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Effect of Nutrient Solution pH on the Growth and Quality of *Lactuca sativa* Grown in a Static Hydroponic System

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ABSTRACT

Lettuce is an easy-to-grow and nutrient-rich leafy vegetable. It grows well using a static hydroponic system, which saves space and is easy to maintain. However, understanding pH's impact on lettuce growth in static hydroponic systems is limited. Hence, this study was conducted to determine the effect of pH nutrient solution on the growth performance and eating quality of lettuce grown in a static hydroponic system. Lettuce was grown in pH 5.2, 6.2, and 7.2 nutrient solutions. Its growth performance was collected weekly, including plant height, root length, number of leaves, leaf area, leaf chlorophyll content, total dry weight, and total moisture content. The harvested lettuce was analyzed for firmness, soluble solids concentration, titratable acidity, pH, and ascorbic acid content by the fourth week after transplanting. The plant height, root length, number of leaves, leaf area, and total dry weight of lettuce were affected by the interaction between nutrient solution pH and weeks after transplanting. By the third week after transplanting, lettuce grown in pH 6.2 was 11.12 and 18.67% taller than those grown in pH 7.2 and 5.2 nutrient solutions, respectively. By the fourth week after transplanting, the firmness of lettuce grown in pH 6.2 was significantly higher than those grown in pH 5.2 and 7.2 nutrient solutions by 2.34 and 7.32%, respectively. It is concluded that lettuce should be grown in a pH 6.2 nutrient solution when using a static hydroponic system.

Keywords: Ascorbic acid content, dry weight, firmness, leaf area, weeks after transplanting

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INTRODUCTION

Urbanization or migration from rural to urban locations is common in developing

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countries. It has also occurred in Malaysia where in 2022, it was reported that 78.21% of Malaysia's total population lived in urban areas such as Kuala Lumpur, Shah Alam, Johor Bahru, Ipoh, Penang Island, and Alor Setar (Statista, 2024). It implies that rural areas are facing a reduction in the labor force to produce food, which leads to food insecurities among city dwellers. The Malaysian government has introduced the National Green Technology Policy (Ministry of Energy, Green Technology and Water, 2009) and Green Earth Program in 2005 (Jabatan Perancangan Bandar dan Desa Semenanjung Malaysia [PLANMalaysia], n.d.) under the Urbanization Program to reduce the dependency on food from rural areas. This program aims to alleviate urban agriculture with particular emphasis on cultivating, processing, and distributing food in or around the city for a better food supply system to ensure food security for the urban community.

For city dwellers, space is a constraint in the production of food. However, producing vegetables through a soilless culture of hydroponics, aquaponics, aeroponics, and vertical farming surrounding their homes is possible and has been given great attention by these communities (Muhammad & Rabu, 2015). In addition, vegetable production using soilless culture is more hygienic, consistent in height, and able to be planted at high density (Hopkinson & Harris, 2019). Among the soilless culture, the static technique is a low-cost and low-maintenance hydroponic production system that removes expenditures associated with greenhouse construction and its infrastructure (Gumisiriza et al., 2022). The system can be installed on verandas, balconies, and front or back gardens, and its materials can be reused numerous times. A nutrient solution is simply poured into a reservoir while plants are grown in the hydroponic net pots of floating polystyrene panels that float on a nutrient solution (Chang et al., 2018). The plant roots are partially or totally submerged in the nutrient solution until harvest. The nutrient solution is either replaced periodically with a fresh one or refilled after reaching a certain level of depletion (Biswas & Das, 2022). However, this system is only suitable for light feeders of leafy vegetables such as lettuce.

