production cycles with a shorter photoperiod of 13 hours.

The respiration rate is a direct indicator of a plant's metabolic activity. A higher respiration rate generally means the plant is more actively using energy (Kozłowski & Pallardy, 1997). In our study, we didn't find a significant difference in respiration rate among the treatments on the harvesting day, which means that there were no effects of UV-C treatments on the metabolic activity of lettuce.

Nutritional quality

Macro and micronutrients are required for crop growth and development and play a crucial role in both plant physiology and human nutrition (Kumar, 2013). Deficiency in any key nutrients like nitrogen (N), phosphorous (P), sulfur (S), iron (Fe), and zinc (Zn) can decrease the productivity of plants (Kumar et al., 2021). Fe and Zn play vital roles in physiological processes in crops because Fe is essential for chlorophyll synthesis and chloroplast structure, while Zn supports growth and development (Colombo et al., 2014; Rehman et al., 2012). These nutrients are absorbed by lettuce during its growth cycle and are also beneficial for human consumption. For example, potassium (K) consumption helps in several metabolic functions and balance between water and electrolytes (Soetan et al., 2010). Our study found no significant impact of UV-C treatment on macro and micronutrients on the uptake in lettuce. This could be attributed to the adequate availability of nutrients in a hydroponic system where lettuce may not rely on beneficial bacteria for nutrient assimilation. This interpretation is supported by previous research done by Aini et al. (2019), who found that uptake of potassium in lettuce grown under electrical conductivity (EC) levels of 1.8 mS/m and 1.4 mS/m are higher compared to lettuce growth with plant growth-promoting bacteria (PGBR).

Vitamin C is a key indicator of lettuce nutritional quality and essential for the human body's physiological functions (Carr & Frei, 1999; Medina-Lozano et al., 2021). Our study revealed that lettuce that was grown in a nutrient solution treated with low-dose UV-C significantly increased Vitamin C content compared to lettuce grown in a nutrient solution treated with high-dose UV-C particularly on day 0 and day 3. This means low-dose UV-C treatment can enhance the Vitamin C content in lettuce, which may be due to the less stress of UV-C light provides to microorganisms. Decreased vitamin C content was observed in lettuce grown in nutrient solutions treated with high-dose UV-C could be due to the elimination of the beneficial bacteria which play role in maintaining

plant health and nutrient uptake. Research reported by Premuzic et al. (2007) observed that antimicrobial treatment by chlorine with low amount (0.55 mg/L) in nutrient solutions enhances Vitamin C content in lettuce var. mantecosa compared to higher amount of chlorine (5.5 and 11mg/L). Our results are further supported by Ikiz et al. (2024), who observed that beneficial microorganisms, such as *Bacillus subtilis*, *Bacillus megaterium*, and *Pseudomonas fluorescens*, enhance Vitamin C in Batavia lettuce by acting as biocontrol agents in hydroponics. However, in our study, there was a significant decrease in Vitamin C during the storage, which could be a reason for respiration that occurs and leads to the breakdown of the stored carbohydrates (sugar) to produce energy. Schmitzer et al. (2021) reported a decline in Vitamin C content in lamb lettuce during storage due to the changes in metabolic pattern.

Conclusion

This study evaluated the impact of UV-C treatment on the nutrient solution of hydroponic lettuce grown in deep-water culture) system on the harvest and storage quality. Our results indicated that low-dose UV-C treatment significantly increases leaf length and fresh weight of lettuce compared to the non-treated lettuce and lettuce grown under the high-dose UV-C application. Also, UV-C treatment, particularly low-dose UV-C treatment, maintained the visual quality of lettuce at the end of the storage. Additionally, dry root weight and water content remained unaffected. Water loss, respiration rate, and texture showed a significant decline during storage, but UV treatments did not affect any of these parameters. Macro- and micronutrient content and color parameters (L^* , a^* , c^*) were unaffected by UV-C, although color stability was observed throughout storage. These findings suggest that UV-C sterilization of nutrient solutions does not negatively impact plant development and shows a potential alternative for food safety without compromising yield. And the potential to maintain better visual quality in lettuce, which is a critical factor for marketability. Overall, this study shows that UV-C treatment of a nutrient solution of hydroponically grown lettuce had no negative impacts on the quality at harvest and during storage. This study recommends that it is a potential alternative as a food safety intervention in hydroponic production systems. It also ensures safe, nutritious, high-quality produce without compromising yield and quality.

Future directions

Our study displayed that UV-C treatments on hydroponic nutrient solutions enhance the yield and maintain, in some case enhance the postharvest quality of romaine lettuce, particularly in improving visual quality and Vitamin C content, especially in lettuce that was grown in a nutrient solution that was treated with low-dose. However, several gaps are identified that need to be further investigated. Although UV-C didn't significantly prevent weight loss, texture, or SPAD value, it could work together with other postharvest strategies, such as modified atmosphere packaging (MAP) or edible coatings, which might need further investigation. In our results, there were improvements in visual quality in UV-C treated lettuce, which was unclear because it is also necessary to understand the microbial changes on lettuce leaves. There was significantly higher vitamin C in low-dose UV-C treated lettuce than in high-dose UV-C treated lettuce, which needs further studies to understand the actual mechanism behind this. Understanding the rate of microbial inactivation and regrowth in the nutrient solution and the root system, after UV-C treatment is crucial, as it may directly influence postharvest quality through plant-microbe interactions.

	Control	Low-dose UV	High-dose UV
Day 0			
Day 3			
Day 5			
Day 7			

Figure 1. Pictures of romaine lettuce (Sparx cultivar) that was grown in a nutrient solution treated with low UV-C dose:6L/min, high UV-C dose: 3L/min) and without UV-C and stored at 4°C and 90% relative humidity (RH) for seven days.

Table 2. Romaine lettuce quality rating score by Jeff Bretch

Rating	Definition
9	Fresh appearance with bright green color; crisp texture; no discoloration or decay.
7	Slight loss of green color; no russetting; slight water loss not objectionable; slight butt-end discoloration.
5	Noticeable loss of green color; noticeable water loss on outer leaves; moderate discoloration of butt-end.
3	More yellow than green; outer leaves limp and need trimming; severe discoloration; decay may be noticeable.
1	Yellow; severe wilting and extreme discoloration; soft rot or fungal mycelium on outer leaves.



