Agrociencia

HYDROPONIC CULTIVATION EXPERIMENT MONITORED BY AN INTERNET OF THINGS SYSTEM

Cristal Yoselin **Moreno-Aguilera**[1], José Enrique **Botello-Álvarez**[2], Juan José **Martinez-Nolasco**[3]*, Jose Alfredo **Padilla-Medina**[4], Coral **Martinez-Nolasco**[3], Raul Omar **Herrera-Arroyo**[5]

[1]Tecnológico Nacional de México, Instituto Tecnológico de Celaya. Doctorate in Engineering Sciences. Antonio García Cubas 600, Celaya, Guanajuato, Mexico. C. P. 38010.
[2]Tecnológico Nacional de México, Instituto Tecnológico de Celaya. Department of Biochemical Engineering. Antonio García Cubas 600, Celaya, Guanajuato, Mexico. C. P. 38010.
[3]Tecnológico Nacional de México, Instituto Tecnológico de Celaya. Department of Mechatronic Engineering. Antonio García Cubas 600, Celaya, Guanajuato, Mexico. C. P. 38010.
[4]Tecnológico Nacional de México, Instituto Tecnológico de Celaya. Department of Electronic Engineering. Antonio García Cubas 600, Celaya, Guanajuato, Mexico. C. P. 38010.
[5]Tecnológico Nacional de México, Instituto Tecnológico de Celaya. Master's in Mechatronic Engineering Science. Antonio García Cubas 600, Celaya, Guanajuato, Mexico. C. P. 38010.
* Author for correspondence: juan.martinez@itcelaya.edu.mx

Citation: Moreno-Aguilera CY, Botello-Álvarez JE, Martinez-Nolasco JJ, Padilla-Medina JA, Martinez-Nolasco C, Herrera-Arroyo RO. 2025. Hydroponic cultivation experiment monitored by an Internet of Things system. **Agrociencia.** https://doi.org/ 10.47163/agrociencia.v59i7.3430

Editor in Chief:
Dr. Fernando C. Gómez Merino

Received: February 07, 2025.
Approved: October 22, 2025.
Published in Agrociencia: October 30, 2025.

ABSTRACT

The application of advanced agricultural technologies such as hydroponics and the Internet of Things (IoT) has the potential to improve cultivation system efficiency and sustainability. This study evaluated the effect of nutrient solution concentration on hydroponic lettuce cultivation (*Lactuca sativa* L. cv Rodhenas). Steiner nutrient solution was used at three concentrations (100, 75, and 50 %, corresponding to treatments T1, T2, and T3, respectively). The experiment was conducted using a completely randomized design, with three treatments and 14 repetitions per treatment, for a total of 42 experimental units. The goal was to reduce the amount of nutrients used while maintaining crop quality and minimizing environmental contamination associated with nutrient leaching. This study also demonstrates the design and implementation of a real-time visualization of variables using IoT technology. The monitoring system was based on a digital temperature and relative humidity sensor connected to a wireless module that transfers data to the cloud, allowing real-time visualization of variable behavior on mobile devices. Cultivation with nutrient solution at 100 % concentration resulted in superior lettuce growth and the highest chlorophyll concentration. This treatment also outperformed the others by nearly 100 g in biomass and showed a significant reduction in fiber content, decreasing to 0.38 % in T2 and 0.46 % in T3.

Keywords: Hydroponics, lettuce, IoT, nutrient solution, chlorophyll.

INTRODUCTION

The global population currently stands at eight billion and is expected to grow by two billion over the next 30 years, requiring a 70 % increase in global food production. This situation calls for radical improvements in the way food is produced and consumed, creating opportunities in urban areas and reducing greenhouse gas emissions through significant changes in traditional agricultural practices (FAO, 2021).

Conventional agricultural practices, including excessive use of water, fertilizers, and pesticides, as well as a high demand for land, result in continuous soil degradation and the depletion of clean water resources, posing significant negative effects on the environment and consumer health (Kazakis and Tsirliganis, 2023). To meet the UN Sustainable Development Goals, the agricultural industry must adapt to modern times by implementing innovative approaches supported by innovative technological and scientific advances, as well as environmentally friendly solutions (Khanal *et al*., 2019).

Agriculture today faces multiple challenges, including land degradation, inefficient management of arable land and water (Mwanake *et al*., 2023), depletion of natural resources, environmental change, meteorological irregularities, pest and disease outbreaks, and increasing food demand and waste (Sharma *et al*., 2022). Addressing these issues requires the adoption of smart agricultural practices and efficient water management techniques (Gupta *et al*., 2020).

Barriers such as limited data processing and storage capacity, along with resistance to technological change, must be overcome to ensure widespread implementation (Symeonaki *et al*., 2022). Adopting new technologies in farming is important to increase productivity, boost economic growth, and make farms more competitive in global markets (Maffezzoli *et al*., 2022; Eze *et al*., 2025).

Protected agriculture involves using controlled environments to maximize crop yields and ensure fruit and vegetable production in the face of current climate change challenges (La Cecilia *et al*., 2023). The Internet of Things (IoT) is an innovative technology that uses intelligent networks, such as the Internet, to virtually connect and communicate with physical objects (Nižetić *et al*., 2020). The interaction of IoT technologies with agriculture could help to ensure a reliable food supply and improve the efficiency of agricultural production processes (Madushanki *et al*., 2019).

Agriculture 4.0, also known as Smart or Digital Agriculture, shares a structural similarity with the concept of Industry 4.0, as it involves the internal and external interconnection of all agricultural production processes. This evolution in agriculture, combined with IoT and data management tools, seeks to address the global challenge of developing sustainable agriculture that meets the food needs of a growing population (Arvanitis and Symeonaki, 2020; Symeonaki *et al*., 2022). Sustainable agriculture and environmental protection can be improved through efficient use of nutrients, accomplished by measuring nutrient availability in the environment and plants (Paul *et al*., 2022).

Hydroponic systems can increase crop growth rates by 10 to 50 % when compared to traditional agricultural practices (Goddek *et al*., 2019), leading to greater productivity and reducing the need for fertilizers. In hydroponic systems, plants develop in controlled, soil-free environments, enabling year-round cultivation (Zhu *et al*., 2023). Hydroponics also has the potential to reduce land, water, and nutrient usage, offering a promising alternative to address global food shortages (FAO, 2021).

Yang *et al*. (2024) installed two hydroponic systems in a controlled-climate greenhouse where they identified water and nutrient absorption patterns for the quality of lettuce grown in these systems during different seasons of the year. They found Deep Water Cultivation (DWC) has a higher yield for total carotenoids, vitamin C, and non-acidified phenols in autumn.