Lettuce or *Lactuca sativa* is widely grown worldwide and can be consumed raw or in salad. It is one of the most popular green leafy vegetables among Malaysians due to its flavor and great nutritional value (Yuen, 2023). Lettuce is low in sodium, calories, and fat but rich in iron, folate, vitamin C, and fiber (Kim et al., 2016). It is thought to be a crucial source of phytonutrients to treat inflammation, pain, gastrointestinal issues, and urinary tract infections (Noumedem et al., 2017). As such, lettuce is commonly cultivated by urban farming communities using a static hydroponic setup. However, the growth performance of lettuce often relies on readily available dissolved formulations of hydroponic fertilizers, which contain all the necessary macro- and micronutrients for optimal plant growth. However, the solubility and availability of essential nutrients for hydroponically cultivated crops are affected by nutrient solution pH (Solis & Gabutan, 2023).

The pH of nutrient solution is known to significantly affect nutrient solubility, particularly for micronutrients such as boron, copper, iron, manganese, and zinc, influencing their availability for uptake by plant roots (Sonneveld & Voogt, 2009). A nutrient solution with a high pH (e.g., > 6.5) may lead to nutrient removal through precipitation and depletion. In contrast, a moderately low pH (e.g., 5.8) helps maintain the availability of most solution ions (Anderson et al., 2017). Kudirka et al. (2023) found that lettuce cultivated in a nutrient solution with a pH of 5.0–5.5 exhibited a 41.4% reduction in zinc accumulation in its roots compared to lettuce cultivated in the pH range of 5.5–6.0. Zinc plays a crucial role as a regulatory component in numerous plant proteins and enzymes, contributing to various cellular and physiological activities related to plant growth, development, and yield (Saleem et al., 2022). Furthermore, the pH of the nutrient solution also influences the lettuce leaf area. Lettuce grown in a pH range of 5.0–5.5 exhibited 36 and 30% smaller leaf areas compared to those cultivated in pH ranges of 5.5–6.0 and 6.0–6.5, respectively (Kudirka et al., 2023). In another study, dandelion (*Taxacum officinale*) grown in pH 4.0 nutrient solution exhibited lower marketable leaf fresh weight compared to those grown in pH 5.5 and 7.0 (Alexopoulos et al., 2021). Additionally, the plants grown at pH 4.0 had less root fresh weight per plant compared to those grown at pH 5.5. However, the study also revealed that dandelion's nutritional and dietary value increased when the crop was grown in a pH 4.0 nutrient solution compared to other pH levels. The total soluble solids, titratable acidity, total phenolics, chlorophyll *a*, chlorophyll *b*, and total chlorophylls of dandelion leaves grown in pH 4.0 nutrient solution increased by 22.9, 29.2, 26.9, 13.45, 12.8, and 13.2%, respectively as compared to those grown in pH 7.0.

Leafy vegetables are usually cultivated in nutrient solutions of pH 5.5–6.5 (Savvas & Gruda, 2018). However, the optimum range of nutrient solution pH for ideal growth differs between plant species, cultivars and environmental, substrate or nutrient solution conditions. Despite the significant impact of pH on nutrient availability to plant roots, it often receives less attention from urban agriculture communities. Instead, they take heed of nutrient solution electrical conductivity (EC). The EC provides a reliable indication of the total ion concentration, facilitating the maintenance of optimal nutrient levels for plant growth (Singh & Bruce, 2016). Nevertheless, the availability of nutrients by plant roots is affected by the pH level of the nutrient solution. Unfortunately, very little information is available on the optimal nutrient solution pH for growing lettuce in a static hydroponic setup. Hence, this study was conducted to determine the effect of the pH of the nutrient solution on growth performance and the eating quality of lettuce grown in a static hydroponic system.

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MATERIALS AND METHODS

Lettuce Cultivation and Experimental Setup

Lettuce seeds (variety 004, Green World, Malaysia) were obtained from a local farm supply store (Dsyira Enterprise, Malaysia). A seed was sown into a sponge (2.5 x 2.5 x 2.5 cm^3), then placed into a plastic container (56 x 42 x 13 cm^3) filled with sufficient clean water. The container was covered with a dark plastic bag for three days. After three days, the bag was removed upon emergence of the lettuce radicles. Two true leaves emerged from each of the germinated seeds after 7 days. The 7-day-old healthy seedlings were transferred into 5-cm hydroponic net pots, with one plant per pot.