Figure 2. Picture of Deep-water culture of hydroponic system used in our experiment.

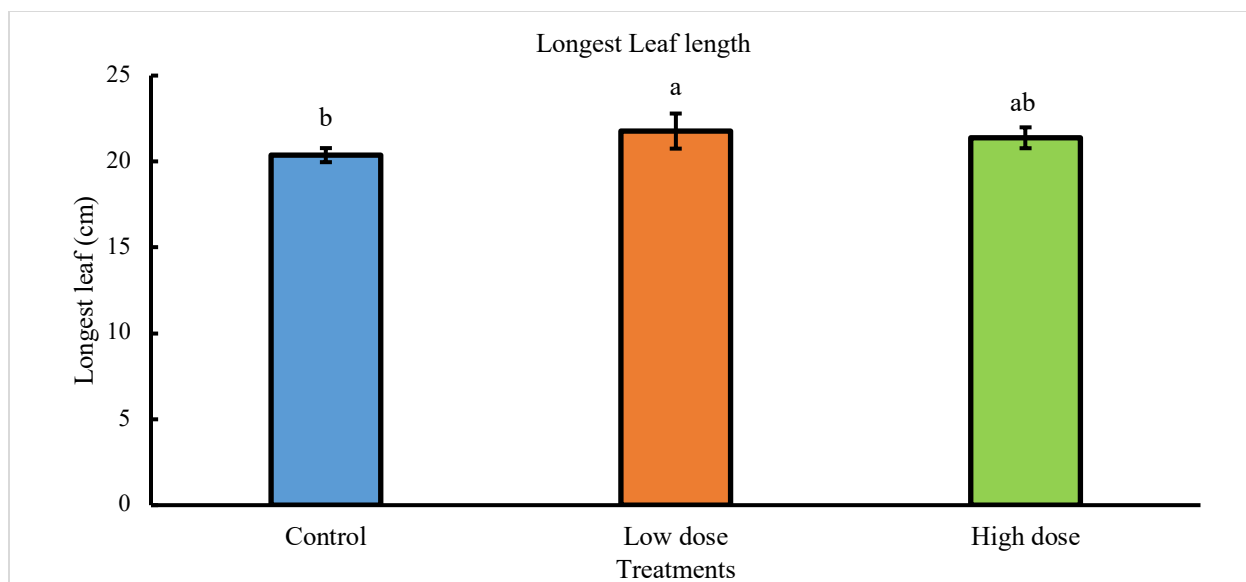


Figure 3. Leaf length (in cm) of romaine lettuce leaves (cultivar: Sparx) that was grown in a nutrient solution treated with low UV-C dose: 6L/min, high UV-C dose: 3L/min) and without UV-C. Measurements were taken on harvest day (Day 0). Error bars represent the standard error of the mean (SEM). Mixed model effects were used to analyze the effects of treatments, with the mean separated using Tukey's HSD test. Different letters 'a' or 'b' above the bars denote significant differences among the treatments ($p < 0.05$). Groups labeled with 'ab' are not significantly different from either 'a' or 'b.'

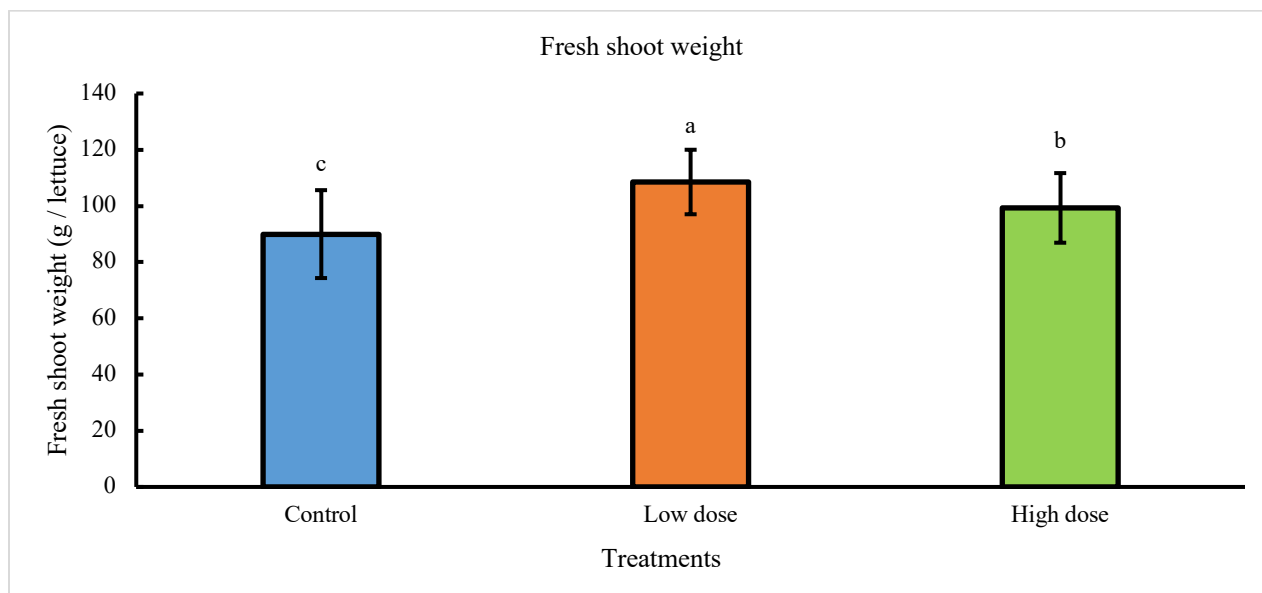


Figure 4. Fresh shoot weight (g/lettuce) of romaine lettuce leaves (cultivar: Sparx) that was grown in a nutrient solution treated with low UV-C dose: 6L/min, high UV-C dose: 3L/min) and without UV-C. Measurements were taken on harvest day (Day 0). Error bars represent the standard error of the mean (SEM). Mixed model effects were used to analyze the effects of treatments, with the mean separated using Tukey's HSD test. Different letters 'a', 'b' or 'c' above the bars denote significant differences among treatments ($p < 0.0001$).