Martínez-Moreno *et al*. (2024) reduced the concentration of Steiner nutrient solution (Steiner, 1961) at the end of the vegetative cycle to decrease nitrate levels in hydroponic lettuce. Reducing the solution concentration from 100 to 50 % decreased nitrate concentration by 14 % in one week and by 22 % in two weeks without affecting vegetative growth.

Furthermore, do Carmo *et al*. (2024) evaluated the growth performance of *Acmella oleracea* L. cultivated in hydroponic systems using nutrient solutions with different electrical conductivity (EC) levels. The results suggest that nutritional management through variations in EC can influence both the growth parameters and the plant's essential oil profile. It was observed that most cultivated species are adversely affected when the conductivity exceeds 2500 μS cm^{-1}.

It is important to consider nutritional performance in cultivated plants, even when attempting to reduce nutrient application costs or environmental impact. Yang *et al*. (2021) evaluated the effect of nutrient solutions with different EC levels while growing *Eruca sativa* Mill. Results showed that applying 1.2 or 1.8 dSm^{-1} improved photosynthetic properties while increasing leaf area, yield, and dry weight.

Other studies evaluated lettuce quality parameters in hydroponic cultivation techniques, including chlorophyll, dissolved solids in the nutrient solution, protein, and fiber content. This crop produced nutritionally superior products compared to conventional cultivation (Ahmed *et al*., 2021). Acharya *et al*. (2021) evaluated the growth of *Spinacia oleracea* L. and *L. sativa* in hydroponic crops compared to conventional crops, where they found higher soluble sugar contents in the soilless cultivated plants, improving the sweetness and texture of green leafy vegetables.

Shin *et al*. (2024) implemented a hydroponic IoT system to supervise and control key plant growth parameters such as pH, EC, and water levels using an ESP32 microcontroller. Hernández-Morales *et al*. (2022) developed and implemented a low-cost IoT system for monitoring microclimates and detecting disease risk factors. The system transmits data to the Internet via the Sigfox network, which includes a cloud-based platform built on microservices and a web application for data analysis and visualization. Meanwhile, Chen *et al*. (2021) developed an IoT system using an STM32 microprocessor to collect real-time data on light, temperature, and humidity, transmitting it via NarrowBand Internet of Things (NB-IoT) to a cloud platform for monitoring and fault detection.

This study presents an innovative hydroponic greenhouse model for lettuce cultivation that integrates advanced technologies and real-time IoT monitoring to optimize resource use and minimize environmental impact. Different nutrient solution treatments were evaluated to determine whether it is viable to reduce the amount of nutrients applied without compromising the quality of the crop. Additionally, a video camera was included for visual crop supervision. It was hypothesized that the concentration of the Steiner nutrient solution has a significant impact on both phenotypic and biochemical parameters, revealing information about the nutritional composition of hydroponically grown lettuce.

MATERIALS AND METHODS

The study was conducted between February and March 2024 at the National Institute of Technology in Celaya, Guanajuato, Mexico (20° 32′ 15″ N 100° 49′ 00″ W). The region features a cloudy and warm climate throughout the year (INEGI, 2020). The average temperature is 18.3 °C, with an average relative humidity of 52.2 % and annual precipitation of 689 mm, typically spread over 65 rainy days, with 5 % rainfall occurring in winter and a photoperiod of 9.2 h per day. The average wind speed during the cultivation experiment was 10.6 km h^{-1}.

The experimental study was conducted in a greenhouse equipped with hydroponic systems (Figure 1A). The structure measured 400 cm in length, 400 cm in width, and 270 cm in height and featured an arched roof covered with a conventional three-layer co-extruded low-density polyethylene (LDPE) white translucent sheet. The greenhouse was fitted with a fixed perimeter and front anti-aphid mesh vents to ensure proper ventilation and pest protection. Inside, it housed three independent hydroponic

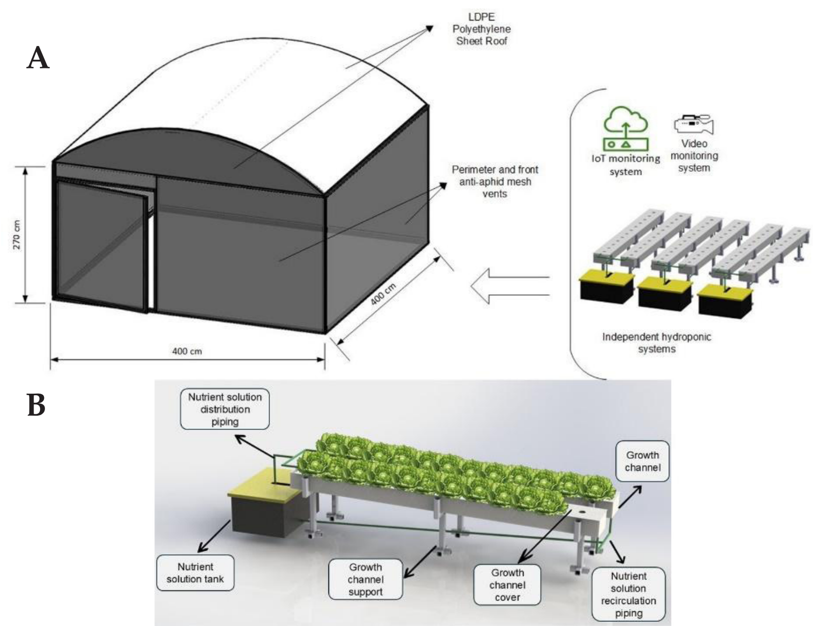

Figure 1. Hydroponic greenhouse system. A: Schematic diagram of the greenhouse and its internal components; B: Hydroponic system model.

systems, an IoT monitoring system that records key environmental variables, and a video monitoring system for continuous visual supervision.

The hydroponic systems were designed and fabricated at the Manufacturing and Prototyping Laboratory of the National Institute of Technology in Celaya. They were constructed using 0.4 cm-thick translucent black polycarbonate sheets (Other), sealed with Pennsylvanian ferrosilicon, and assembled with a heat gun to ensure airtightness and long-lasting durability. Each of the three independent hydroponic systems inside the greenhouse consisted of two polycarbonate channels designed according to plant development parameters, measuring 280 × 25 × 15 cm in length, width, and height, respectively.