A total of eight 5-cm hydroponic net pots were then placed into the hole of a polystyrene panel that was set on the top of a nutrient reservoir (56 x 42 x 13 cm^3). The reservoirs were then filled with 18 L nutrient solutions prepared from AB Mix (Dsyira Enterprise, Malaysia). The AB Mix of hydroponic nutrition comprises A and B nutrients. Each component, weighing 12.5 kg, was simultaneously dissolved in 100 L of water using two separate tanks, creating stock solutions. The composition of stock A and B nutrient solutions is provided in Table 1.

The EC of nutrient solution in the reservoirs was maintained at 0.75, 1.0, 1.5, and 1.75 mS/cm during 0, 1, 2, and 3 weeks after transplanting, respectively (Nursyafiza, 2023). The EC levels were adjusted by adding stock solutions A and B to increase the nutrient solution EC or by reducing the water volume to lower the nutrient solution EC. An EC meter (DIST4 Hl98304, Hanna Instruments, Romania) was used to monitor the EC levels of nutrient solution weekly. The initial pH of the 18-L nutrient solution was 7.2 (after mixing 40 ml stock solution A and 40 ml solution B into water). Hence, a nutrient solution of pH 7.2 was used as

Table 1
Composition of nutrient solution stock A and stock B that forms AB Mix (Dsyira Enterprise, Malaysia)

Stock A		Stock B	
Nutrients	Quantity (g)	Nutrients	Quantity (g)
Calcium nitrate	18,720	Potassium nitrate	16,240
Iron (Ethylenediaminetetraacetic acid [EDTA])	328	Magnesium sulfate	9,840
		Monopotassium phosphate	5,260
		Cuprum (EDTA)	1.56
		Manganese sulfate	30
		Boric acid	60
		Zinc (EDTA)	4.40
		Ammonium molybdate	0.36

a control in the current study, while pH 5.2 and 6.2 were used as treatments. A 35% hydrochloric acid (Nacalai Tesque, Inc., Japan) was used to lower the nutrient solution pH to 5.2 and 6.2. The nutrient solution's pH was monitored weekly using a pH meter (HI98107, Hanna Instruments, Romania).

The study was laid in a completely randomized design with three treatments (pH 5.2, 6.2, and 7.2) and three replications. Three reservoirs of lettuce plants were prepared for each replication, leading to 72 plants per treatment, and a total of 216 plants were used in this study. The 27 reservoirs were arranged in a fully netted rain shelter with solid roofs of clear plastic. A 50% shade mesh net was used to reduce sunlight from the roof. The maximum day temperature and minimum night temperature of the rain shelter were 41 and 24.5°C, respectively. At the same time, the relative humidity of the rain shelter ranged from 49.5 to 54.0% during the day and 72.5 to 91% at night with the help of a data logger (EL-USB-2, Lascar, Hong Kong).

Since the lettuce was grown in a fully netted rain shelter, agrochemicals were not used to control pests and diseases. The depleted nutrient solution was topped up weekly to maintain a volume of 18 L in each reservoir while ensuring the nutrient solution was retained at a defined pH level. For growth performance analysis, one lettuce plant was harvested from each reservoir at weeks 1, 2, 3, and 4 after transplanting before 8.30 a.m. Nine plants per treatment were carefully placed in clear plastic bags and immediately transported to the laboratory for growth performance analysis. The growth performance of lettuce was analyzed for its shoot height, root length, leaf number, leaf chlorophyll content, leaf area, total dry weight, and total moisture content. By week 4, after transplanting, the remaining lettuces were harvested, packed in clean plastic bags, and carefully transported to the laboratory. The samples were kept in a 10±2°C chiller, and eating quality analysis was carried out within 48 hr. The eating quality, including leaf firmness, soluble solids concentration (SSC), titratable acidity (TA), pH, and ascorbic acid content, was analyzed.

