Integration of IoT and Bioponics for Sustainable Urban Agriculture: Performance Evaluation of an Intelligent Hydroponic System for Lactuca sativa

Hounaida Nedjla Berrah
hounaidaberrah33@gmail.com

University Ferhat Abbas of Setif
Amira Soualmia
University Ferhat Abbas of Setif
Yacine Louadj
University Ferhat Abbas of Setif
Nassir Harrag
University Ferhat Abbas of Setif

Research Article

Keywords: Hydroponics, Bioponics, Internet of Things (IoT), Lactuca sativa, Urban Agriculture, and Environmental Monitoring

Posted Date: January 27th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8457375/v1

Additional Declarations: No competing interests reported.

Abstract

This study investigates the development and evaluation of an innovative hydroponic system powered by bioponic nutrition and integrated with IoT-based environmental monitoring, aimed at cultivating romaine lettuce (**Lactuca sativa** var. **Romana**) over a 35-day growth cycle. The bioponic nutrient solution was prepared in two stages: first, **compost tea** (pH 8.20 ± 0.01; EC 263 µS/cm), followed by enrichment with diluted **organic manure** to reach optimized conditions (pH 7.05 ± 0.01; EC 1467 µS/cm). Real-time environmental data indicated an average temperature of 21.26 ± 2.3°C and relative humidity of 61.28 ± 8.5%. Plant growth exhibited three distinct phases: **establishment** (D1–D5), **active growth** (D5–D25), and **stabilization** (D25–D35), with corresponding growth rates of 0.6, 0.75, and 0.2 cm/day. Leaf production increased from 2–3 to 9–16 leaves per plant, with a mean leaf emission rate of 0.37 leaves/day. Final biomass measurements averaged 11.92 ± 6.84 g (fresh) and 2.1 ± 1.3 g (dry), with a DM/FM ratio of **0,176**, indicating excellent water uptake efficiency. These results demonstrate the feasibility and efficiency of a biologically driven hydroponic system supported by IoT technology, providing a promising approach to sustainable and resource-efficient urban agriculture.

Introduction

Rapid population growth, accelerated urbanization and climate change are putting increasing pressure on food production systems worldwide. Traditional agriculture, heavily dependent on soil, water, and agrochemicals, faces significant challenges, including land degradation, water scarcity, and environmental pollution (FAO, 2021). According to the World Health Organization (WHO), global food production must increase by nearly 70% by 2050 to meet the food demands of a growing population. Urban agriculture has emerged as a promising alternative, providing local, fresh, and sustainable food directly within cities (Mougeot, 2000; Orsini et al., 2013).

Among innovative approaches, soilless systems such as hydroponics, aquaponics, bioponics and aeroponics offer efficient use of water and space while reducing environmental impacts (Despommier, 2010; Goddek et al., 2015). Aquaponics, which integrates aquaculture with hydroponics, has shown high water-use efficiency and biomass productivity (Yep & Zheng, 2019), while bioponics, an evolution of hydroponics using organic inputs has demonstrated the potential to achieve comparable yields while reducing synthetic inputs (Chinta et al., 2023). The integration of IoT technologies into soilless systems can further optimize resource use, improve nutrient management, and enhance system automation (García et al., 2022). Hybrid systems combining aquaponics and bioponics have been shown to enhance nitrogen recovery and improve overall system sustainability (Wongkiew et al., 2021).

This study aims to develop and evaluate an intelligent bioponic hydroponic system for the cultivation of romaine lettuce (**Lactuca sativa** var. **Romana**), focusing on plant growth performance, environmental conditions, and water-nutrient management efficiency. The objective of this study is to design and evaluate an integrated urban agriculture model that combines hydroponics, bioponics, and IoT technologies to address food security challenges, reduce water consumption, replace chemical nutrients with organic alternatives, and shorten food supply chains.

Materials and Methods

System Design

A two-level vertical hydroponic system was designed using PVC pipes **the material is shown in supplementary figure S1** (80 cm and 40 cm as shown in Fig. 01) to optimize space and increase planting density additional levels can be added if desired. The system operated in a closed-loop configuration, continuously circulating a nutrient solution prepared from organic compost tea (500g of mature compost in 5L of water, aerated for 24 h) and later enriched with an organic manure-based solution. A submersible pump ensured constant nutrient flow throughout the system **(**Fig. 02**).**

Artificial Lighting

Horticultural LED lamps with a full spectrum were used to provide artificial lighting, with a photoperiod of 16 h light and 8 h dark. This ensured optimal photosynthesis and supported the vegetative growth of the plants.