The Nutrient Film Technique (NFT) system model (Figure 1B) had a heavy-duty plastic with a capacity of 102 L at the beginning of the channels, equipped with a 25 W submersible pump and a flow rate of 3500 L h^{-1}. The piping was made of Tuboplus hydraulic (PP-R) and included recirculation piping at the end of each channel to facilitate drainage. The channels had three supports that allowed for a 2 % inclination, ensuring a constant and adequate flow of the nutrient solution with a film thickness of 4 to 5 mm. Each of the channels was fitted with covers featuring plant spacings of 18.5 cm.

Cultivation experiment

The hydroponic cultivation experiment for lettuce was conducted in four stages: germination (2 d), root growth (27 d), transplant to the cultivation system and vegetative growth (29 d), and harvest on day 30 after transplanting. The total cultivation duration was 60 d. According to Ruangrak *et al.,* 2023, the nutrient solution was replaced with water for 24 h before cultivation to minimize undesirable flavors in the leaf area associated with the accumulation of salts or mineral compounds, which can alter the sensory characteristics of the final product.

Lettuce seedlings (*Lactuca sativa* L. cv. Rodhenas), measuring 7 cm and exhibiting new leaves and primary root shoots, were positioned in agricultural foam with their roots extending through the bottom and placed into hydroponic baskets. Thirty days after germination (DAG), 30 seedlings per treatment were transplanted into the hydroponic system. This day was considered day zero for monitoring the system. The universal Steiner-type solution (Al Meselmani, 2023) was used, with the constant NFT in the hydroponic system channels. The nutrient formulation was dissolved in 10 L of water with a pH of 6, adjusted using 70 % nitric acid to create a stock solution A-B.

Three nutrient treatments were prepared by diluting the A-B solution at 100 % (T1), 75 % (T2), and 50 % (T3), corresponding to 10, 7.5, and 5 mL per liter of nutrient solution, respectively. The electrical conductivities of these solutions were 1.970, 1.621, and 1.272 dS m^{-1}. T1 served as the control, representing the standard hydroponic formulation that provides a balanced supply of macro- and micronutrients for optimal plant growth (Dasgan *et al*., 2022; Miller *et al*., 2020). The nutrient solution was based on the universal formula proposed by Steiner (1961) with the following concentrations (mg L^{-1}): NO_3, 224; NH_4, 14; P, 47; K, 371; Ca, 180; Mg, 24; S, 66.5; B, 0.25; Fe-EDTA, 2.61; Zn-EDTA, 0.357; Ce-EDTA, 0.179; Mn-EDTA, 1.39; and Mo, 0.11.

The experiment was conducted under a completely randomized design, with three treatments and 14 repetitions per treatment, for a total of 42 experimental units. Prior to analysis, the normality of the data was verified using the Shapiro-Wilk test, and homogeneity of variances was assessed. The data was analyzed using an analysis of variance (ANOVA). When significant differences among treatments were found, Turkey's test ($p \leq 0.05$) was applied. All statistical analyses were performed using Microsoft Excel (version 2021).

Internet of Things monitoring system

During the cultivation experiment, a remote monitoring system based on IoT was used (Figure 2). The system consisted of four components: 1) a digital ambient temperature and relative humidity sensor AM2302 (DHT22, Aosong Electronics Co., Ltd., China); 2) a wireless module based on an ESP8266 NodeMCU development board (Espressif Systems, Shanghai, China); 3) a cloud server using ThingSpeak (The MathWorks Inc., Natick, MA, USA); and 4) a mobile application provided by ThingSpeak for quick data consultations and the MIT App Inventor created by the Massachusetts Institute of Technology (MIT), which features a customized interface for real-time and local data visualization.

The digital sensor AM2302 (DHT22) measured temperature from relative humidity with a sampling frequency of 0.5 Hz and a response time of 2 s. The supply voltage

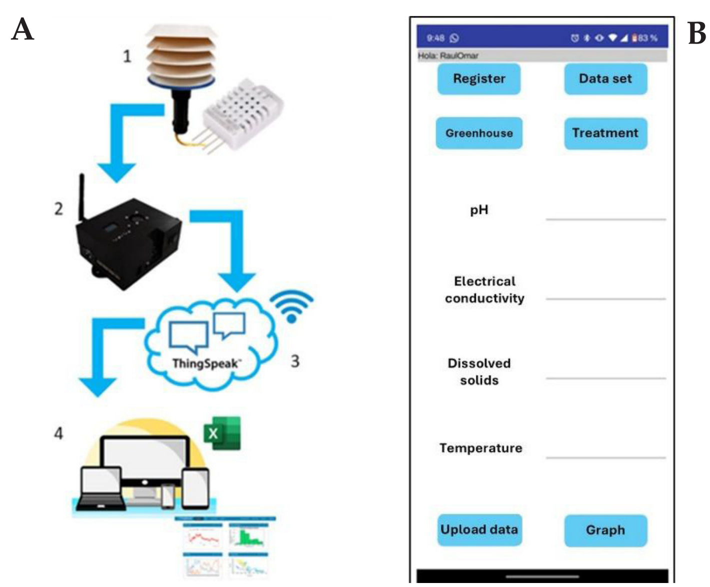

Figure 2. Internet of Things monitoring system. A: Environmental variables monitoring system; B: Mobile application interface used for storing nutrient solution data.

ranged from 3.3 to 5.5 V, and the maximum current consumption was 2.5 mA during measurement and less than 1 mA in idle mode. This sensor acquires ambient temperature and relative humidity data and transmits information to the wireless module every 5 min using the 1-Wire protocol. The sensor's data pin was connected to the general-purpose input/output (GPIO) pin 6 of the ESP8266. The sensor was powered by the development board with 5 V, supplied by the system's main power source.

The sensor data was transmitted to the cloud through a wireless module connected to 2.4 GHz networks. The module featured an I²C bus general-purpose input/output (GPIO) ports, powered by either 127 V alternating current (AC) or 5 V direct current (DC). It also included a human-machine interface (HMI) to provide users with local real-time information. The data collected by the wireless module was uploaded to the ThingSpeak server via HTTP, where it was stored, analyzed, and visualized. This platform enables remote monitoring via mobile applications, allowing users to access real-time data, view time-series graphs, configure automatic alerts, and receive notifications when conditions exceed set thresholds.

During the experiment, lettuce cultivation in a greenhouse without environmental control was maintained under ideal conditions of 18–26 °C ambient temperature and 55–70 % relative humidity. Each nutrient treatment was monitored daily in the morning for pH, temperature, EC, and dissolved mineral content (ppm) using a C-600 multiparameter water quality meter (Dr. Meter, Shenzhen, China). The manually collected data were stored in a database through the mobile application (Figure 1B) to ensure that the established levels for each treatment were consistently maintained.

