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RESEARCH ARTICLE

Sustainable hydroponic lettuce production with artificial lighting and different nutritional irrigation parameters

Glauco V. Miranda[1*], Oneir S. Molina[1], Dayane Carvalho[2], Jakeline da S. Andrade[3], and Pedro L. de Paula Filho[3]

[1]Universidade Tecnológica Federal do Paraná, Santa Helena, Paraná, Brasil.
[2]Faculdade Uniguaçu, São Miguel do Iguaçu, Paraná, Brasil.
[3]Universidade Tecnológica Federal do Paraná, Medianeira, Paraná, Brasil.
*Corresponding author (glaucovmiranda@utfpr.edu.br).
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ABSTRACT

The hydroponic indoor production of lettuce (*Lactuca sativa* L.) represents a technological advancement in cultivation methods, emphasizing sustainability. This study aimed to identify the optimal management strategy for indoor hydroponic crisp lettuce (*L. sativa* L. var. *crispa* L.) production under artificial lighting and varied nutritional and irrigation parameters. Experiments were conducted in a refrigerated container using hydroponic benches with six hydroponic profiles with nutrient film techniques, each with an independent management system. The crisp lettuce 'BS AC0055' was harvested 21 d post-transplantation. The optimal management for combinations of irrigation interval (IR), electrical conductivity (EC), and pH was found to be 16 min, 1.6 dS m^{-1}, and 6.10, respectively, resulting in productivity of 138 g plant^{-1}. It is concluded that optimal pH plays a crucial role in determining the significant impact of IR and EC on plant productivity. Once the ideal EC 1.9 dS m^{-1} is achieved, the irrigation interval becomes secondary in the range of 22 to 42 min, given that the pH is also maintained within the appropriate range of 6.0 to 6.2. The study also demonstrated the attainment of highest productivity through various combinations of irrigation interval, EC, and pH.

Key words: Controlled environment agriculture, protected environment, urban agriculture, vertical farm.

INTRODUCTION

Closed environments employing artificial lighting in agriculture, known as Controlled Environment Agriculture (CEA), with automated monitoring and control systems, are revolutionizing plant production (Kozai et al., 2021). These environments, such as vertical farms, are creating new business models (Lucena, 2016; Kozai et al., 2021; Wicharuck et al., 2023). The CEA represents an advanced and intensive form of indoor hydroponic production designed to maximize yields, minimize resource waste, and accelerate plant cycles, a practice often referred to as "speed breeding" (Watson et al., 2018).

New research is exploring the integration of emerging technologies, such as smart sensors and advanced automation, to continuously monitor and adjust cultivation parameters in real time (Kozai, 2021; Hubner et al., 2024). This not only enhances cultivation efficiency but also enables the production of high-quality food in urban environments, reducing reliance on traditional agricultural methods and promoting sustainability (Kozai et al., 2019; Wicharuck et al., 2023). The integration of these technologies can revolutionize urban agriculture and ensure a continuous supply of fresh, nutritious produce regardless of external climatic conditions.

Hydroponic systems under artificial lighting can play a pivotal role in the circular economy by minimizing waste and reusing resources. The nutrient solution used in hydroponics can be recycled and adjusted to maintain optimal growing conditions, reducing the need for freshwater and fertilizers. This aligns with the principles of a circular economy, which aims to create closed-loop systems that minimize waste and make the most of available resources (Ellen MacArthur Foundation, 2017). By integrating waste management and resource efficiency, hydroponic systems can contribute to more sustainable agricultural practices and support urban food security.

Hydroponics, the method of growing plants without soil by providing nutrients through an aqueous solution, is a highly sustainable approach, reducing water usage and improving energy efficiency. In lettuce cultivation, hydroponics offers advantages in obtaining higher yields, with daily control of nutrient solutions. The optimal water flow rate for nutrient uptake was investigated in hydroponic lettuce using the nutrient film technique (Al-Tawaha et al., 2018). Flow rates of 10, 20, and 30 L h^{-1} were tested, with 20 L h^{-1} showing the best results for growth parameters such as plant height and leaf count. Increasing the flow rate to 30 L h^{-1} led to decreased growth and biomass. The study concluded that a flow rate of 20 L h^{-1} is ideal for enhancing lettuce growth, as it provides effective nutrient absorption without excessive water movement.