IoT Monitoring and Control System

An IoT-based control unit, built on an ESP8266 microcontroller, was implemented to monitor and regulate environmental parameters in real-time. The system utilized the following sensors (**as shown in supplementary figure S2)**:

- DHT22 sensors for air temperature and relative humidity.
- pH and EC probes for nutrient solution monitoring.

The system automatically controlled the irrigation pump and lighting based on pre-defined thresholds (humidity 50–70%, temperature 20–24°C during the day and 15–18°C at night). All data were transmitted via Wi-Fi for real-time monitoring and logging.

Plant Material and Growth Conditions

The plant material used was romaine lettuce (**Lactuca sativa** var. **Romana**), transplanted at the 2–3 true leaf stage **(supplementary figure S3).** Before planting, the entire system was disinfected with 3% hydrogen peroxide solution. Plants were grown on an inert gravel substrate for 35 days.

Environmental conditions were maintained as follows: temperature 18–22°C (day), 15–18°C (night), relative humidity 60–70%, irrigation cycles of 15 min every 2 h during the day, and two cycles during the night.

Data Collection and Measurements

The following parameters were measured:

- **Vegetative growth**: plant height and number of leaves every 5 days
- **Biomass**: fresh and dry weight (drying at 100°C for 24 h)

Environmental parameters

daily monitoring of temperature, humidity, pH, electrical conductivity (EC), and dissolved oxygen.

Statistical Analysis

A one-way Analysis of Variance (ANOVA) was performed to determine whether the type of nutrient solution (compost tea vs. diluted organic manure) had a significant effect on lettuce growth. Each treatment consisted of multiple plant height measurements recorded over the cultivation period. The significance level was set at $\alpha = 0.05$.

Results

Morphological Analysis and Vegetative Development of Lettuce under bioponic conditions

A progressive increase in leaf length was observed throughout the cultivation period, indicating **optimal vegetative growth (**Fig. 03**)**. This longitudinal development is characteristic of the **Romaine lettuce variety**, which exhibits an elongated leaf architecture and robust axial structure. Such morphology contributes to an **upright growth habit**, enhancing light interception and photosynthetic efficiency **(The progression of leaf number over the 35-day growth cycle is presented in Supplementary Figure S3**).

Vertical Growth

Analysis of vertical growth revealed the significant influence of two key environmental factors: **horticultural lighting** and **biological nutrition**. The balanced nutrient supply, derived from **compost tea** and **organic manure**, promoted harmonious plant development. Height increased from 3–5 cm to 10–15 cm **(**Fig. 04**)** initially, followed by a slight slowdown due to changes in **pH** and **EC**.

Biomass Analysis

Biomass is a key integrative indicator of plant development, reflecting the efficiency of the cultivation system. Our measurements recorded an average **fresh biomass** of **11.92 g** (range: 6–25 g) and an average **dry biomass** of **2.1 g** (range: 0.7–5 g) during the **vegetative stage**. Although modest, these values should be interpreted considering the **physiological stage** and **varietal characteristics**. The Romaine variety initially prioritizes **root development**, which explains the relatively low aerial biomass at this stage.

Environmental Parameter Influence

a. Thermal Regulation and Humidity Management

Temperature monitoring revealed initial instability (**25–28°C**), which negatively affected vegetative development, followed by a more favorable stabilization (**20–24°C**). This thermal dynamic, consistent with observations by Both (1995), underscores the critical importance of **temperature control** in optimizing physiological processes. Relative humidity fluctuations (**42–72%**) were primarily due to the absence of an adequate ventilation system. Although Soares et al. (2015) highlighted the phytopathological risks associated with high humidity, **no disease symptoms** were observed during our trial **(**Fig. 05**).**

b. Physicochemical Parameters of the Nutrient Solution

The evolution of physicochemical parameters showed significant improvement after the incorporation of **diluted organic manure**: the **pH** stabilized at a more favorable value (**7.05**), and the **electrical conductivity** reached an optimal level (**1.46 dS/cm**), in line with Wortman (2015) recommendations. This optimization likely contributed to the **successful root development** and **overall plant growth** observed in the bioponic system.

- ANOVA:

The average plant height for the compost tea treatment was 5.73 cm, while the manure-based solution resulted in a higher mean height of 10.10 cm.

The ANOVA revealed a statistically significant difference between the two nutrient solutions ($F = 27.29$, $p < 0.05$), indicating that the type of nutrient source had a significant effect on lettuce growth.