The "Invernadero" application was developed specifically for this project using MIT App Inventor (MIT) and is designed to run exclusively on Android devices. The application communicates with the ThingSpeak platform, where the database is organized into three channels (one for each treatment). Each channel contains four fields storing information on pH, temperature, EC, and dissolved mineral content. This setup allows users to visualize and export data, analyze system behavior across treatments, and maintain optimal nutrient solution conditions. The source code for both the system and mobile application is publicly available (https://github.com/DSM40/GreenHouse).

In the hydroponic greenhouse, HD C10_wjmozu-gj WIFI video cameras with integrated microphones were installed at specific points for crop video monitoring. Real-time monitoring is enabled through the Smart mobile application (Tuya Inc., Hangzhou, China), an IoT development platform that allows users to observe the crops remotely from any mobile device. The integrated microphones also provide audio feedback, enabling users to verify the proper operation of the hydroponic systems.

Crop parameters evaluated

Several plant parameters were evaluated, including growth, dry matter, water content, and nutritional profile. The Chlorophyll Content Index (CCI) was evaluated using an SPAD-502 Plus 2900P-C (2900P-C model, Konica Minolta Inc., Osaka, Japan).

Measurements were taken on the leaflets of the third and fourth leaves of the lettuce plants between 9:00 am and 12:00 pm every three days.

Leaf area was determined using an image processing system developed in MATLAB (The MathWorks Inc., Natick, MA, USA) through the App Designer environment. The system integrated the Image Processing Toolbox and the Computer Vision Toolbox, which enabled image segmentation, grayscale conversion, binarization, and pixel counting to calculate leaf area (cm^2) based on a physical reference. Image acquisition was conducted in 10 sessions distributed throughout the growth period. The MATLAB source code for the developed system is available for consultation (https://github.com/DSM40/GreenHouse).

After 30 days in the hydroponic cultivation system, 30 lettuce plants were harvested from each treatment, and the fresh weight of each plant was recorded. Stem diameter was measured at the root insertion point using a Mitutoyo vernier caliper (model 505-742J; Mitutoyo Corporation, Kawasaki, Japan). Root length was determined with a tape measure, and the number of leaves was counted visually.

Lettuce dry weight was measured using 14 replicates per treatment. Leaves and roots were separated, placed in Kraft paper bags, and dried in an FE-131AD oven (Felisa, Mexico) at 72 °C for 48 h. The dry weight was determined gravimetrically using a precision electronic balance with 2000 g capacity and 0.01 g sensitivity (VENOR, analytical laboratory model). Water content was then calculated as the difference between the fresh and dry weights of each sample.

Three plants were randomly selected from each treatment to determine their proximate composition. Samples were taken from the lower, middle, and upper parts of each plant to ensure representativeness. The percentages of moisture, protein, fat, fiber, ash, and carbohydrates present in the crop were determined. Moisture content was obtained by drying the samples in a vacuum oven at 70 °C until a constant weight was achieved, according to AOAC Official Method 934.01 (AOAC, 2000).

Protein content was measured using the Kjeldahl method, AOAC Official Method 984.13 (AOAC, 2000), with an MDK-6 micro-digestion unit (Novatech, Mexico) and applying a conversion factor of 6.25 to transform total nitrogen into crude protein. Ash content was determined by incineration dried samples in an Indet muffle furnace model 273 (Indet, Mexico) at 550 °C for 24 h, according AOAC Official Method 923.03 (AOAC, 2000). Total fat was measured using the Soxhlet extraction method with n-hexane as the solvent, following the AOAC Official Method 920.39 (AOAC, 2000). Carbohydrate content was calculated by difference using the formula described by Fennema (1996).

This experiment followed a completely randomized design, with three replicates per treatment. The experimental unit was the lettuce plant cultivated in the hydroponic system, for a total of nine experimental units. Data normality was verified using the Shapiro-Wilk test, and homogeneity of variances was confirmed. Biochemical variable data were analyzed using analysis of variance (ANOVA), and when significant differences were identified among treatments ($p \leq 0.05$), Tukey's test was applied.

Statistical analysis was carried out using Microsoft Excel (version 2021) with built-in data analysis tools.

RESULTS AND DISCUSSION

Protected agriculture in Mexico covers more than 25 000 ha, with 1728 ha dedicated to hydroponic cultivation (SIAP, 2022). Protected agriculture provides greater environmental and economic benefits than conventional agriculture. However, the country still shows limited development in technologies, tools, materials, and supplies for this sector, leading to a strong dependence on foreign imports. The increasing availability of low-cost electronic components in the national market and on global digital platforms enables the creation of innovative, affordable, and regionally adaptable agricultural technologies. The estimated cost of implementing the proposed system was approximately USD 38, considering low-cost components such as the ESP8266, environmental sensors, and free platforms like ThingSpeak and MIT App Inventor for data development and storage.

Figure 3 illustrates the experimental setup inside the hydroponic greenhouse, including the three nutrient treatments T1 (100 %), T2 (75 %), and T3 (50 %) ,the IoT monitoring system, and the video monitoring camera used for real-time observation of crop development.

Singh and Benbi (2016) reported that the optimal conditions for hydroponic lettuce cultivation include an electrical conductivity (EC) between 1200 and 1800 μS cm^{-1} and a pH of 6–7. Similarly, Samarakoon *et al*. (2019) found that an EC of 1800 μS cm^{-1} in

Figure 3. Experimental setup of the hydroponic greenhouse showing the arrangement of nutrient treatments T1 (100 %), T2 (75 %), and T3 (50 %), the IoT monitoring unit, and the video monitoring system used for data acquisition and environmental control.

nutrient film technique systems enhances photosynthetic activity and fresh weight. However, when EC increased to 2400 μS cm^{-1}, leaf burn occurred without further yield improvement. In contrast, Abou-Hadid *et al*. (1995) observed that lettuce fresh weight decreased when EC exceeded 1000 μS cm^{-1}, although phosphorus and potassium uptake improved at 1800 μS cm^{-1}. These authors recommended maintaining dissolved solid concentrations between 1000 and 1500 ppm to optimize osmotic pressure and promote nutrient absorption through the roots.

In this work, all treatments maintained the recommended conditions from the literature (Figure 4A). In treatment T1, which contained the highest nutrient concentration, EC remained above 100 μS cm^{-1}, which, according to previous reports, can pose a risk to plant development. Moreno-Pérez *et al*. (2015) emphasize the importance of monitoring and recording EC levels, as they can rise to 5000 μS cm^{-1} due to the accumulation of magnesium and calcium salts, negatively impacting nutrient absorption and utilization efficiency.