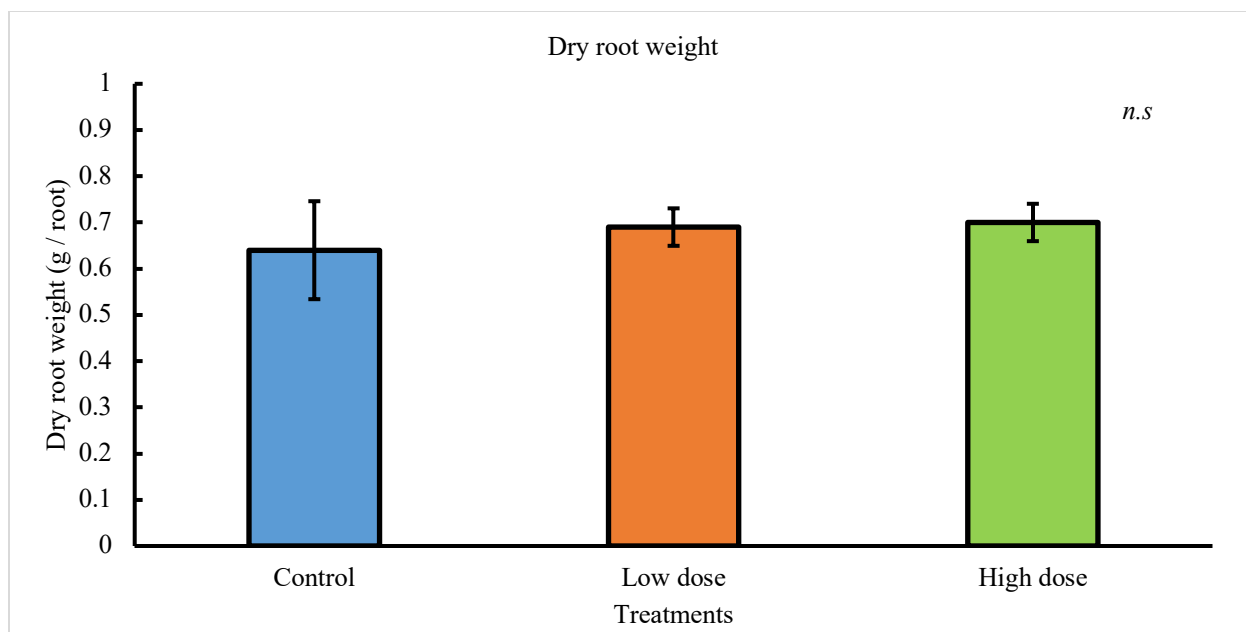


Figure 5. Dry root weight (g/root) of romaine lettuce leaves (cultivar: Sparx) that was grown in a nutrient solution treated with low UV-C dose:6L/min, high UV-C dose: 3L/min) and without UV-C. Measurements were taken on harvest day (Day 0). Error bars represent the standard error of the mean (SEM). 'n.s.' indicates that there were no statistically significant differences among the treatments according to the mixed model effects.

Table 3. Probability values for SPAD, visual quality, weight loss, respiration rate, texture, vitamin C, and color (L*, a*, c*) of romaine lettuce (Sparx cultivar) that was grown in a nutrient solution treated with low UV-C dose: 6L/min, high UV-C dose: 3L/min) and without UV-C, and stored at 4°C and 90% relative humidity (RH) for seven days.

Parameters	Treatments ^x	Storage Days ^y	Treatments x Days
Weight loss (%)	ns ^z	< 0.0001	ns
Texture	ns	< 0.01	ns
Peak force(N)			
Visual quality	< 0.001	< 0.0001	ns
Color: Lightness (L*)	ns	< 0.01	ns
Red - Green (a*)	ns	< 0.05	ns
Chroma (c*)	ns	< 0.001	ns
SPAD Value	ns	< 0.01	ns
Respiration rate (mg CO ₂ /kg hr)	ns	-	-
Vitamin C (mg/100g FW)	< 0.05	< 0.0001	ns

Mixed model effects were used to test which factors and interactions significantly affected the examined quality parameters ($P \leq 0.05$).

^x Treatments (control, low UV dose, high UV dose)

^y the impact of storage (in days: day 0, day 3, day 5, and day 7). All quality parameters mentioned above were measured on each exit day, while visual quality was measured from day 0 to day 7, and respiration rate was measured only on harvesting day. ^z ns: not significant