Discussion

The morphological study of **Lactuca sativa** var. **Romana** conducted over a 35-day growth period revealed a vigorous vegetative development characterized by a dense and complex foliar architecture. Plants exhibited intense chlorophyll pigmentation, evidenced by a deep green coloration of the leaf tissues, while the root system showed substantial branching and significant elongation, indicating an enhanced nutrient uptake capacity **(**Fig. 06**)**. This overall vegetative vigor reflects an efficient adaptation of plants to the specific conditions of the implemented hydroponic system. Our findings also demonstrate that lettuce growth in this controlled system is significantly accelerated, with a complete cycle achieved within 35–40 days compared to the slower development typically observed in open-field cultivation.

Our experimental results demonstrate that lettuce cultivated in a bioponic system required **35 days** to reach its optimal harvest size. These findings are consistent with those reported by Benjamin (2016), Zorrig (2014), and Abbas (2018), who observed growth cycles ranging between **25 and 30 days**, thus confirming the reliability and reproducibility of our cultivation system.

The absence of synthetic agrochemicals likely contributed to the optimal growth observed, supporting findings by Smith et al. (2016) on the negative impact of chemical inputs on plant physiology.

The final height range of **20–25 cm** during the vegetative stage is intermediate compared to results reported by Azariane (2019) and Abbas (2018), confirming satisfactory growth under our experimental conditions.

The study of phyllotaxis revealed a **positive correlation between cultivation time and the number of functional leaves**, alongside a reduction in leaf senescence. Our results (3–16 functional leaves vs. 1–3 senescent leaves per plant) differed from those of Bechenab and Ben Achour (2015), likely due to different cultivation conditions. This favorable functional-to-senescent leaf ratio is an important indicator of **vegetative vigor**. Moreover, a **strong correlation** was observed between **plant height** and **leaf number** throughout the vegetative cycle, as illustrated in this Fig. 07.

Interestingly, the observed Dry Matter/Fresh Matter (**DM/FM**) ratio of **0.176** is significantly higher than the average values typically reported for hydroponic lettuce (**usually ranging from 0.04 to 0.08**). This high dry matter accumulation suggests that the bioponic nutrient solution, derived from compost tea and organic manure, provided a superior balance of micronutrients and organic compounds compared to standard mineral solutions. This suggests that while bioponic systems may sometimes yield lower total fresh biomass, they enhance the nutritional density and structural robustness of the plant, making it a highly qualitative approach for urban agriculture.

Interpretation about ANOVA analysis

These results suggest that the manure-based nutrient solution provides more favorable conditions for plant development compared to compost tea, likely due to higher nutrient availability and improved nutrient uptake.

Conclusion

This research demonstrates the feasibility and effectiveness of a bioponic cultivation system for *Lactuca sativa* var. *Romana*, highlighting its potential as a sustainable and technologically advanced solution for future urban agriculture. By integrating a remote monitoring system supported by a network of interconnected environmental sensors, the study achieved continuous, real-time control over critical growth parameters, enabling rapid and precise adjustments to cultivation conditions.

The morpho-physiological analysis revealed robust vegetative development characterized by balanced leaf architecture and efficient nutrient uptake. Notably, while the total fresh biomass was moderate, the system achieved a high dry matter/fresh matter ratio (0.176), suggesting that bioponic nutrition enhances the structural robustness and nutritional density of the plants compared to conventional hydroponics. This underscores the compatibility of organic nutrient inputs—such as diluted manure—with intensive soilless cultivation systems and highlights the qualitative advantages of biologically driven production.

Telemetric environmental monitoring identified early fluctuations in temperature and humidity, which were swiftly mitigated using adaptive control strategies. This proactive, data-driven approach exemplifies the potential of precision agriculture to anticipate and respond to abiotic stresses before they impact productivity, thereby improving system resilience and resource efficiency.

Overall, the findings of this study represent an important step toward the development of a fully automated, environmentally responsible, and resource-efficient bioponic production protocol. Future research directions should focus on integrating predictive algorithms for nutrient management, designing autonomous environmental regulation systems, and expanding sensor networks to include physiological indicators. Such innovations will be crucial to scaling bioponic systems as part of sustainable urban food production strategies, contributing significantly to global food security and climate resilience.

Declarations

Supplementary Data

Supplementary Figures S1–S3, showing additional images of the hydroponic system and lettuce growth stages, are available online at HEB.

Author Contribution Statement

Berrah Hounaida Nedjla: Conceptualization, experimental design, hydroponic and bioponic system setup, plant cultivation, data collection, manuscript writing.
Soualmia Amira: Assisted with system monitoring, plant care, and data recording.
Louadj Yacine: Statistical analysis and data interpretation.
Harag Nassir: IoT system design, sensor integration, environmental monitoring, and technical support.