Determination of Lettuce Plant Growth Performance

The plant height of lettuce was measured from the aboveground base to the tip of the highest shoot using a ruler and expressed in centimeters (cm). The root length of lettuce was measured using a ruler from the base of the aboveground to the tip of the longest root and expressed in cm. The number of completely formed leaves was counted manually and recorded. An automatic leaf area meter (Model LI-3100, LI-COR, USA) was then used to quantify the leaf area of lettuce and expressed in cm^2. It was followed by collecting lettuce leaf chlorophyll with a soil plant analysis development (SPAD) meter (SPAD-502, Minolta, Japan). The leaf chlorophyll was collected by scanning leaves positioned at the top, middle and bottom of a lettuce plant, and the average of the leaf chlorophyll was expressed in the SPAD unit. The fresh weight (FW) of a lettuce plant (including both shoot and root) was weighed using an electronic balance (FX-300i, A&D, Japan) before drying in an oven (Memmert-Schutzart DIN40050-IP20, Germany) at 50±2°C. After 72 hr, the total dry weight (DW) (including both shoot and root) of a lettuce plant was weighed, and the total moisture content (including both shoot and root) of the lettuce was calculated as follows: total moisture content (%) = (FW – DW)/FW * 100%.

Determination of Lettuce Eating Quality Characteristics

The firmness of lettuce leaf was measured using the Instron Universal Testing Machine (5543P5995, Instron Corp., USA) fitted with a 6-mm diameter cylindrical probe and a 5-kg load cell. The leaf was penetrated with a probe to a depth of 1 mm at a crosshead speed of 20 mm/min. The force penetrating the leaf was recorded in Newton (N) with the help of Instron Merlin Software version M12-13664-EN. For SSC, 5 g of lettuce leaf was homogenized with 40 ml of distilled water. The homogenate was then filtered using cotton, and two drops of the filtrate were placed on the prism of a hand-held digital refractometer (ATAGO RX-5000, USA). The reading was then recorded as %SSC. The remaining filtrate prepared for SSC analysis was then used for TA and pH analysis. TA was determined using the acid-base titration method (Md Nor et al., 2023). The titration was performed using a 5-ml filtrate to which 2 drops of 1% phenolphthalein (Sigma-Aldrich, USA) were added. It was titrated against 0.1 N sodium dioxide (Sigma-Aldrich, USA) until a light pink color solution appeared. The results were expressed as a percentage of citric acid. The pH of lettuce filtrate was measured with the help of a pH meter (Crison Micro pH 2000, Crison Instruments, Spain). A modified method from Mariani et al. (2018) was used to determine the ascorbic acid content in lettuce. Five grams of lettuce leaves with their stems were homogenized with 45 ml of 2% metaphosphoric acid (HPO_3, Sigma-Aldrich, USA). After filtering the homogenate through cotton, 5 ml of filtrate was added to 10 ml of 2,6-dichlorophenol-indophenol dye solution (Sigma-Aldrich, USA). The mixture was then measured at a wavelength of 518 nm using a spectrophotometer (WPA S1200, SpectraWAVE, USA). The concentration of ascorbic acid in the lettuce was determined from the standard curve, and the amount of ascorbic acid in the lettuce was calculated using the following equation: ascorbic acid (mg/100 g) = (ascorbic acid content × volume made up × 100) / (volume of solution taken for estimation × 1000 × weight of sample taken).

Statistical Analysis

The collected data were analyzed using analysis of variance (ANOVA). Duncan's multiple range test (DMRT) was applied to separate the means when *F*-values showed significance at the 5% level, using Statistical Analysis System software (version 9.4). A two-factor ANOVA was utilized to assess growth performance, while a single-factor analysis was employed to evaluate the eating quality of lettuce.

RESULTS

Growth Performance

The results of the ANOVA showed a significant interaction between the pH levels of the nutrient solution of the static hydroponic system and the weeks after transplanting (Table 2). This interaction affects various aspects of lettuce growth, including plant height, root length, number of leaves, leaf area, and total dry weight.