The combination of hydroponics with smart technology offers a promising approach to efficient and environmentally friendly crop production (Rajaseger et al., 2023). This method eliminates the need for soil and reduces water usage by delivering nutrients directly to plant roots. "Smart farming" incorporates Internet of Things (IoT), sensors, and automation for continuous monitoring and fine-grained management of farming conditions, enhancing crop output, growth rates, and year-round optimal conditions. It also reduces the need for organic chemical inputs, supports eco-friendly pest management, and minimizes waste. This innovative approach could transform agriculture by promoting localized food production, improving food security, and fostering resilient farming practices.

Real-time control of the cultivation environment ensures optimal production factors, including increased CO_2 levels stimulating plant growth, and the absence of abiotic and biotic stresses that typically limit productivity. However, this environment necessitates specific management practices, such as precise fertilization, irrigation interval, etc. (Kozai et al., 2021; Wicharuck et al., 2023).

Despite advancements in lighting, robotics, artificial intelligence, big data, and the IoT, the role of cultivars in CEA is often underutilized to plant production. The full potential of indoor production platforms will only be realized when cultivars are specifically selected and optimized for these conditions. Previous research emphasizes the importance of selecting cultivars tailored to the production environment for maximizing productivity (Folta, 2019; Borém et al., 2021).

It is now possible to obtain and select genotypes suitable for controlled environments, producing cultivars that enhance the sensory experience for consumers, increase profitability for producers, and reduce energy requirements in their production (Folta, 2019). The ultimate goal of CEA is to produce fresh, high-value-added products and new plant genetics with maximum productive potential.

Plants can be genetically improved to enhance the accumulation of specific nutrient compounds and secondary metabolites (Hefferon, 2015). Secondary metabolites, such as antioxidants, polyphenols, anthocyanins, and essential oils, are often under the influence of light signals (Kopsell et al., 2015). Environmental variables, especially light, can modulate the accumulation of these compounds in various plant species, leading to improved nutritional profiles (Kopsell et al., 2014; Carvalho and Folta, 2014; Ghaffari et al., 2019).

Researchers have successfully produced lettuce under artificial lighting conditions, achieving favorable results. For example, Matysiak et al. (2022) produced heavier romaine lettuce under different light intensities in a controlled environment with a 20 h photoperiod and a photosynthetic photon flux density (PPFD) of 240 µmol m^{-2} s^{-1}. Hubner et al. (2024) evaluated lettuce 'BS AC0055', 'BS AC0155', and 'BS AL0071' in the experiment with nutrient film technique (NFT) hydroponic system with photoperiods set at 14, 16, 18, and 20 h, maintaining a photosynthetically active radiation (PAR) of 248 µmol m^{-2} s^{-1}. The significant effects observed in the interaction between cultivar and photoperiod emphasize the distinct behaviors exhibited by each cultivar under different photoperiods, and vice versa. This conclusion underscores the importance of selecting specific cultivars tailored for indoor production, as cultivars demonstrate varied responses to varying photoperiods.

This study aimed to identify the optimal management strategy for indoor hydroponic lettuce production under artificial lighting and varied nutritional and irrigation parameters.

MATERIALS AND METHODS

The experiments were conducted at the Federal Technological University (UTFPR) Campus Santa Helena between April and September 2023. The Agroindoor Laboratory, located on-site, is housed within a thermally insulated shipping container measuring 12 m (L) × 2.39 m (W) × 2.90 m (H) (Figure 1). The laboratory ensures complete absence of natural light, equipped with a 30 000 BTU air conditioner for cooling, and monitored and maintained relative humidity through exhaust systems. In this controlled indoor production environment, temperatures range from 25 °C under artificial lighting to 19 °C without artificial lighting.

Figure 1. Repurposed ship container with a refrigerated environment used for indoor plant production.

The experiments were arranged on a hydroponic bench, each measuring 6 m in length and 0.8 m in width. This bench accommodated six hydroponic profiles with a plant spacing of 12.5 cm and a depth of 3 cm (Figure 2). Each hydroponic profile received nutrient solution from a dedicated reservoir, with varying concentrations of electrical conductivity (EC) and pH based on the irrigation management strategy (Figure 2).

Figure 2. Details of the hydroponic bench with lights and hydroponic profiles and individual solution reservoirs.

The air and light conditions in the hydroponic benches were continuously monitored using sensors. The lighting setup for vegetative growth consisted of red and blue lights in a 3:1 ratio, maintaining a light intensity of photosynthetic photon flux density (PPFD) at 200 µmol m^{-2} s^{-1}. These conditions were measured using a spectrometer spectrum analyzer (model OHSP-350C, Hopoocolor, Shenzhen, Guangdong Province, China) and monitored on a weekly basis (Figure 2).