Acknowledgements

Not applicable.

Funding

This research did not receive external grant funding from public, commercial, or not-for-profit agencies. However, the IoT sensors used in the prototype were supported by the university incubator, and additional expenses were personally funded by the authors.

Ethics approval

Not applicable. This study did not involve human participants or animals beyond standard agronomic practices approved by the Department of Agronomy, Université Ferhat Abbas Sétif 1.

Conflict of interest

The authors declare no conflict of interest.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

1. Abbas, H., Saha, I., Shoukry, Y., Ehlers, R., Fainekos, G., Gupta, R., Majumdar, R., & Ulus, D. (2018). Embedded software for robotics: Challenges and future directions. *Proceedings of the 2018 ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS)*, 1–12pp. https://doi.org/10.1109/ICCPS.2018.00010
2. Ammari, A., & Khelil, I. (2019). *Essai sur la culture de laitue (Lactuca sativa) sous un système hydroponique dans la région de Ouragla* (PhD thesis).
3. Both, A. J. (1995). *Dynamic temperature effects on plant growth in controlled environments*. Rutgers University, New Brunswick, NJ, USA.
4. Brandon Yep, & Zheng, Y. (2019). Aquaponic trends and challenges – A review. *Journal of Cleaner Production*, *228*, 1586–1599pp.
5. Chinta, Y. R., Parra, L., Osorio, J. C., Martínez-Núñez, M., Cornejo, P., & Pérez, R. (2023). Bioponics: An evolution of hydroponics using organic inputs. *Horticulturae*, *9*(3), 324p. https://doi.org/10.3390/horticulturae9030324
6. Despommier, D., Carter, M., & Giacomelli, G. A. (2010). *The vertical farm: Feeding the world in the 21st century*. St. Martin’s Publishing Group.
7. FAO. (2012). *World agriculture towards 2030/2050: the 2012 revision*. Rome: Food and Agriculture Organization of the United Nations.
8. FAO. (2021). *The State of the World’s Land and Water Resources for Food and Agriculture – Systems at breaking point (SOLAW 2021)*. Rome: Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cb7654en

9. García, R., Rodríguez, F., Guzmán, J. L., & Castilla, M. (2022). IoT-based monitoring and control architecture for hydroponic systems. *Computers and Electronics in Agriculture*, *193*, 106702.
10. Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K. V., Jijakli, H., & Thorarinsdottir, R. (2015). Challenges of sustainable and commercial aquaponics. *Sustainability*, *7*(4), 4199–4224.
11. Mougeot, L. J. A. (2000). Urban agriculture: definition, presence, potentials and risks. In N. Bakker, M. Dubbeling, S. Gündel, U. Sabel-Koschella, & H. de Zeeuw (Eds.), *Growing cities, growing food: Urban agriculture on the policy agenda. A reader on urban agriculture* (pp. 1–42). Feldafing, Germany: Deutsche Stiftung für Internationale Entwicklung (DSE), Food and Agriculture Development Centre.
12. Orsini, F., Kahane, R., Nono-Womdim, R., & Gianquinto, G. (2013). Urban agriculture in the developing world: a review. *Agronomy for Sustainable Development*, *33*(4), 695–720pp.
13. Soares, A. S. (2015). Effects of relative humidity on the development of fungal diseases in lettuce cultivated in controlled environments. *Journal of Horticultural Science and Biotechnology*, *90*(4), 350–358pp.
14. Wongkiew, S., Hu, Z., Lee, J. W., Chandran, K., Nhan, H. T., Marcelino, K. R., & Khanal, S. K. (2021). Nitrogen recovery via aquaponics–bioponics: Engineering considerations and perspectives. *ACS Engineering*, *1*(3), 326–339pp.
15. Wortman, S. E. (2015). Crop physiological response to nutrient solution electrical conductivity and pH in hydroponic production. *Scientia Horticulturae*, *194*, 34–42pp.
16. Zorrig, W., Rouached, A., Abdelly, C., & Berthomieu, P. (2014). Identification of genes involved in heavy metal accumulation in lettuce (Lactuca sativa). *Plant Physiology and Biochemistry*, *82*, 72–80pp.