^z ns: not significant

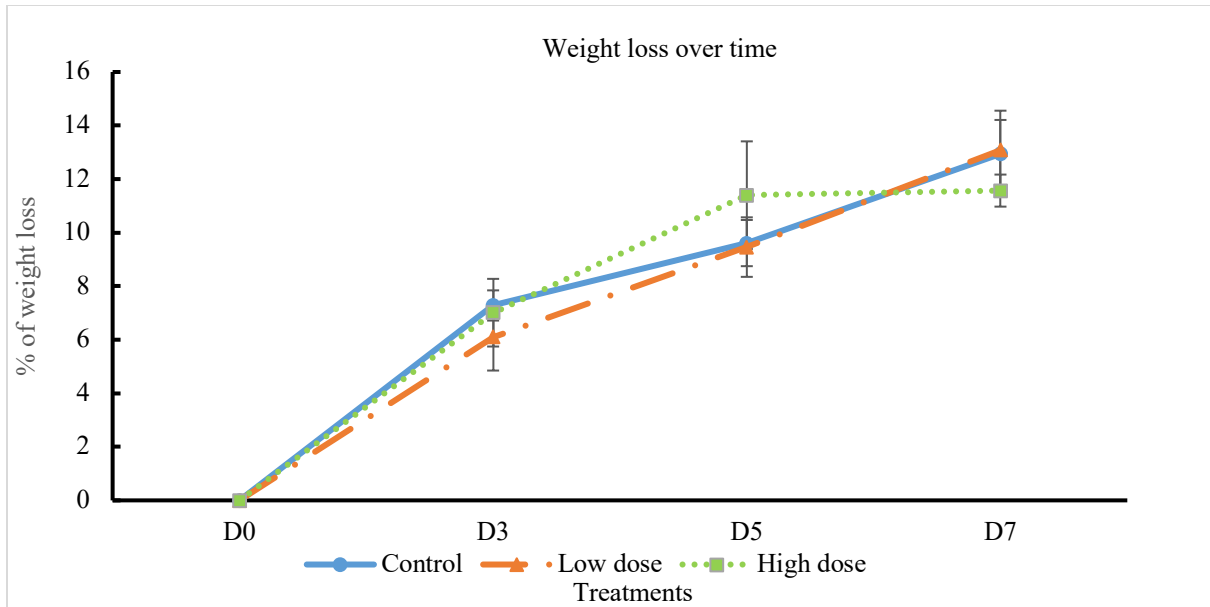


Figure 6. Cumulative water loss percentage of romaine lettuce leaves (cultivar: Sparx) that was grown in a nutrient solution treated with low UV-C dose:6L/min, high UV-C dose: 3L/min) and without UV-C, and 90% relative humidity (RH) for seven days. Samples were stored at 4°C and 90% relative humidity (RH) for seven days. Water loss was measured separately for each exit day: day 3 (D3), day 5 (D5), and day 7 (D7) by comparing the final weight of lettuce at each exit day to its initial weight recorded on day 0. Error bars represent the standard error of the mean (SEM). Mixed model effects were used to analyze the effects of treatments, days, and their interaction.

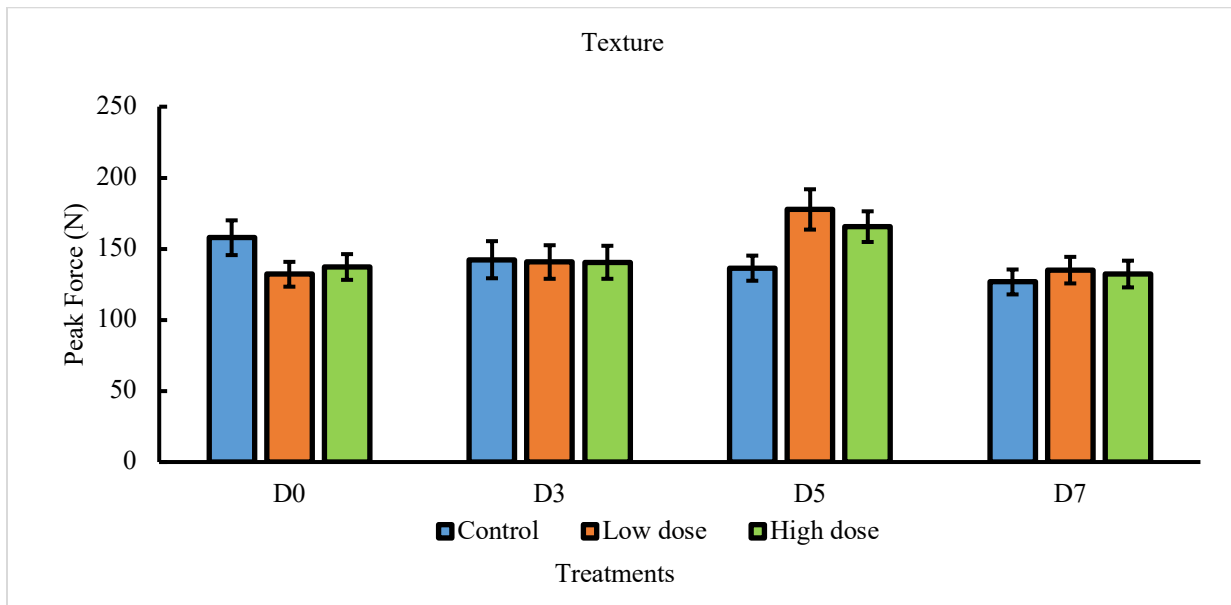


Figure 7. Peak Force (N) of romaine lettuce leaves (cultivar: Sparx) that was grown in a nutrient solution treated with low UV-C dose:6L/min, high UV-C dose: 3L/min) and without UV-C and stored at 4°C and 90% relative humidity (RH) for seven days. The texture was measured in terms of peak force on day 0 (D0), day 3 (D3), day 5 (D5), and day 7 (D7). Error bars represent the standard error of the mean (SEM). Mixed model effects were used to analyze the effects of treatments, days, and their interaction.