Figure 1 shows the interaction effects of nutrient solution pH and weeks after transplanting on lettuce plant height. Regardless of the pH levels, there was no significant difference in plant height during the first and second weeks of growing. By week 3, after transplanting, the plant height of lettuce grown in a static hydroponic system with pH 6.2 was higher than the other two pH levels. A more obvious increase in height was observed when lettuce grew to week 4 after transplanting. The height of lettuce grown in nutrient solution pH 6.2 was the highest, followed by lettuce grown in pH 7.2 and 5.2.

The root length of lettuce follows the trend of its height, where the nutrient solution pH did not affect the root length during the initial stage of growth (Figure 2). By week 3, after transplanting, the root lengths of lettuce grown at pH 6.2 and 7.2

Table 2
Main and interaction effects of nutrient solution pH and weeks after transplanting on growth characteristics of lettuce grown in a static hydroponic system

Factors	Plant height (cm)	Root length (cm)	No. of leaves	Leaf chlorophyll (SPAD unit)	Leaf area (cm^2)	Total dry weight (g)	Total moisture content (%)
Levels of pH (L)							
5.2	10.21 c^z	9.57 c	10.53 b	21.07 a	288.41 b	0.81 b	94.77 a
6.2	12.32 a	13.67 a	12.22 a	20.59 a	552.18 a	1.41 a	94.85 a
7.2	10.85 b	12.15 b	10.13 b	20.68 a	321.67 b	0.82 b	93.88 b
Weeks after transplanting (W)							
1	2.40 d	5.67 c	3.00 d	12.38 d	0.94 c	0.003 c	93.24 b
2	4.19 c	4.87 c	5.00 c	16.01 c	5.96 c	0.021 c	93.73 b
3	12.56 b	16.60 b	13.26 b	28.19 a	225.79 b	0.571 b	94.61 a
4	25.16 a	19.83 a	22.26 a	25.93 b	1282.84 a	3.365 a	95.28 a
Interaction							
L x W	*	*	*	NS	*	*	NS

Note. ^{z}Means separation (n = 9) followed by the same letters is significantly different at $P \leq 0.05$ according to Duncan's multiple range test
NS, * = Nonsignificant or highly significant at $P \leq 0.05$, respectively; SPAD = Soil plant analysis development

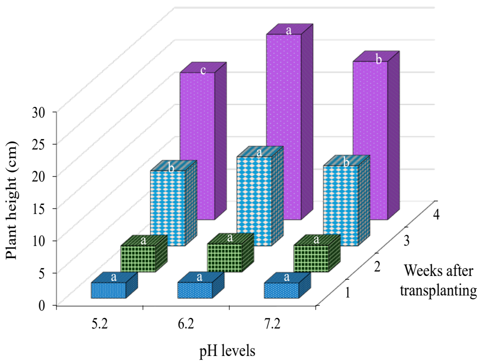

Figure 1. The effects of nutrient solution pH levels and weeks after transplanting on the plant height of lettuce grown in a static hydroponic system

Note. Means followed by different letters are significantly different ($P \leq 0.05$) within each pH level

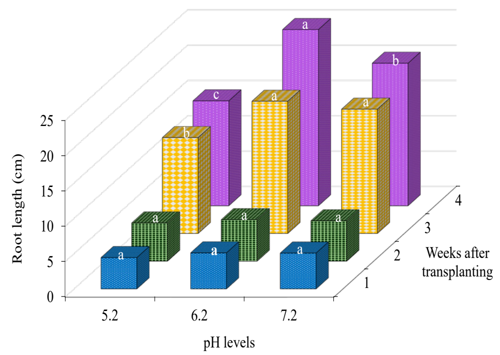

Figure 2. The effects of nutrient solution pH levels and weeks after transplanting on the root length of lettuce grown in a static hydroponic system

Note. Means followed by different letters are significantly different ($P \leq 0.05$) within each pH level

were significantly longer than those grown at pH 5.2. However, by week 4, the root length of lettuce grown in nutrient solution pH 6.2 surpassed those grown in pH 7.2 and 5.2.