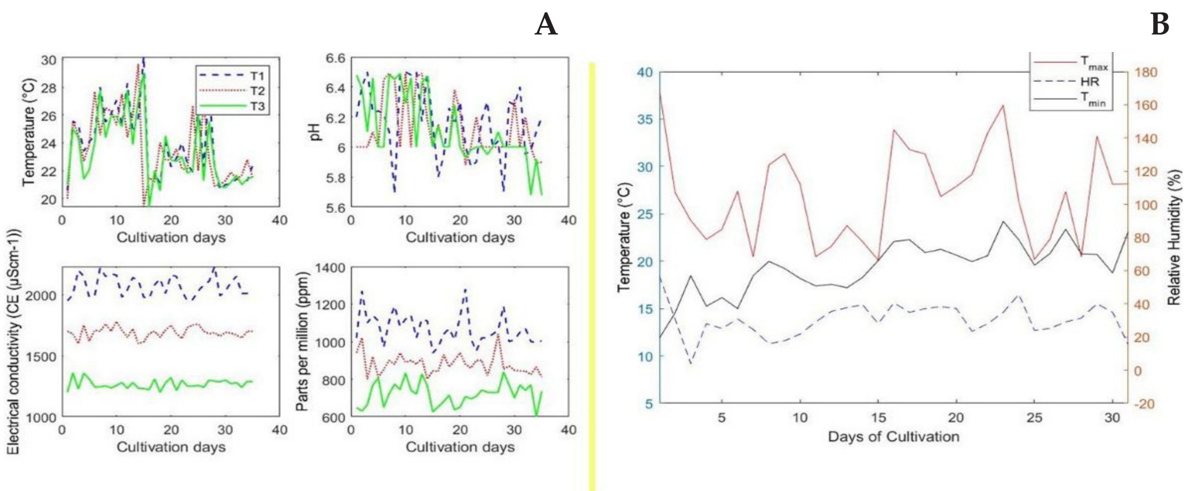

Figure 4. Behavior of the monitored variables in the hydroponic cultivation system. A: Nutrient solution with respect to each treatment; B: Internal environmental variables of temperature (°C) and relative humidity (%) with daily frequency in the Days Post Adaptation (DPA).

Monitoring of physical variables such as relative humidity (%) and temperature (°C) inside the greenhouse was carried out over a 30 d period, producing 6539 consecutive records for each parameter (Figure 4B). Throughout the cultivation experiment, from seedling transplantation to harvest, including the vegetative growth phase, environmental data influencing crop development under actual conditions were collected continuously. The IoT monitoring system enabled real-time tracking and constant access to this information, ensuring precise control of the greenhouse environment.

The recorded data revealed the behavior of ambient temperature and relative humidity, providing a detailed view of thermal fluctuations and their inverse relationship. The average temperature was 21.56 °C, ranging from 13.9 to 29.6 °C, while relative humidity averaged 49.28 %, with values between 11.1 and 87.6 %. Integrating video cameras with the IoT system allowed the surveillance and monitoring of the hydroponic greenhouse, improving security, operational efficiency, and environmental control, guaranteeing greater productivity and sustainability of the hydroponic system.

Crop parameter evaluation results

No significant differences in lettuce morphology were observed among the treatments. All plants exhibited a fresh, vibrant appearance, a characteristic that is highly desirable and valued in this crop. Lettuce is among the most widely consumed vegetables and is generally perceived by consumers as fresh and healthy. This perception is largely influenced by its phenotypic characteristics. In recent years, various technological tools have been developed to monitor lettuce growth and development in greenhouse cultivation (Du *et al*., 2022).

The hydroponic system significantly improved vegetative growth. Leaf area measurements averaged 759.93 mm^2 for T1, 710.43 mm^2 for T2, and 715.29 mm^2 for T3. However, Tukey's test indicated no significant differences in leaf area among the treatments (Figure 5A). T1 exhibited the greatest lettuce fresh weight, with a difference of nearly 100 g compared to the other treatments (Table 1). This difference was statistically significant.

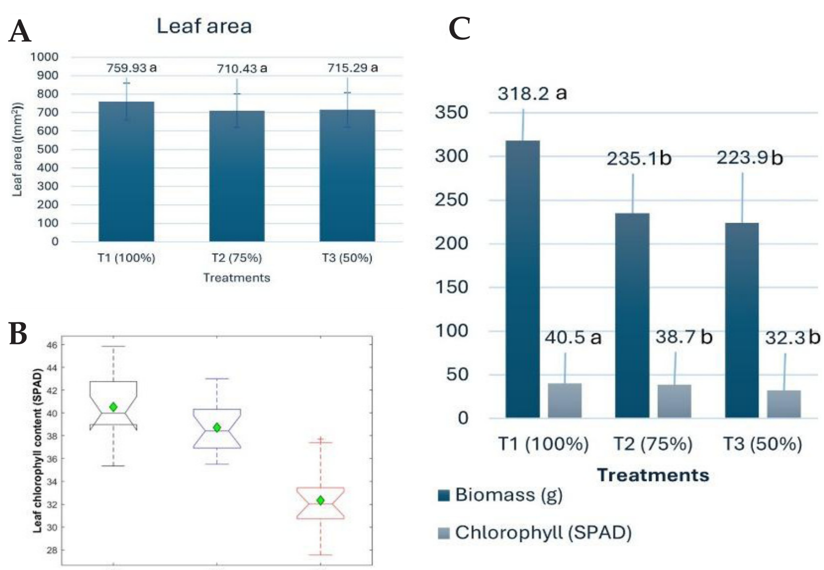

Figure 5. Statistical analysis of phenotypic parameters of lettuce (*Lactuca sativa* L. cv Rodhenas). A: Leaf area of the crop for each treatment; B: Leaf chlorophyll content index for T1 (100 %), T2 (75 %), and T3 (50 %) (mean ± standard error); C: Comparison of arithmetic means of biomass and chlorophyll content in the leaves.

Table 1. Mean fresh and dry weights of aerial and root parts of lettuce plants (*Lactuca sativa* L. cv Rodhenas) under different hydroponic nutrient treatments.

Treatment	Growth parameters			Fresh matter		Dry matter		Number of leaves	Water content (%)
	Leaf height (cm)	Root length (cm)	Stem width (mm)	Leaf weight (g)	Root weight (g)	Leaf weight (g)	Root weight (g)		
T1 (100 %)	23.40 a	16.37 a	22.21 a	329.06 b	24.25 a	10.81 a	0.81 a	27.50 b	95.62 a
T2 (75 %)	22.37 a	14.18 b	21.77 a	244.25 a	24 a	9.06 ab	0.81 a	25.18 a	95.09 b
T3 (50 %)	22.12 a	16.18 a	20.86 a	232.37 a	23.62 a	8.43 b	0.81 a	24.81 a	95.28 ab

Different letters represent significant differences between groups ($p \leq 0.05$).