Figures

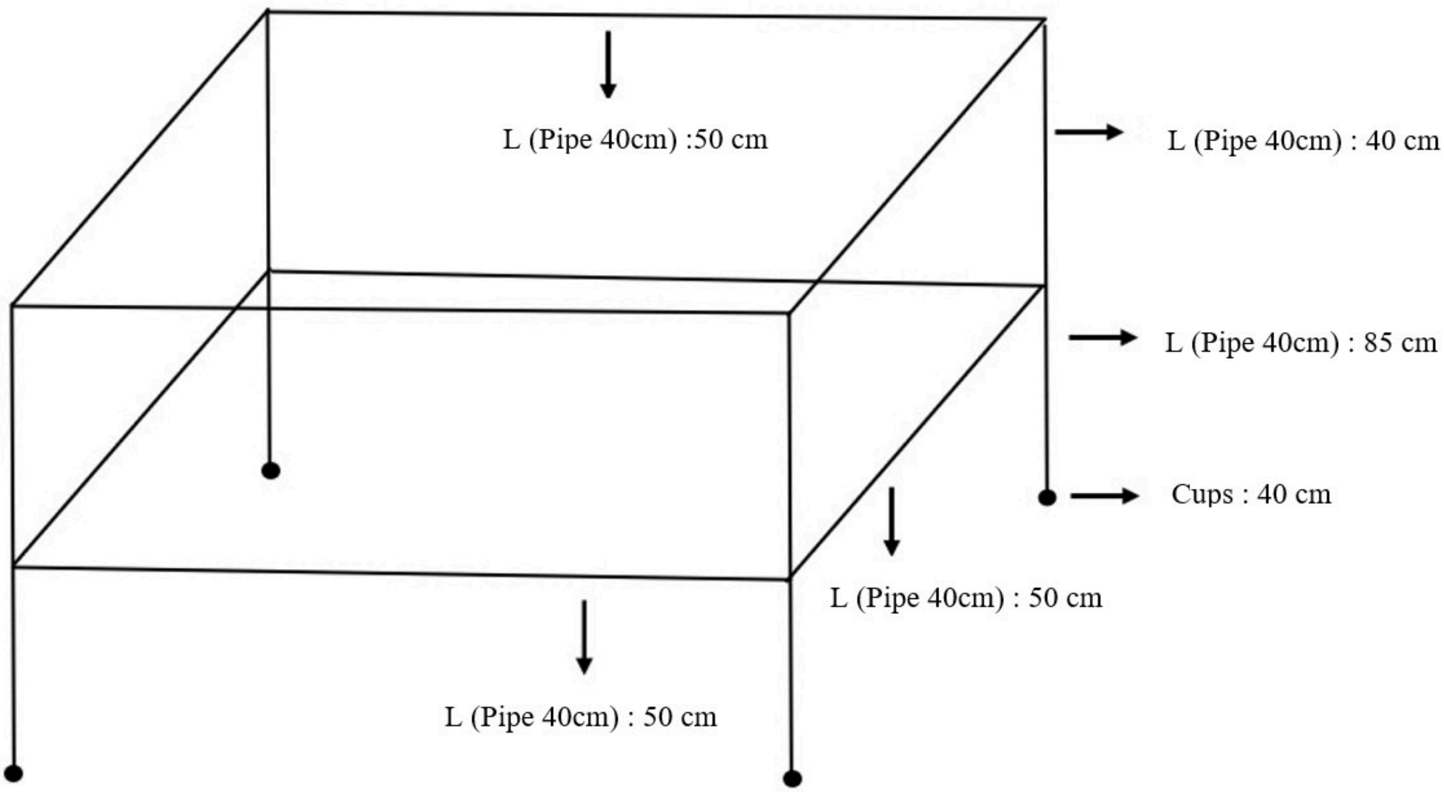

Figure 1

Schematic representation of the hydroponic system layout, including pipe lengths and diameters used in the setup.

Figure 2

The hydroponic system.