The number of lettuce leaves was not affected by weeks after transplanting until it was ready to be harvested by week 4 (Figure 3). Lettuce grown in nutrient solution with a pH of 6.2 had the most leaves, followed by plants grown at pH 5.2 and 7.2. Similar to the number of leaves, there were no changes in the leaf area of lettuce that grew in nutrient solution pH 5.2, 6.2, and 7.2 during the initial stage of growth (Figure 4). By week 3, the leaf area of lettuce grown in nutrient solution pH 6.2 had surpassed other pH levels, and the trend continued until the lettuce was harvested at week 4 after transplanting.

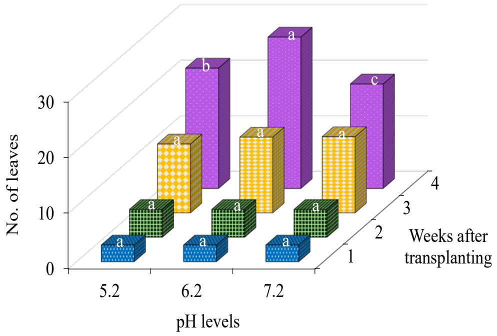

Figure 3. The effects of nutrient solution pH levels and weeks after transplanting on the leaf number of lettuce grown in a static hydroponic system

Note. Means followed by different letters are significantly different ($P \leq 0.05$) within each pH level

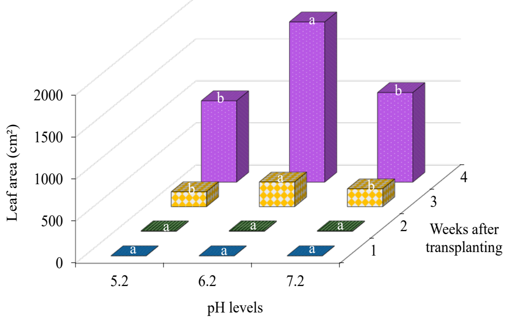

Figure 4. The effects of nutrient solution pH levels and weeks after transplanting on the leaf area of lettuce grown in a static hydroponic system

Note. Means followed by different letters are significantly different ($P \leq 0.05$) within each pH level

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As found in plant height, root length, number of leaves and leaf area, the dry weight of lettuce during the first two weeks of growth did not show any differences among nutrient solutions with various pH levels (Figure 5). The differences can be found after the lettuce has grown for three weeks. When lettuce grows in nutrient solution pH 6.2, it shows a higher dry weight than other pH levels. The significant differences extended to week 4 after transplanting.

The ANOVA results show no significant interaction between the pH of the nutrient solution and the weeks after transplanting on leaf chlorophyll content and total moisture content (Table 2). Unlike other growth parameters, the chlorophyll content of lettuce was not affected by the pH of the nutrient solution. However, as measured using SPAD, the leaf chlorophyll content increased as the lettuce grew, reaching its maximum at 3 weeks after transplanting. After that, the leaf chlorophyll decreased as the lettuce approached harvest readiness. It implies that lettuce enters the senescence phase by week 4 after transplanting, which is marked by the deterioration of leaf chlorophyll pigment. For total moisture content, lettuce grown in a nutrient solution of pH 7.2 has significantly lower moisture content than those grown in pH 5.2 and 6.2 (Table 2). During initial growth, there was no change in lettuce moisture content. However, the moisture content increased by the third week after transplanting and plateaued throughout its growth.