While chlorophyll content tends to increase with higher EC, elevated EC levels can also cause excessive nitrate accumulation, posing potential health risks if concentrations exceed the permissible limits for fresh produce. Lettuce grown with very high EC values (10 000 μS cm^{-1}) had reduced fresh weight despite an increase in chlorophyll content, which reflects a physiological response to salt stress (Kappel *et al*., 2021). High nitrate levels in vegetables are associated with nitroso compounds, which result in the formation of nitrosamines and methemoglobinemia when metabolized in the human body. Regulating the EC in the nutrient solution is essential to ensure product safety and nutritional quality (Guffanti *et al.*, 2022).

Under the studied conditions, no adverse effects on lettuce growth were observed. The highest nutrient concentration (T1) produced plants with greater fresh weight and chlorophyll content, without visible stress symptoms. Significant differences were detected in growth variables (Table 1), supporting the beneficial effect of optimized nutrient levels. Excessive fertilizer input or salt accumulation in closed hydroponic systems can eventually cause leaf discoloration and tip burn (Samarakoon *et al*., 2019), emphasizing the importance of regular EC monitoring and adjustment.

Treatments T2 and T3 had no significant differences in fresh foliar weight or leaf number, nor did treatments T1 and T3 in root length. However, significant differences were observed between T1 and T3 for dry matter of the leaves (Table 1). This could indicate a deficiency in nutrient absorption due to reduced nutrient concentrations, potentially affecting crop quality and yield. In terms of water percentage, a difference was observed in T2 compared to T1 and T3. However, these variations did not affect crop quality or nutrient absorption. This suggests that the treatment system maintained its efficiency in nutrient delivery. Additionally, the results indicate that T1 promoted more efficient growth, confirming the effectiveness of cultivation under hydroponic conditions.

Lettuce is primarily composed of water, which contributes to its low caloric content. However, its nutritional contribution is significant due to the presence of vitamins, minerals, and bioactive compounds (Madhusudan and Baskaran, 2023). The biochemical parameters obtained from the proximate analyses contributed to determining its composition and nutritional value (Table 2). Although its overall

Table 2. Average biochemical composition (%) of lettuce plants (*Lactuca sativa* L. cv Rodhenas) under different nutrient treatment concentrations.

	Nutritional composition (%)					
Treatment	Moisture	Ashes	Protein	Oils	Fiber	Carbohydrates
T1 (100 %)	95.62 a	0.97 a	0.80 a	0.20 a	1.19 a	1.21 a
T2 (75 %)	95.09 b	0.97 a	0.97 a	0.21 a	1.57 b	1.16 a
T3 (50 %)	95.28 ab	0.89 a	0.90 a	0.13 a	1.65 b	1.13 a

Different letters represent significant differences between groups ($p \leq 0.05$).

nutritional value is relatively low, lettuce contains a high water content (90–95 %) and is a good source of antioxidants, contributing to its health-promoting properties.

The ash, protein, fat, and carbohydrate percentages showed no significant differences between treatments. T1 showed a significant difference for fiber, reducing its percentage to 0.38 % for T2 and 0.46 % for T3. Significant differences were found among treatments in terms of moisture percentage; T1 had the highest, while T2 had the lowest. In contrast, T3 had an intermediate value that did not interfere significantly with either T1 or T2. The weight of the harvested pieces from T2 and T3 (foliar tissue) was not significantly affected by the lower nutrient concentration in the nutrient solution.

During cultivation, chlorophyll content readings were taken every third day until harvest using the non-destructive, dimensionless Soil-Plant Analysis Development (SPAD) method. A significant effect was observed for the interactions between the foliar portion factor (Figure 5B). The readings demonstrate stable values with a low coefficient of variation. The SPAD values were highest in T1 (40.5 ± 1.01), followed by T2 (38.7 ± 0.97) and T3 (32.3 ± 0.97), demonstrating that nutrient concentration significantly affected the chlorophyll levels during the cultivation experiment.

These values align with ranges reported for leafy crops grown under hydroponic conditions. Ahmad *et al*. (2022) demonstrated that SPAD values above 38 are associated with active photosynthetic activity. According to Zhang *et al*. (2022), these chlorophyll values are positively correlated with biomass and yield in lettuce crops. The low value observed in T3 may indicate possible nitrogen or nutrient deficiency, which limited photosynthetic capacity, as noted by Luna-Fletes *et al*. (2023) in their research. Choi *et al*. (2024) validated the use of the SPAD meter as a non-invasive and reliable tool for monitoring crop status. The findings highlight the critical role of maintaining optimal nutrient solution conditions, as the efficient physiological responses in treatments T1 and T2 helped sustain plant balance and vigor.

Cultivation efficiency, assessed through biomass, yielded values of 318.25 g for T1, 235.18 g for T2, and 223.93 g for T3, with no significant difference between T2 and T3 (Figure 5C). The purpose of the greenhouse is to create controlled environmental conditions within a confined space that promote growth and productivity. It is important to monitor, record, and have quick and convenient access to the greenhouse status, which was achieved in this project. The IoT-based environment monitoring system worked efficiently, registering real-time data and providing precise information on environmental variables, ensuring the optimal conditions for hydroponic cultivation development.

CONCLUSIONS

Environmental conditions were continuously monitored using IoT-based devices. The plants exhibited accelerated and vigorous growth, with roots exposed to the nutrient film showing robust and healthy development. No significant differences were found in the nutritional composition of the harvested lettuce among treatments. The IoT monitoring and data recording system functioned reliably throughout the 30-day cultivation period, with no reported failures and constant electronic access to cultivation information. Looking forward, developing a system with failure alarms and automation protocols for correction would be pursued. Overall, these technologies represent an important step toward the development of low-cost, locally adaptable systems that strengthen agricultural innovation and food production efficiency.

ACKNOWLEDGEMENTS

To the Secretariat of Science, Humanities, Technology, and Innovation (SECIHTI) and the National Institute of Technology of Mexico in Celaya for their support and financing for this project.

REFERENCES

AOAC. 2000. Official Methods of Analysis of AOAC International (17th ed., Vols. 1–2). Association of Official Analytical Chemists, Gaithersburg, MD, USA. Available at: https://www.aoac.org.