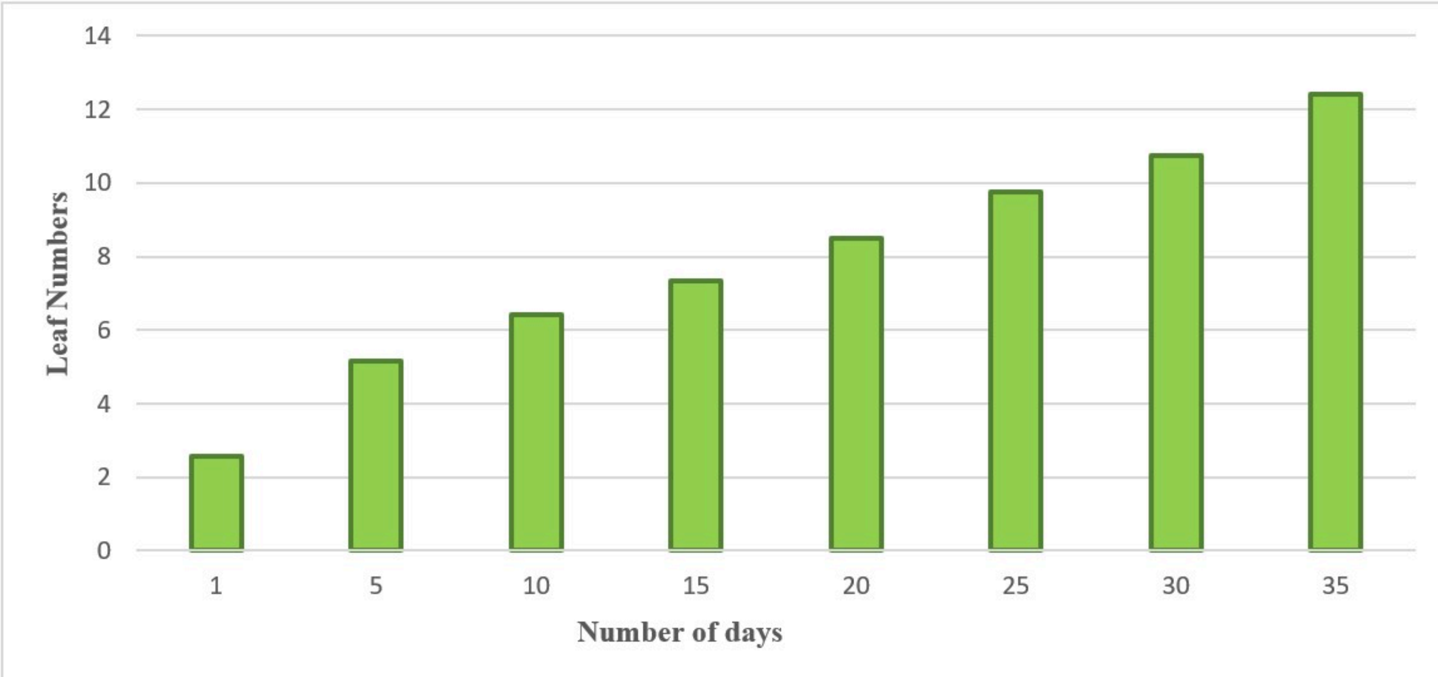

Figure 3

Phenological stages of romaine lettuce development.