The experimental conditions were carefully controlled throughout the hydroponic cultivation process. The relative humidity was maintained at 50 ± 10% and under artificial lighting conditions and 80 ± 10% without artificial lighting. Real-time monitoring of air temperature was conducted using the AM2302 DHT22 sensor integrated into Arduino (Aosong Electronics, Guangzhou, Guangdong Province, China), and the readings were displayed on a digital monitor.

A consistent photoperiod of 16:8 h with artificial lighting was meticulously controlled using an analog timer. The nutrient solution's temperature was maintained at 20 °C, ensuring the oxygen saturation in the solution remained at 80%. Parameters such as temperature, EC, pH, and dissolved oxygen in the nutrient solution were monitored daily using the multiparameter sensor Akso, AK 88 (Akso, São Leopoldo, Rio Grande do Sul, Brazil). The pH and EC were checked daily and adjusted according to the treatments.

In each hydroponic bench profile, specific treatments were applied by combining irrigation intervals, pH levels, and EC values. The irrigation process was regulated by a timer, allowing water flow for 1 min at a rate of 1 L min^{-1} profile^{-1}, and then turned off based on the designated treatment.

The nutrient solution composition was adjusted for each EC. This nutrient solution comprised 14.2 µmol L^{-1} N, 1.26 µmol L^{-1} P, 4.68 µmol L^{-1} K, 4.24 µmol L^{-1} Ca, 1.65 µmol L^{-1} S, 1.69 µmol L^{-1} Mg, 0.0073 µmol L^{-1} Mn, 0.0925 µmol L^{-1} B, 0.0032 µmol L^{-1} Zn, 0.0451 µmol L^{-1} Fe, 0.00104 µmol L^{-1} Mo and 0.0079 µmol L^{-1} Cu.

Each hydroponic bench profile or treatment underwent evaluation with 20 plants. The experimental design included four replicates conducted over time, with each transplant season considered as a repetition or experimental block. The crisp lettuce (*Lactuca sativa* L. var. *crispa* L.) cultivar used was BS AC0055 from Blueseeds (Holambra, São Paulo, Brazil), and plant harvesting occurred at 21 d post-transplanting, focusing on assessing the plant's fresh weight (Figure 3). Statistical analyses, including ANOVA and the Tukey test at a 5% probability level, were employed to evaluate the effectiveness of different management practices.

Figure 3. Lettuces from indoor production experiments at different stages of development with details of the hydroponic bench.

RESULTS AND DISCUSSION

In the initial experimental set, the electrical conductivity (EC) was held constant at 1.6 dS m^{-1}. Various combinations of irrigation intervals, ranging from 14 to 42 min, were examined alongside pH values spanning from 5.7 to 6.3 (Table 1). The most favorable productivity, at 138 g plant^{-1}, was achieved with a 16 min irrigation interval and a pH of 6.10. Another noteworthy result was a productivity of 94 g plant^{-1} obtained with a 34 min irrigation interval and a pH of 6.0. Conversely, the lowest productivity was observed when combining lower pH values with both higher and lower irrigation intervals, indicating that lower pH levels acted as limiting factors for productivity. Furthermore, productivity was minimized with the highest pH of 6.3, suggesting an upper threshold for this parameter.

Table 1. Fresh weight of lettuce plants cultivated with different irrigation intervals (IR) and pH, and electrical conductivity of 1.6 dS m^{-1}. Distinct letters in the row indicate significant differences according to Tukey's test ($P \leq 0.05$).

Management	Irrigation intervals	pH	Productivity
	min		g plant^{-1}
Management 1_IR_pH	14	5.9	82^{c}
Management 2_IR_pH	16	6.1	138^{a}
Management 3_IR_pH	34	6.0	94^{b}
Management 4_IR_pH	34	6.3	85^{c}
Management 5_IR_pH	42	5.7	82^{c}

According to the lettuce production manual for controlled environments authored by Brechner and Both (2013), the optimal pH for lettuce cultivation is 5.8, with a permissible range of 5.6-6.0. In this study, considering the irrigation interval dependency, the ideal pH was identified as 6.1, with the lower limit approaching pH 6.0 and the upper limit reaching around 6.2.

Irrigation management for indoor production significantly differs from field irrigation and traditional hydroponics. In conventional hydroponics, the irrigation frequency is temperature-dependent, typically activated for 10 to 20 min and then deactivated for 10 min, with a flow rate of 1 to 3 L min^{-1} (Çekin et al., 2024). Notably, water consumption in indoor production is only 4 L h^{-1} profile^{-1} during 16 h^{-1} d^{-1}, whereas in traditional hydroponics, it ranges from 30 to 40 L h^{-1} profile^{-1} with a flow rate of 1 L min^{-1} during 12 h d^{-1}.