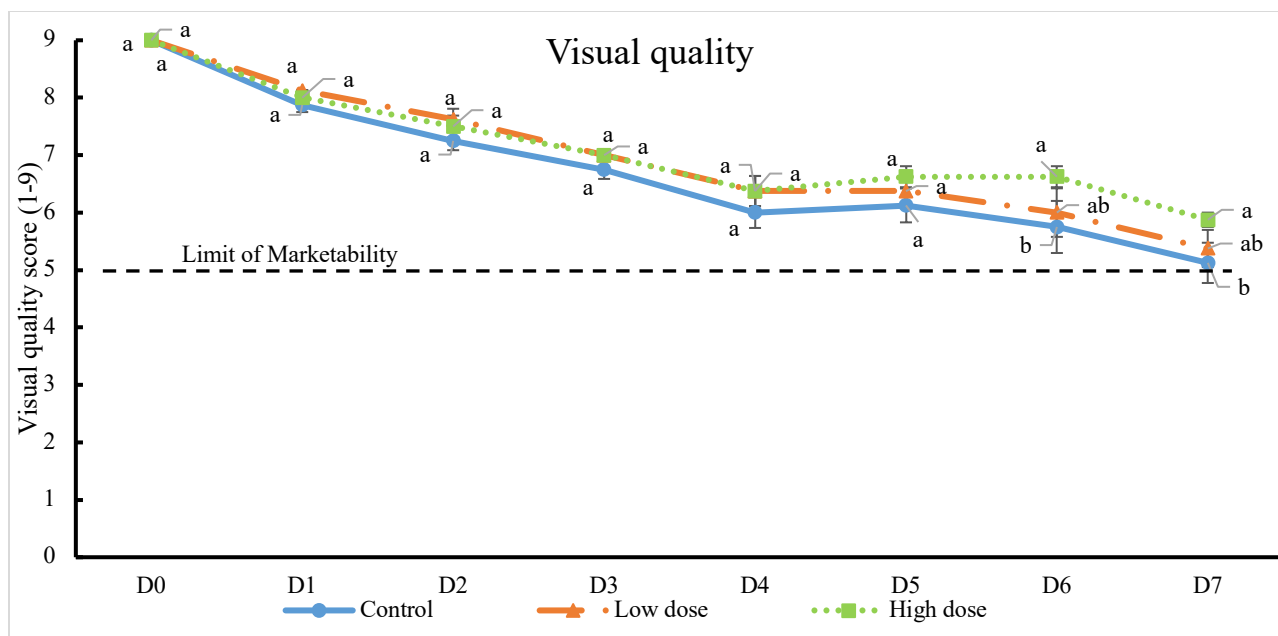


Figure 8. Visual quality of romaine lettuce leaves (cultivar: Sparx) that was grown in a nutrient solution treated with low UV-C dose:6L/min, high UV-C dose: 3L/min) and without UV-C and stored at 4°C and 90% relative humidity (RH) for seven days. Means of each treatment were recorded from day 0 (D0) to day 7 (D7). Error bars represent the standard error of the mean (SEM). Mixed model effects were used to analyze the effects of treatments, days, and their interaction. Similar letters ‘a’ are not significantly different among the treatments. Different letters ‘a’ or ‘b’ bars denote significant differences among the treatments. Groups labeled with ‘ab’ are not significantly different from either ‘a’ or ‘b’

Table 4. Color attributes of romaine lettuce leaves (cultivar: Sparx) that was grown in a nutrient solution treated with low UV-C dose:6L/min, high UV-C dose: 3L/min) and without UV-C and stored at 4°C and 90% relative humidity (RH) for seven days.

Days	Treatment	Lightness (L*)	Red - green (a*)	Chroma (c*)
0	Control	38.46 ± 5.47	-14.01 ± 1.29	21.24 ± 1.96
0	Low dose	40.54 ± 4.39	-14.5 ± 1.47	22.51 ± 2.56
0	High dose	39.81 ± 4.34	-14.32 ± 1.79	21.74 ± 2.99
3	Control	40.94 ± 2.09	-13.77 ± 0.8	20.76 ± 1.3
3	Low dose	41.32 ± 1.61	-13.98 ± 1.29	21.35 ± 2.35
3	High dose	41.94 ± 0.47	-14.24 ± 1.09	21.79 ± 1.99
5	Control	41.87 ± 2.33	-14.35 ± 0.97	22.13 ± 1.58
5	Low dose	39.79 ± 1.58	-14.45 ± 0.95	22.59 ± 1.67
5	High dose	41.81 ± 2.41	-14.75 ± 1.07	22.88 ± 2.01
7	Control	42.68 ± 0.51	-14.8 ± 0.84	22.91 ± 1.74
7	Low dose	42.65 ± 0.72	-14.74 ± 0.79	22.91 ± 1.79
7	High dose	43.19 ± 1.22	-14.42 ± 0.46	22.04 ± 0.95

L* represents Lightness, a* represents red-green, and c* represents chroma. Measurements were taken on day 0, day 3, day 5, and day 7. Results are presented as mean ± standard deviation (SD). Mixed model effects were used to analyze the effects of treatments, days, and their interaction.

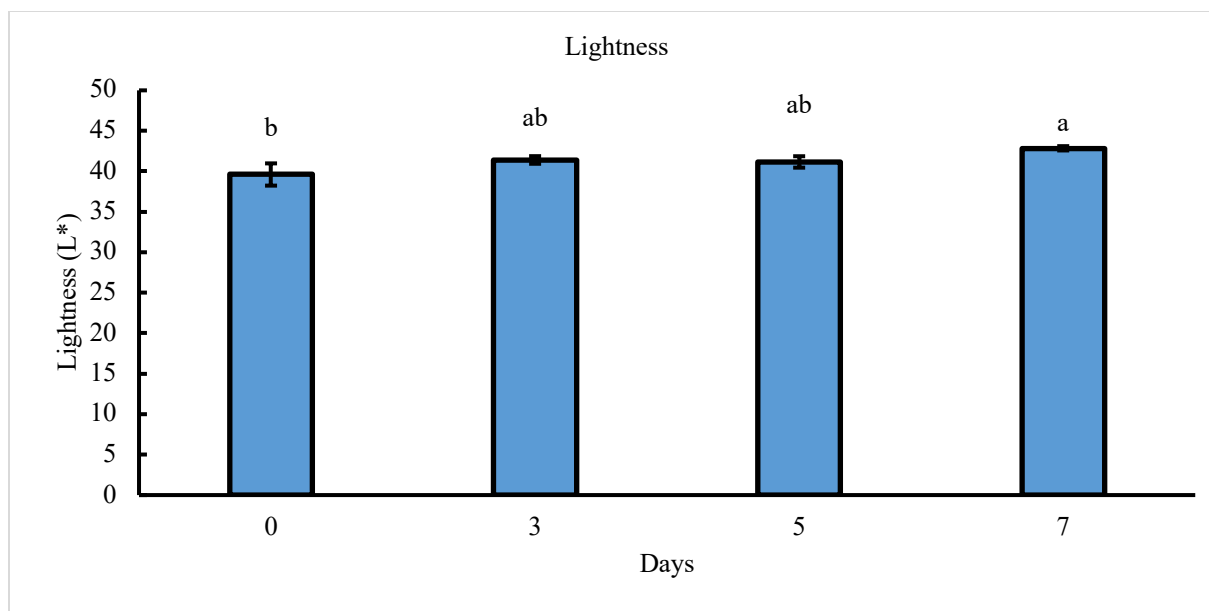


Figure 9. Values represent the least square mean color lightness (L^*) of romaine lettuce leaves that was grown across all treatments (UV-C dose: 6L/min, high UV-C dose: 3L/min) and without UV-C) and stored at 4°C and 90% relative humidity (RH) for seven days. Measurements were taken on exit days: 0, 3, 5, 7. Mixed model effects were used to analyze the effects of days ($p < 0.01$), with the mean separated using Tukey's HSD test. Error bars indicate the standard error of means (SEM). Different letters 'a' or 'b' above the bars denote significant differences among the days. Groups labeled with 'ab' are not significantly different from either 'a' or 'b'.