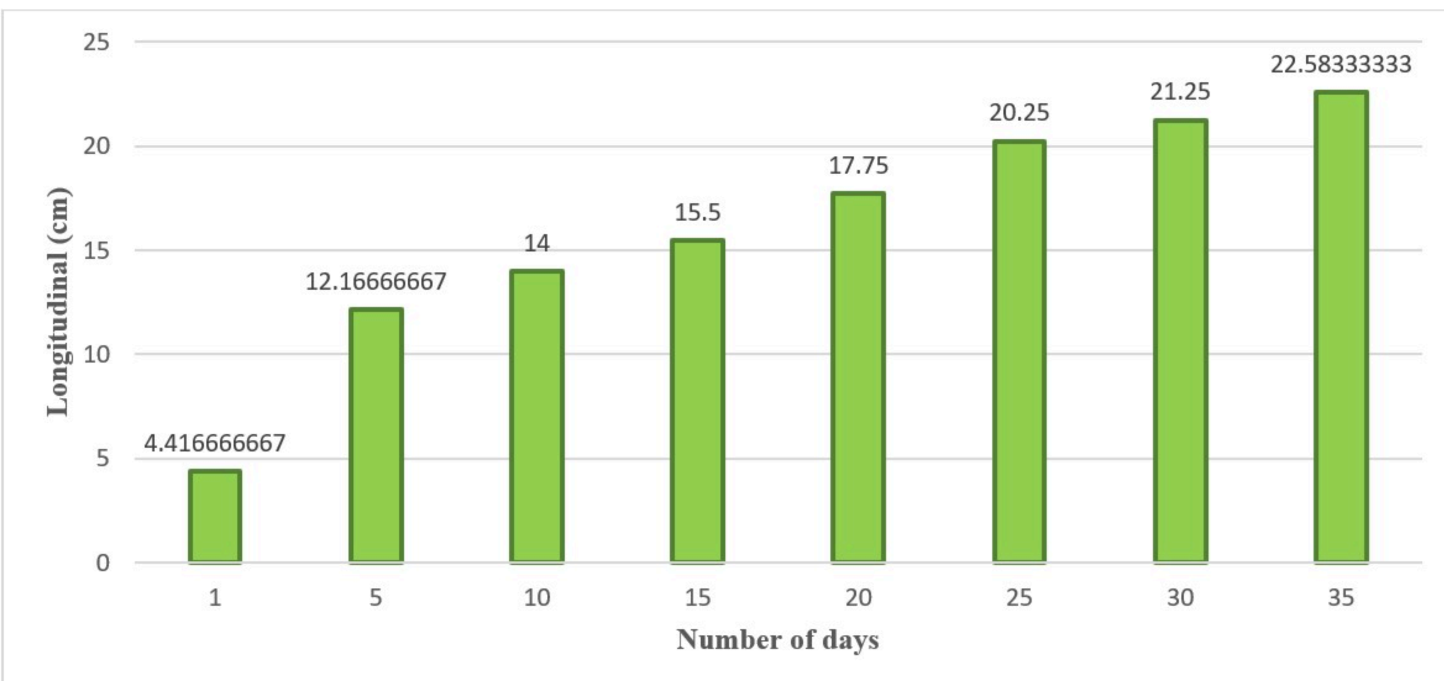

Figure 4

Evolution of average plant height during the 35- day growth cycle of Romaine lettuce.