Irrigation intervals should be adjusted according to the water needs of the plants and environmental conditions. Mineral content, fresh and dry weight of lettuce under four different ebb and flow irrigation intervals suggest most optimal irrigation conditions between 5 and 15 min within this experimental set-up (Post, 2023). In indoor cultivation systems, where humidity and temperature can be controlled, it is possible to optimize the irrigation frequency to avoid both excess and lack of water. Studies show that regular irrigation intervals, adapted to the plant's developmental stage, cultivar and environmental conditions contribute to uniform growth and the quality of the final product (Silva et al., 2016; Post, 2023).

In the second experimental set, the irrigation interval was fixed at 34 min, and the EC varied from 1.6 to 1.9 dS m^{-1}, with pH ranging from 6.0 to 6.4 (Table 2). The highest productivity recorded was 120 g plant^{-1} for the combination of 1.9 dS m^{-1} EC with pH 6.2, while a productivity of 94 g plant^{-1} was observed for 1.6 dS m^{-1} EC with pH 6.0. Conversely, the lowest productivities were 74 g plant^{-1} for 1.7 dS m^{-1} EC with pH 6.4 and 85 g plant^{-1} for 1.6 dS m^{-1} EC with pH 6.3. It is evident that productivity decreases with pH above 6.2, and an increase in EC enhances productivity as long as the pH does not exceed 6.2. These findings align with the results obtained from treatments combining irrigation interval and pH with 1.6 dS m^{-1} EC. Sapkota et al. (2019), in their study involving two lettuce cultivars and different nutrient dosages, achieved a fresh weight per plant of up to 115 g, harvested 30 d after transplanting.

The nutrient film technique (NFT) and floating systems produced the highest leaf yield and quality, particularly with a nutrient solution concentration of 1.60 dS m^{-1} (Góis et al., 2024). The 'Cinderella' lettuce exhibited the greatest average leaf fresh mass, total dry mass, leaf area, and vitamin C content. Meanwhile, the semi-hydroponic system fostered greater plant development when using a more concentrated nutrient solution (2.90 dS m^{-1}).

Table 2. Fresh weight of lettuce plants cultivated with different electrical conductivity (CE) and pH, with a constant irrigation interval of 34 min. Distinct letters in the row indicate significant differences according to Tukey's test ($P \leq 0.05$).

Management	Electrical conductivity	pH	Productivity
	dS m^{-1}		g $plant^{-1}$
Management 1_CE_pH	1.6	6.3	85^{bc}
Management 2_CE_pH	1.6	6.0	94^{b}
Management 3_CE_pH	1.7	6.4	74^{c}
Management 4_CE_pH	1.9	6.2	120^{a}

In the third experimental set, the pH was maintained at 6.0, while the irrigation interval ranged from 22 to 41 min, and EC varied from 1.3 to 2.2 dS m^{-1} (Table 3). The highest productivity recorded was 127 g $plant^{-1}$ for the combination of 2.2 dS m^{-1} EC with a 22 min irrigation interval, and 125 g $plant^{-1}$ for 1.9 dS m^{-1} EC with a 41 min irrigation interval. These results suggest that an EC above 1.9 dS m^{-1} had a more positive impact on productivity than the irrigation interval. Conversely, the lowest productivity, at 65 g $plant^{-1}$, was observed for 1.3 dS m^{-1} EC with a 35 min irrigation interval, emphasizing the detrimental effect of low EC on productivity.

Table 3. Fresh weight of lettuce plants cultivated with irrigation intervals (IR) and electrical conductivity (CE) with constant pH of 6.0. Distinct letters in the row indicate significant differences according to Tukey's test ($P \leq 0.05$).

Management	Electrical conductivity	pH	Productivity
	dS m^{-1}		g $plant^{-1}$
Management 1_IR_CE	22	2.2	127^{a}
Management 2_IR_CE	34	1.6	94^{b}
Management 3_IR_CE	35	1.3	65^{c}
Management 4_IR_CE	41	1.9	125^{a}

For growing lettuce in hydroponics at vertical systems, it is recommended to maintain the pH between 5.5 and 6.5. In this range, nutrients are more available for root absorption, promoting healthy and vigorous plant growth (Carotti et al., 2023).

In conclusion, once the optimal EC of 1.9 dS m^{-1} is established, the irrigation interval becomes secondary in the range of 22 to 42 min, provided the pH is within the appropriate range of 6.0 to 6.2. Additionally, higher productivities were achieved with various combinations of irrigation intervals: 16 min irrigation interval, 1.6 dS m^{-1} EC, and pH 6.1; 34 min irrigation interval, 1.9 dS m^{-1} EC, and pH 6.2; 22 min irrigation interval, 2.2 dS m^{-1} EC, and pH 6.0; 41 min irrigation interval, 1.9 dS m^{-1} EC, and pH 6.0.