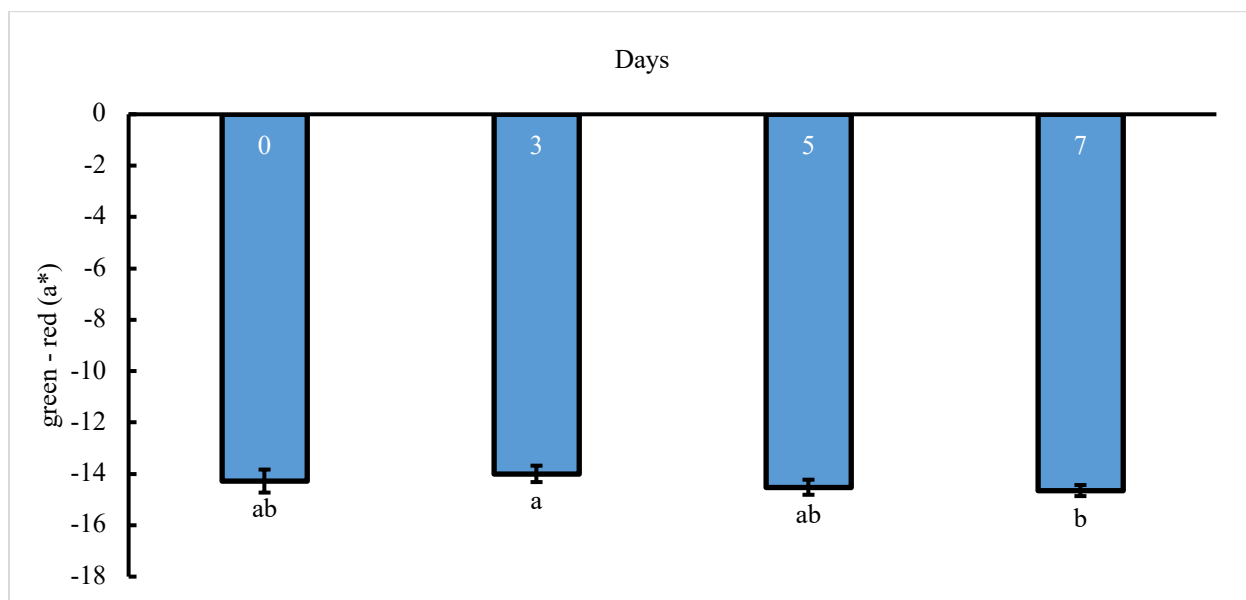


Figure 10. Values represent the least square means color (a^*) of romaine lettuce leaves grown across all treatments (UV-C dose: 6L/min, high UV-C dose: 3L/min) and without UV-C) and stored at 4°C and 90% relative humidity (RH) for seven days. Measurements were taken on exit days: 0, 3, 5, 7. Negative values of a^* indicate green tones, while positive values of a^* indicate red tones. A value of 0 represents a neutral color (neither green nor red). Mixed model effects were used to analyze the effects of days ($p < 0.05$), with the mean separated using Tukey's HSD test. Error bars indicate the standard error of

means (SEM). Different letters 'a' or 'b' below the bars denote significant differences among the days. Groups labeled with 'ab' are not significantly different from either 'a' or 'b'.

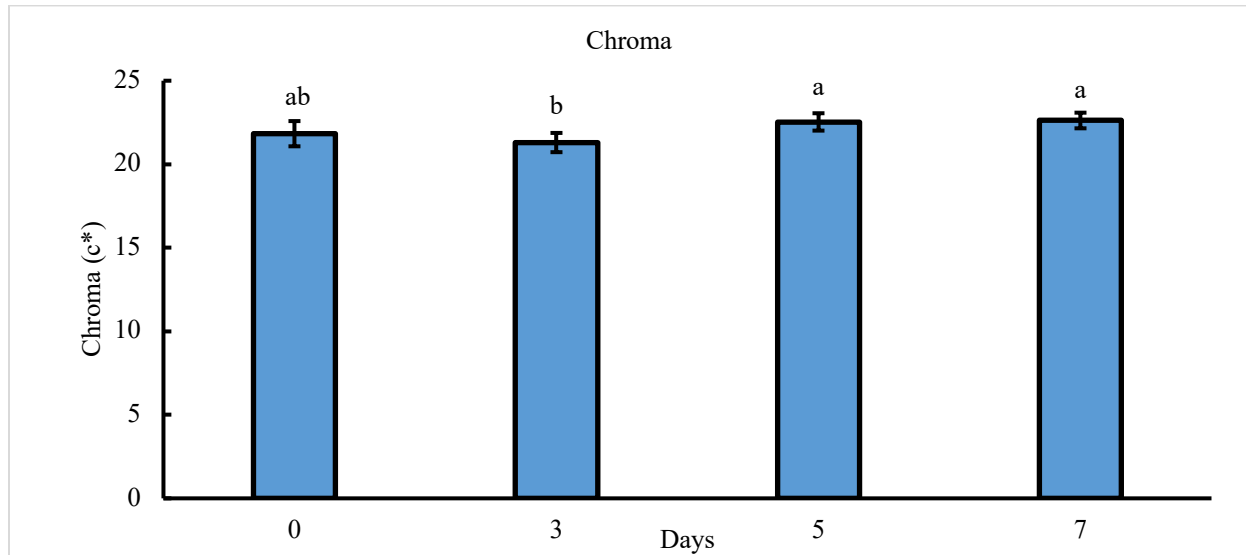


Figure 11. Values represent the least square means color chroma (c^*) of romaine lettuce leaves grown across all treatments (UV-C dose:6L/min, high UV-C dose: 3L/min) and without UV-C) and stored at 4°C and 90% relative humidity (RH) for seven days. Measurements were taken on exit days: 0, 3, 5, 7. Mixed model effects were used to analyze the effects of days ($p < 0.001$), with the mean separated using Tukey's HSD test. Error bars indicate the standard error of means (SEM). Different letters (a, b) above the bars denote significant differences among the days. Groups labeled with 'ab' are not significantly different from either 'a' or 'b', and groups labeled with a similar letter 'a' are not significantly different from each other.