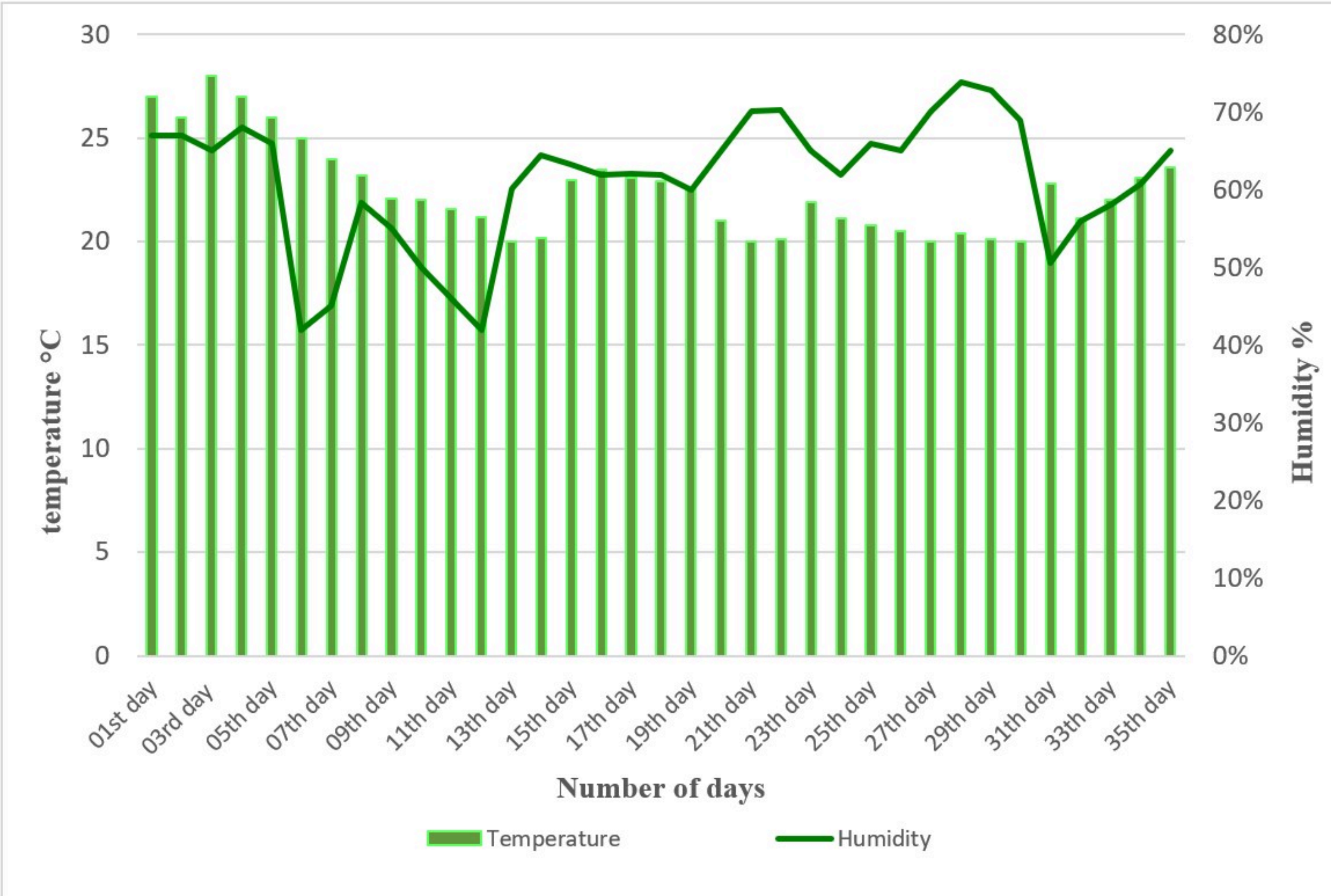

Figure 5

Monitoring of abiotic factors (relative humidity and temperature) using remote-controlled sensors during the lettuce growth cycle in bioponic conditions.

Figure 6

Root biomasse and shoot biomasse of the vegetative stage of Romana Lettuce.

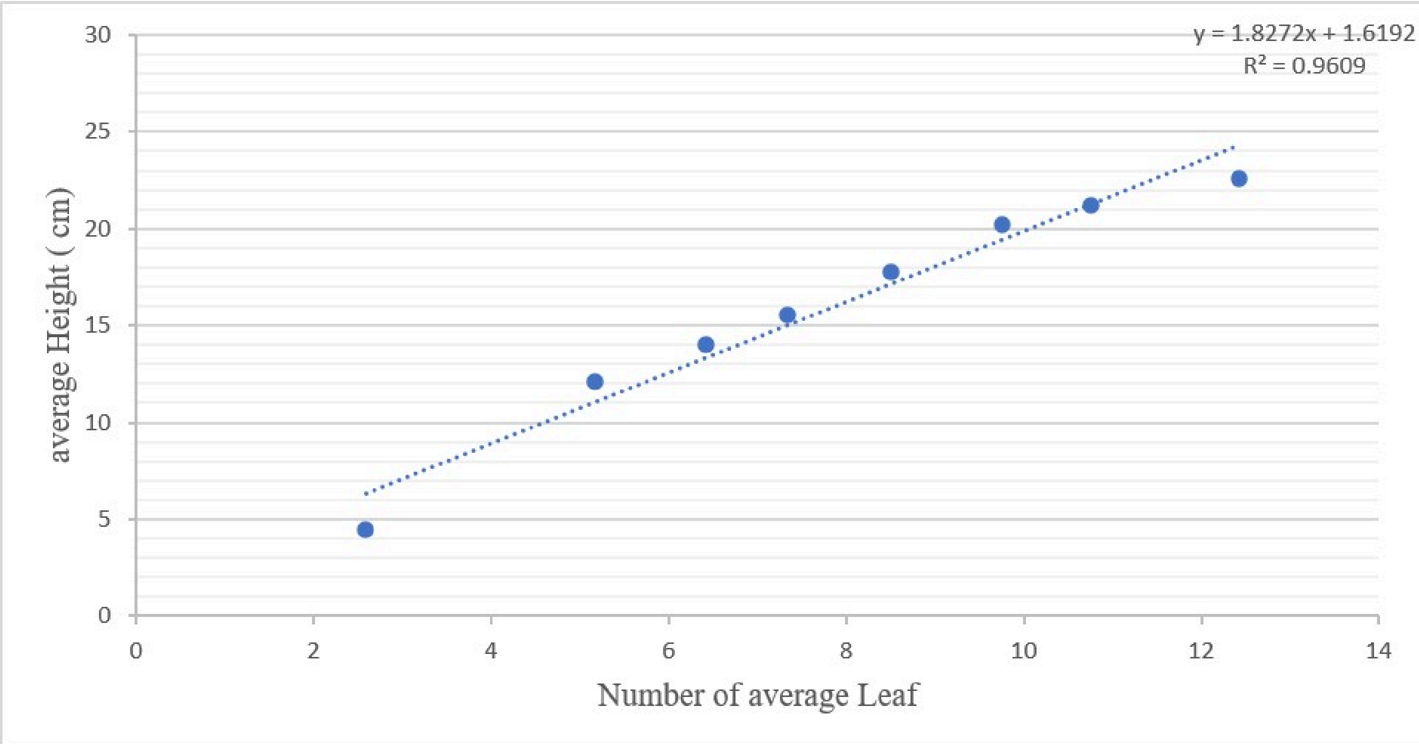

Figure 7

Linear regression between average plant height and average leaf number throughout the 35-days vegetative cycle.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementarymaterial.docx