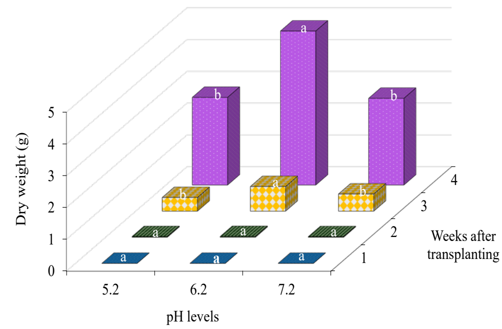

Figure 5. The effects of nutrient solution pH levels and weeks after transplanting on the dry weight of lettuce grown in a static hydroponic system

Note. Means followed by different letters are significantly different ($P \leq 0.05$) within each pH level

Eating Quality

The eating quality of lettuce was determined immediately after harvesting. The firmness of lettuce was influenced by the pH levels of the nutrient solution during planting, with pH 6.2 yielding the firmest lettuce, followed by pH 5.2 and 7.2 (Table 3). Similarly, the concentration of soluble solids in lettuce produced from pH 6.2 nutrient solution was significantly higher than those from pH 5.2 and 7.2. However, the pH levels of the nutrient solution did not affect the TA of lettuce. Furthermore, the pH of lettuce was influenced by the pH of the nutrient solution, with lettuce grown in a system with pH 6.2 exhibiting a significantly higher pH than those grown in pH 5.2 and 7.2 solutions. Interestingly, the ascorbic acid content of lettuce did not follow the trend observed in other eating quality characteristics, as lettuce harvested from pH 6.2 nutrient solution had lower ascorbic acid content than those grown in pH 5.2.

Table 3
Eating quality characteristics of lettuce grown in a static hydroponic system using three levels of nutrient solution pH

Nutrient solution pH levels	Firmness (N)	Soluble solids concentration (%SSC)	Titratable acidity (%)	pH	Ascorbic acid content (mg/100 g)
5.2	57.33 b[z]	0.63 b	0.31 a	6.13 b	20.68 a
6.2	58.67 a	0.87 a	0.32 a	6.24 a	20.00 b
7.2	54.67 c	0.68 b	0.27 a	6.17 b	20.16 ab

Note. [z]Means separation (n = 9) followed by the same letters within a column is significantly different at $P \leq 0.05$ according to Duncan's multiple range test

DISCUSSION

The optimal pH range for most hydroponically grown leafy vegetables ranges between pH 5.5 and 6.5 (Savvas & Gruda, 2018). The current study reveals that the growth performance of lettuce grown in pH 6.2 nutrient solution is superior to those cultivated in pH 5.2 and 7.2. A similar finding was also reported in lettuce grown using the nutrient-film technique, where the performance of lettuce grown in pH 6.0 and 6.2 nutrient solutions was better than those grown in pH 5.8 and 6.4 (Samarakoon et al., 2020). *Taraxacum officinale* and *Reichardia picroides* plants grown in pH 5.5 nutrient solution using a floating hydroponic system exhibited better growth performance than those grown in pH 4.0 and 7.0 solutions (Alexopoulos et al., 2021). For 'Corvair' spinach grown in pH 4.0, 4.5, 5.0, and 5.5 nutrient solutions, shoot, and root mass decreased with decreasing nutrient solution pH, with lower pH levels producing lighter plants (Gillespie et al., 2021). The stunted growth of spinach cultivated in a pH 4.0 nutrient solution severely inhibited root development. Nutrient solution pH plays an important role in crop growth.

The significant reduction in lettuce height (Figure 1) and root length (Figure 2) grown in this study's 5.2 nutrient solution is likely due to reduced nutrient uptake by plants. Previous studies have highlighted that nutrient solution pH is one of the most critical factors affecting nutrient availability, uptake, and solubility by plants (Fathidarehnijeh et al., 2023). When pH deviates from the optimal range, nutrients become less available, rendering plants unable to absorb them efficiently. Under high pH conditions, calcium and magnesium precipitate, while iron and phosphate remain insoluble. As a result, these ions become unavailable for root absorption, leading to the inhibition of micronutrient absorption such as iron, copper, zinc, and manganese (Gillespie et al., 2020; Singh et al., 2019; Velazquez-Gonzalez et al., 2022). By analyzing spinach tissue grown in pH 4.0, 4.5, 5.0, and 5.5 nutrient solutions, it was observed that the concentration of nitrogen, phosphorus, potassium, magnesium, copper, iron, manganese, and zinc decreased as the pH of the nutrient solution decreased (Gillespie et al., 2021). Samarakoon et al. (2020) reported that lettuce grown in a pH 6.0 nutrient solution exhibited higher nitrogen levels in its tissue, resulting in a greater yield compared to lettuce grown in a pH 5.8 nutrient solution.