Abou-Hadid AF, Abd-Elmoniem EM, El-Shinawy MZ, Abou-Elsoud M. 1995. Electrical conductivity affects the growth and mineral composition of lettuce plants in hydroponic systems. Acta Horticulturae 434: 59–66. https://doi.org/10.17660/ActaHortic.1996.434.6

Acharya S, Kumar K, Sharma N, Tiwari VK, Chaurasia OP. 2021. Yield and quality attributes of lettuce and spinach grown in different hydroponic systems. Journal of Soil and Water Conservation 20 (3): 342–349. https://doi.org/10.5958/2455-7145.2021.00043.6

Ahmad U, Alvino A, Marino S. 2022. Solar fertigation: A sustainable and smart IoT-based irrigation and fertilization system for efficient water and nutrient management. Agronomy 12 (5): 1012. https://doi.org/10.3390/agronomy12051012

Ahmed ZF, Alnuaimi AK, Askri A, Tzortzakis N. 2021. Evaluation of lettuce (*Lactuca sativa L.*) production under hydroponic system: Nutrient solution derived from fish waste vs. inorganic nutrient solution. Horticulturae 7 (9): 292. https://doi.org/10.3390/horticulturae7090292

Al Meselmani M. 2023. Nutrient solution for hydroponics. *In* Turan M, Argin S, Yildirim E, Güneş A. (eds.), Recent Research and Advances in Soilless Culture. IntechOpen. https://doi.org/10.5772/intechopen.101604

Arvanitis KG, Symeonaki EG. 2020. Agriculture 4.0: The role of innovative smart technologies towards sustainable farm management. The Open Agriculture Journal 14 (1): 130–136. https://doi.org/10.2174/1874331502014010130

Chen X, Wang X, Shen H. 2021. Design of greenhouse environment monitoring system based on NB-IoT and edge computing. *In* Proceedings of the 2021 IEEE 5th Advanced Information Technology, Electronic and Automation Control Conference (IAEAC). Institute of Electrical and Electronics Engineers: Chongqing, China, pp: 1319–1324. https://doi.org/10.1109/iaeac50856.2021.9390671

Choi SH, Kim DY, Lee SY, Lee KH. 2024. Effect of nutrient management during the nursery period on the growth, tissue nutrient content, and flowering characteristics of hydroponic strawberry in 2022. Horticulturae 10 (11): 1227. https://doi.org/10.3390/horticulturae10111227

Dasgan HY, Aldiyab A, Elgudayem F, Elansari AM, Çömlekçioğlu N. 2022. Effect of biofertilizers on leaf yield, nitrate amount, mineral content and antioxidants of basil (*Ocimum basilicum* L.) in a floating culture. Scientific Reports 12 (1), 20917. https://doi.org/10.1038/s41598-022-24799-x

do Carmo AP, Freitas MS, Machado LC, do Santos Silva L, Petri DJ, Vimercati JC, de Carvalho AJ. 2024. The electrical conductivity of nutrient solutions affects the growth, nutrient levels, and content and composition of essential oils of *Acmella oleracea* (L.) RK Jansen from southeastern Brazil. Journal of Agriculture and Food Research 15: 100968. https://doi.org/10.1016/j.jafr.2024.100968

Du J, Li B, Lu X, Yang X, Guo X, Zhao C. 2022. Quantitative phenotyping and evaluation for lettuce leaves of multiple semantic components. Plant Methods 18 (1): 54. https://doi.org/10.1186/s13007-022-00890-2

Eze VHU, Eze EC, Alaneme GU, BUBU PE, Nnadi EOE, Okon MB. 2025. Integrating IoT sensors and machine learning for sustainable precision agroecology: Enhancing crop resilience and resource efficiency through data-driven strategies, challenges, and future prospects. Discover Agriculture 3 (1): 1–34. https://doi.org/10.1007/s44279-025-00247-y

FAO (Food and Agriculture Organization of the United Nations). 2021. The State of Food Security and Nutrition in the World 2021 (SOFI). Rome, Italy. https://doi.org/10.4060/cb4474es

Fennema OR. 1996. Food Chemistry (Third edition). CRC Press: Boca Raton, FL, USA. 1158 p.

Goddek S, Joyce A, Kotzen B, Burnell GM. 2019. Aquaponics food production systems: Combined aquaculture and hydroponic production technologies for the future. Springer Nature: Cham, Switzerland. 619 p. https://doi.org/10.1007/978-3-030-15943-6

Guffanti D, Cocetta G, Franchetti BM, Ferrante A. 2022. The effect of flushing on the nitrate content and postharvest quality of lettuce (*Lactuca sativa* L. var. Acephala) and rocket (*Eruca sativa* Mill.) grown in a vertical farm. Horticulturae 8 (7): 604. https://doi.org/10.3390/horticulturae8070604

Gupta AD, Pandey P, Feijóo A, Yaseen ZM, Bokde ND. 2020. Smart water technology for efficient water resource management: A review. Energies 13 (23): 6268. https://doi.org/10.3390/en13236268

Hernández-Morales CA, Luna-Rivera JM, Pérez-Jiménez R. 2022. Design and deployment of a practical IoT-based monitoring system for protected cultivations. Computer Communications 186: 51–64. https://doi.org/10.1016/j.comcom.2022.01.009

INEGI (National Institute of Statistics and Geography). 2020. Statistical and geographical yearbook of Guanajuato 2020. INEGI. Aguascalientes, Mexico.

Kappel N, Boros IF, Ravelombola FS, Sipos L. 2021. EC sensitivity of hydroponically-grown lettuce (*Lactuca sativa L.*) types in terms of nitrate accumulation. Agriculture 11 (4): 315. https://doi.org/10.3390/agriculture11040315

Kazakis NA, Tsirliganis NC. 2023. Holistic approach to Agriculture 4.0 for new farmers. Societal Impacts 1 (1–2): 100007. https://doi.org/10.1016/j.socimp.2023.100007

Khanal AR, Mishra AK, Lambert DM, Paudel KP. 2019. Modeling post adoption decision in precision agriculture: A Bayesian approach. Computers and Electronics in Agriculture 162: 466–474. https://doi.org/10.1016/j.compag.2019.04.025

La Cecilia D, Tom M, Stamm C, Odermatt D. 2023. Pixel-based mapping of open field and protected agriculture using constrained Sentinel-2 data. ISPRS Open Journal of Photogrammetry and Remote Sensing 8: 100033. https://doi.org/10.1016/j.ophoto.2023.100033

Luna-Fletes JA, Cruz-Crespo E, Can-Chulim Á, Chan-Cupul W, Luna-Esquivel G, García-Paredes JD, Mancilla-Villa OR. 2023. Biofertilizantes y sustratos orgánico-minerales en el cultivo de chile habanero. Revista Fitotecnia Mexicana 46 (2): 137–146. https://doi.org/10.35196/rfm.2023.2.137