These results are supported by studies indicating the importance of adjusting these parameters to optimize irrigation efficiency, crop productivity and other parameters. Samarakoon et al. (2019) reported that maximum yields were observed at 1.8 mS cm^{-1} in hydroponics but increasing EC beyond this level did not contribute to higher yields and increased the incidence of tip burn. Their experiments demonstrated that while nutrient absorption and photosynthetic rate increased with higher EC, the fresh and dry weights of lettuce decreased beyond 1.8 mS cm^{-1}, indicating an optimal EC threshold for maximizing yield without compromising plant health.

Different supplementary light spectra (red ratios) and growing seasons were investigated by fresh weight, DM percentage (DMP), leaf number, and antioxidant activity in ‘Lavinia’ lettuce cultivated in a hydroponic system under a plastic greenhouse (Hernández-Adasme et al., 2023). Results indicate that the interaction between light and season is crucial, with the highest fresh weight observed in early autumn due to more favorable environmental conditions such as temperature and radiation. Under a red:blue ratio between 1.6 to 4.2, DMP was higher, whereas antioxidant activity was reduced as the red light component increased. Seasonal variation affected antioxidant capacity and total phenolic content, showing higher values in early autumn.

To develop a new hydroponic nutrient management strategy, ‘Corvair’ spinach was grown at pH levels of 4.0, 4.5, 5.0, and 5.5 in a deep-water culture system (Gillespie et al., 2021). Results showed a decline in spinach shoot and root mass as pH decreased, with the most severe growth inhibition at pH 4.0. at pH 4.5 and 5.0, growth was normal but reduced, likely due to decreased nutrient uptake. Plant tissue analysis revealed reduced concentrations of N, P, K, Mg, S, Cu, Fe, Mn, and Zn as pH lowered. Increasing nutrient solution strength threefold at pH 4.5 (EC 3.4 dS·m^{-1}) improved growth but still lagged behind control (pH 5.5 and EC 1.4 dS·m^{-1}). Lowering pH to 4.5 significantly reduced tissue concentrations of several nutrients compared to the control, though higher nutrient concentrations under increased EC treatment suggested potential for further optimization.

Jambu (*Acmella oleracea* (L.) R.K. Jansen), a plant native to the Amazon, is rich in essential oils, including spilanthols and phytols (Carmo et al., 2024). Six nutrient solutions with EC ranging from 0.5 to 4.0 mS cm^{-1} showed that jambu growth improved at EC close to 3.5 mS cm^{-1}, with increases in levels of N, P, K, B, Zn, Mn, and essential oils. A total of 23 essential oil compounds were detected, with significant increases in several compounds such as caryophyllene and decreases in others like spilanthol as conductivity increased.

The optimization of resources and time in producing quality seedlings within a legal framework is crucial for greenhouse vegetable crops (Carballo-Méndez et al., 2023). This study assessed the impact of different EC of nutrient solutions on the survival and growth of bell pepper and tomato seedlings propagated by cuttings. Electrical conductivities of 0.92, 1.25, 1.50, and 1.75 dS m^{-1} were evaluated using a randomized complete block design with four replicates. The lowest EC yielded the highest number of rooted cuttings, while medium EC (1.25 to 1.50 dS m^{-1}) enhanced leaf number, leaf area, biomass, and seedling quality indices. These findings suggest that bell pepper and tomato seedlings can be effectively produced using Steiner nutrient solutions with 1.25 to 1.50 dS m^{-1} without compromising seedling quality.

CONCLUSIONS

The optimal pH plays a crucial role in determining the significant impact of irrigation interval and electrical conductivity (EC) on plant productivity. Once the ideal EC of 1.9 dS m^{-1} is achieved, the irrigation interval becomes secondary in the range of 22 to 42 min, given that the pH is also maintained within the appropriate range of 6.0 to 6.2. The study also demonstrated the attainment of highest productivity of crisp lettuce through various combinations of irrigation interval, EC, and pH.

Author contribution

Conceptualization: G.V.M. Methodology: D.C. Formal analysis: D.C., O.S.M. Investigation: O.S.M., J.S.A. Writing-original draft: G.V.M. Writing-review & editing: J.S.A., P.L.P.F. Funding acquisition: G.V.M., P.L.P.F. All co-authors reviewed the final version and approved the manuscript before submission.

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