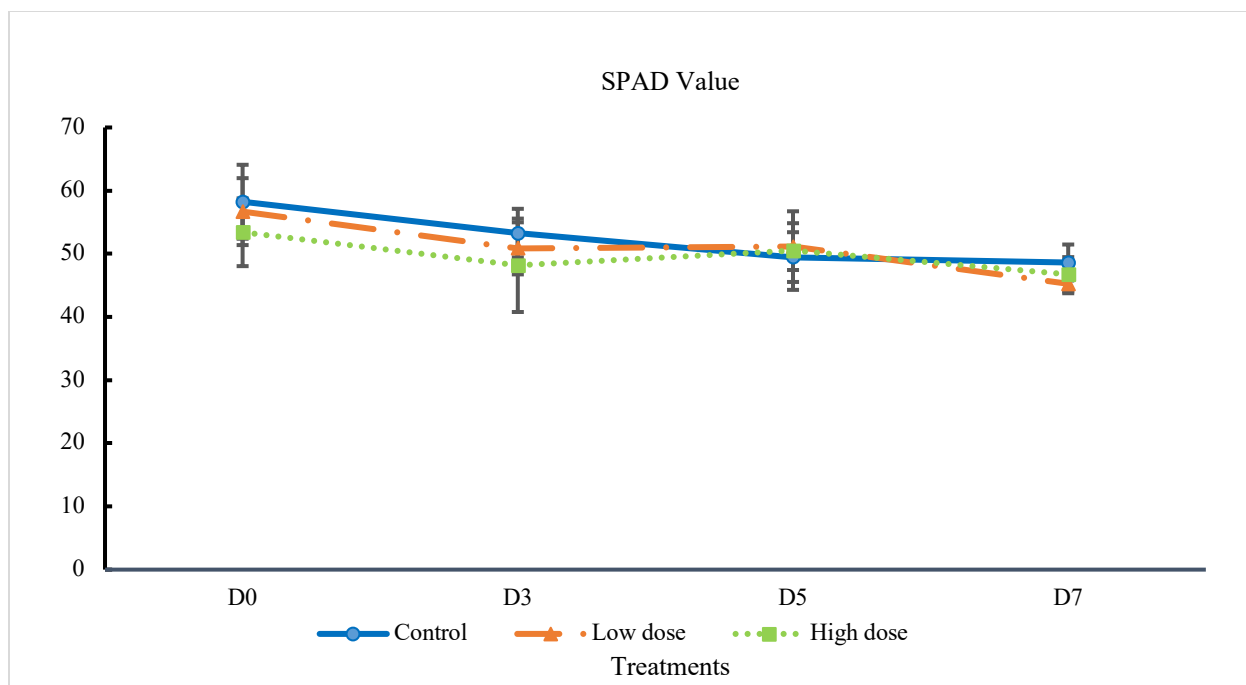


Figure 12. Soil Plant Analysis Development (SPAD) value of romaine lettuce that was grown in a nutrient solution treated with low UV-C dose: 6L/min, high UV-C dose: 3L/min) and without UV-C and stored at 4°C and 90% relative humidity (RH) for seven days. SPAD was measured on day 0 (D0), day 3 (D3), day 5 (D5), and day 7 (D7). Error bars represent the standard error of the mean (SEM). Mixed model effects were used to analyze the effects of treatments, days, and their interaction.

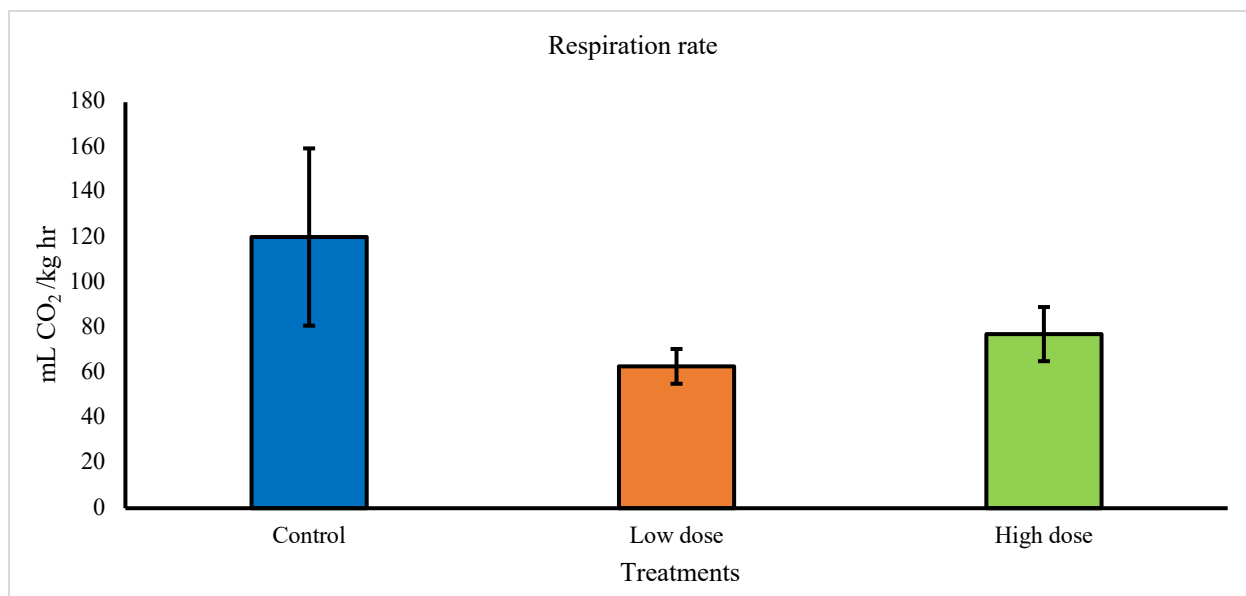


Figure 13. Respiration rate of romaine lettuce leaves (cultivar: Sparx) that was grown in a nutrient solution treated with low UV-C dose: 6L/min, high UV-C dose: 3L/min) and without UV-C. Measurements were taken on harvesting day. Error bars represent the standard error of the mean (SEM). Mixed model effects were used to analyze the effects of treatments.