Madhusudan S, Baskaran R. 2023. The sea lettuce *Ulva* sensu lato: Future food with health-promoting bioactives. Algal Research 71: 103069. https://doi.org/10.1016/j.algal.2023.103069

Madushanki AR, Halgamuge MN, Wirasagoda WS, Syed A. 2019. Adoption of the Internet of Things (IoT) in agriculture and smart farming towards urban greening: A review. International Journal of Advanced Computer Science and Applications 10 (4): 11–28. https://doi.org/10.14569/ijacsa.2019.0100402

Maffezzoli F, Ardolino M, Bacchetti A, Perona M, Renga F. 2022. Agricultura 4.0: Una revisión sistemática de la literatura sobre el paradigma, las tecnologías y los beneficios. Futures 142: 102998. https://doi.org/10.1016/j.futures.2022.102998

Martínez-Moreno A, Carmona J, Martínez V, Garcia-Sánchez F, Mestre TC, Navarro-Pérez V, Cámara-Zapata JM. 2024. Reducing nitrate accumulation through the management of nutrient solution in a floating system lettuce (*Lactuca sativa L.*). Scientia Horticulturae 336: 113377. https://doi.org/10.1016/j.scienta.2024.113377

Miller AJ, Adhikari R, Nemali KS. 2020. Recycling nutrient solution can reduce growth due to nutrient deficiencies in hydroponic production. Frontiers in Plant Science 11: 607643. https://doi.org/10.3389/fpls.2020.607643

Moreno-Pérez EDC, Sánchez-Del Castillo F, Gutiérrez-Tlaque J, González-Molina L, Pineda-Pineda J. 2015. Greenhouse lettuce production with and without nutrient solution recycling. Revista Chapingo Serie Horticultura 21 (1): 43–55. https://doi.org/10.5154/r.rchsh.2013.12.047

Mwanake H, Mehdi-Schulz B, Schulz K, Kitaka N, Olang LO, Lederer J, Herrnegger M. 2023. Agricultural practices and soil and water conservation in the Kenya-Uganda transboundary region: Farmers' perspectives on current soil erosion. Agriculture 13 (7): 1434. https://doi.org/10.3390/agriculture13071434

Nižetić S, Šolić P, Gonzalez-De DLDI, Patrono L. 2020. Internet of Things (IoT): Opportunities, issues, and challenges towards a smart and sustainable future. Journal of Cleaner Production 274: 122877. https://doi.org/10.1016/j.jclepro.2020.122877

Paul K, Chatterjee SS, Pai P, Varshney A, Juikar S, Prasad V, Dasgupta S. 2022. Viable smart sensors and their application in data driven agriculture. Computers and Electronics in Agriculture 198: 107096. https://doi.org/10.1016/j.compag.2022.107096

Ruangrak E, Salaemae N, Sornnok S, Htwe NMPS. 2023. Effect of pre-harvest periods by replacing nutrient solution with tap water on nitrate and quality in hydroponic lettuce. ASEAN Journal of Scientific and Technological Reports 26 (1): 76–83. https://doi.org/10.55164/ajstr.v26i1.247666

Samarakoon UC, Fyffe C, Bale J, Ling P, Basnagala S, Donley N, Altland J. 2019. Effect of electrical conductivity on the productivity and nutrient uptake of *Lactuca sativa* L. grown using nutrient film technique (NFT). Acta Horticulturae 1266: 137–144. https://doi.org/10.17660/actahortic.2019.1266.19

Sharma U, Bhardwaj DR, Sharma S, Sankhyan N, Thakur CL, Rana N, Sharma S. 2022. Assessment of the efficacy of various mulch materials on improving the growth and yield of ginger (*Zingiber officinale*) under bamboo-based agroforestry system in NW-Himalaya. Agroforestry Systems 96 (5): 925–940. https://doi.org/10.1007/s10457-022-00753-8

Shin KKY, Ping TP, Ling MGB, Jiun CC, Bolhassan NAB. 2024. SMART GROW–Low-cost automated hydroponic system for urban farming. HardwareX 17: e00498. https://doi.org/10.1016/j.ohx.2023.e00498

SIAP (Servicio de Información Agroalimentaria y Pesquera). 2022. Agricultura protegida por entidad federativa y tipo de tecnología. Gobierno de México. Secretaría de Agricultura y Desarrollo Rural. Servicio de Información Agroalimentaria y Pesquera. Ciudad de México, México. https://www.gob.mx/siap (Retrieved: June 2025).

Singh S, Benbi DK. 2016. Punjab-soil health and green revolution: A quantitative analysis of major soil parameters. Journal of Crop Improvement 30 (3): 323–340. https://doi.org/10.1080/15427528.2016.1157540

Steiner AA. 1961. A universal method for preparing nutrient solutions of a certain desired composition. Plant and Soil 15: 134–154. https://doi.org/10.1007/BF01347224

Symeonaki E, Arvanitis KG, Piromalis D, Tseles D, Balafoutis AT. 2022. Ontology-based IoT middleware approach for smart livestock farming toward Agriculture 4.0: A case study for controlling thermal environment in a pig facility. Agronomy 12 (3): 750. https://doi.org/10.3390/agronomy12030750

Yang T, Samarakoon U, Altland J, Ling P. 2021. Photosynthesis, biomass production, nutritional quality, and flavor-related phytochemical properties of hydroponic-grown arugula (*Eruca sativa* Mill.) 'standard' under different electrical conductivities of nutrient solution. Agronomy 11 (7): 1340. https://doi.org/10.3390/agronomy11071340

Yang T, Samarakoon U, Altland J. 2024. Growth, phytochemical concentration, nutrient uptake, and water consumption of butterhead lettuce in response to hydroponic system design and growing season. Scientia Horticulturae 332: 113201. https://doi.org/10.1016/j.scienta.2023.113201

Zhang R, Yang P, Liu S, Wang C, Liu J. 2022. Evaluation of the methods for estimating leaf chlorophyll content with SPAD chlorophyll meters. Remote Sensing 14 (20): 5144. https://doi.org/10.3390/rs14205144

Zhu Z, Yogev U, Keesman KJ, Rachmilevitch S, Gross A. 2023. Integrated hydroponics systems with anaerobic supernatant and aquaculture effluent in desert regions: Nutrient recovery and benefit analysis. Science of the Total Environment 904: 166867. https://doi.org/10.1016/j.scitotenv.2023.166867