Nitrogen is an important element in chlorophyll pigment and is essential for photosynthesis. In the present study, SPAD was used to measure the chlorophyll content of lettuce, and the finding reveals that the pH of the nutrient solution did not affect lettuce leaf chlorophyll content (Table 2). A similar result was reported by Singh et al. (2019), where no significant difference was observed in Swiss chard (*Beta vulgaris* L.) SPAD values among different pH levels of nutrient solutions. The SPAD meter is recognized as a useful tool for measuring leaf greenness, as it is closely linked to chlorophyll content (Azia & Stewart, 2001). The chlorophyll content in leaves is known to reflect the physiological status of a plant (Gitelson et al., 2003). It is commonly used to indicate chloroplast development, photosynthetic capacity, leaf nitrogen content, or overall plant health (Ling et al., 2011). Previous studies have reported that the SPAD value can estimate the nitrogen status of various plant species (Colla et al., 2010). This finding corroborates that the pH of nutrient solutions did not affect nitrogen availability in the lettuce of the current study. Although the chlorophyll content of lettuce in this study was not affected by the pH of the nutrient solution, it exhibited an increase from weeks 1 to 3 after transplanting, followed by a subsequent decrease (Table 2). The decline in chlorophyll content in lettuce leaves indicates the onset of senescence. The primary morphological sign of leaf senescence is the transition of leaf colour from green to yellow (Zhao et al., 2022). This phenomenon is attributed to nitrogen redistributing during leaf senescence, leading to leaf yellowing (Havé et al., 2017).

Nutrient content in the growing medium affects the eating quality of vegetables. Nitrogen application rate can affect the head compactness of crisphead varieties of lettuce, and the head weight of cos lettuce cultivated in an automated glasshouse (Konstantopoulou et al., 2010). Fresh-cut celery (*Apium graveolens*) quality was improved when grown under low or adequate nitrogen fertilization (Babalar et al., 2022). Increasing nitrogen levels decreases the vitamin C content of cauliflower (*Brassica oleracea* Botrytis Group) (Lee & Kader, 2000). In another study, increased nitrogen fertilizer rate decreased harvested cabbage's vitamin C and dietary fiber (*B. oleracea* Capitata Group). However, a contradicting finding was reported in minimally processed Swiss chard, where plants treated with higher nitrogen content contained higher vitamin C levels compared to those grown with lower fertilizer rates (Miceli et al., 2018). The nitrogen fertilization rates affect the eating quality of vegetables.

In addition to nitrogen, it was found that high rates of phosphorus fertilizer increase the SSC of tomatoes (Weston & Barth, 1997). If there is a lack of phosphorus, the filling of corn ears (*Zea mays* L.) will be affected, leading to poor-quality ears. In hydroponically grown lettuce, an increase in nutrient solution pH elevates the proportion of potassium compared to magnesium or calcium. Insufficient calcium causes tip burn in leafy crops, blossom-end rot in tomatoes, and blackheart in celery during vegetable cultivation. These insights underscore the importance of nutrient management strategies tailored to specific crop requirements to optimize yield and quality in agricultural production. Unfortunately, the tissue nutrients of lettuce leaves were not analyzed in this study to correlate the pH of the solution with the nutrient contents in lettuce.

CONCLUSION

The pH of the nutrient solution in a static hydroponic system can significantly impact lettuce growth, including plant height, root length, number of leaves, leaf area, and weight, particularly after 3 weeks of transplanting. Additionally, the pH of the nutrient solution influences the firmness, SSC, TA, pH, and ascorbic acid content of lettuce. In conclusion, maintaining a pH of 6.2 in a static hydroponic setup is recommended to achieve optimal growth performance and eating quality of lettuce.

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