Table 5. Macro-nutrient contents such as nitrogen, phosphorous, potassium, calcium, magnesium, and sulfate-sulfur in romaine lettuce leaves (cultivar: Sparx) that was grown in a nutrient solution, treated with low UV-C dose: 6L/min, high UV-C dose: 3L/min and without UV-C.

Treatments	Nitrogen (N %)	Phosphorous (P %)	Potassium (K %)	Calcium (Ca %)	Magnesium (Mg %)	Sulfate-sulfur (SO ₄ -S %)
Control	5.11 ± 0.23 a	1.02 ± 0.09 a	7.13 ± 1.22 a	0.84 ± 0.04 a	0.33 ± 0.02 a	0.29 ± 0.01 a
Low dose	5.05 ± 0.09 a	1.05 ± 0.06 a	7.08 ± 0.84 a	0.85 ± 0.03 a	0.33 ± 0.02 a	0.27 ± 0.02 a
High dose	5.03 ± 0.21 a	1.06 ± 0.09 a	6.94 ± 0.77 a	0.87 ± 0.04 a	0.35 ± 0.03 a	0.28 ± 0.01 a

Measurements were taken on harvest day (day 0). Results are presented as mean ± standard deviation (SD). Mixed model effects were used to analyze followed by Tukey's Honest Significant Difference (HSD) test. Means with the same connecting letter 'a' within each column were not significantly different among the treatments.

Table 6. Micro-nutrient contents such as copper, iron, manganese, and zinc in romaine lettuce leaves (cultivar: Sparx) that was grown in a nutrient solution treated with low UV-C dose:6L/min, high UV-C dose: 3L/min and without UV-C.

Treatments	Copper (Cu)	Iron (Fe)	Manganese (Mn)	Zinc (Zn)
..... ug/g DW.....				
Control	3.37 ± 2.25 a	139.07 ± 34.91 a	69.03 ± 7.8 a	36.23 ± 6.7 a
Low dose	4.46 ± 1.84 a	154.08 ± 61.1 a	77.29 ± 21.78 a	48.87 ± 26.25 a
High dose	4.68 ± 2.12 a	148.64 ± 30.81 a	68.96 ± 10.81 a	43.51 ± 11.68 a

Measurements were taken on harvest day (day 0). Results are presented as mean ± standard deviation (SD). Mixed model effects were used to analyze followed by Tukey's Honest Significant Difference (HSD) test. Means with the same connecting letter 'a' within each column was not significantly different among the treatments.

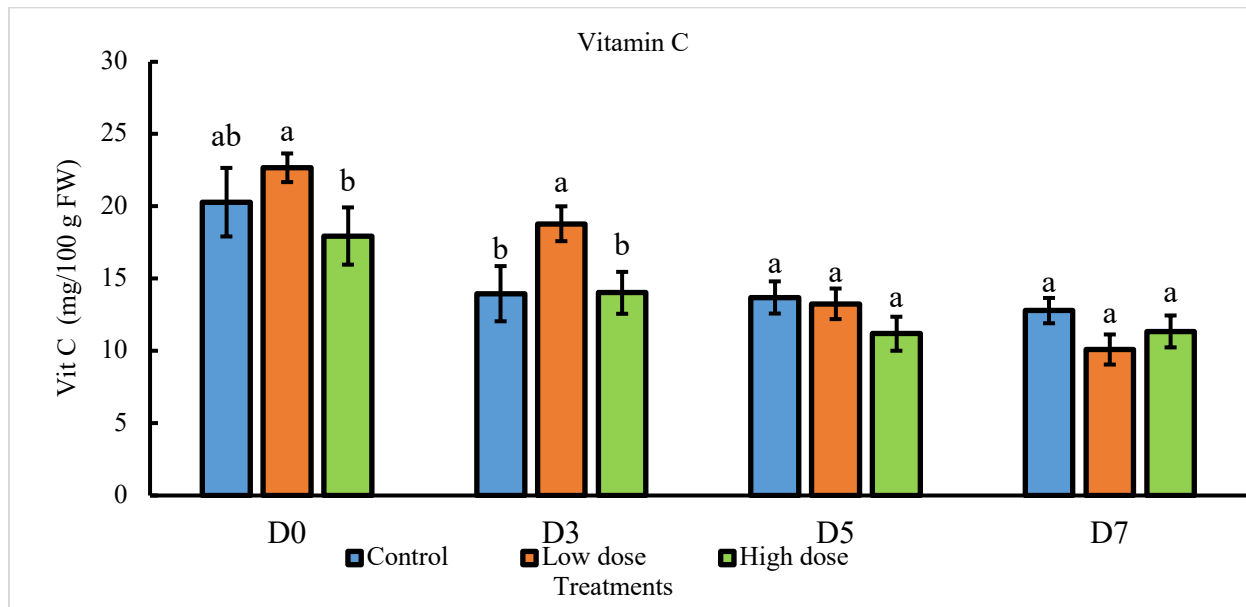


Figure 14. Vitamin C of romaine lettuce leaves (cultivar: Sparx) that was grown in a nutrient solution treated with low UV-C dose:6L/min, high UV-C dose: 3L/min) and without UV-C and stored at 4°C and 90% relative humidity (RH) for seven days. Vitamin C was measured on day 0 (D0), day 3 (D3), day 5 (D5), and day 7 (D7). Error bars represent the standard error of the mean (SEM). Similar letters 'a' are not significantly different among the treatments. Different letters (a, b) bars denote significant differences among the treatments. Groups labeled with 'ab' are not significantly different from either 'a' or 'b'.

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