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RESEARCH PAPER

Development of an automated portable aquaponic system and assessment of LED lighting impact on *Mentha piperita* L.

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Abstract

The growing global population and increasing food demand require innovative agricultural techniques that enhance yield per unit area. Compounded by climate change and shrinking arable land, sustainable and efficient food production methods are essential. In this context, a digital prototype of a portable aquaponic farming system was developed to evaluate the effectiveness of LED-supported and non-LED-supported growth platforms.

The experiment involved peppermint plants (*Mentha piperita* L.) and Tilapia fish (*Oreochromis niloticus*) in a closed-loop aquaponic system. In the LED-supported platform, red (660 nm) and blue (450 nm) LEDs were used for 4 hours daily in addition to natural sunlight, while the non-LED platform relied solely on sunlight.

Daily monitoring included water quality (ammonia, nitrite, nitrate, pH, temperature), water consumption, fish growth, and plant development. Plant performance was assessed by chlorophyll content index (CCI), color values (L*, a*, b*), fresh and dry weights, and stomatal conductance, measured at day 0th, day 20th, and day 40th.

Results showed the LED-supported system significantly enhanced plant growth and quality. Chlorophyll content increased by 29% (27.175 vs. 21.00), fresh weight by 14% (1.871 g), and dry weight by 30% (0.270 g). Plants under LED light also had higher brightness (L*: 48.716), deeper green (a*: -9.155), and more intense yellow (b*: 23.395) compared to the non-LED group. In conclusion, LED-supported aquaponic systems effectively improve peppermint growth and visual quality, highlighting their potential in sustainable agricultural production.

Keywords

Aquaponics, agriculture, hydroponics farming, fish, Tilapia, peppermint

Introduction

The agricultural sector today faces challenges such as population growth, climate change, and diminishing freshwater resources. According to the Food and Agriculture Organization of the United Nations (FAO), the global population is expected to reach 9.7 billion by 2050, requiring a 60% increase in agricultural production (FAO 2021). Traditional agricultural models are insufficient to meet this demand. Additionally, the agricultural sector consumes 70% of global freshwater resources, exacerbating water scarcity problems (Goddek et al. 2019; FAO and UN-Water 2024). Consequently, research on sustainable agricultural systems is increasing.

Aquaponic systems combine aquaculture and soilless farming, creating a natural cycle through water and nutrient recycling (Kloas et al. 2015). In these systems, fish waste is converted by bacteria into nutrients usable by plants, reducing the need for chemical fertilizers (Palm et al. 2018). To achieve sustainable food production, agricultural technologies that enhance resource efficiency, reduce waste, and minimize carbon footprints are essential.

Aquaponic systems minimize chemical usage, facilitating the production of healthy and natural crops (Izci et al. 2020). These systems also contribute to environmental sustainability by conserving water and requiring low energy consumption (Massa et al. 2008). Moreover, because aquaponic production occurs in controlled environments, it enables continuous agricultural production throughout the year, regardless of outdoor conditions (Kloas et al. 2015).

The use of LED lighting in aquaponic systems plays a critical role in enhancing photosynthetic efficiency and plant productivity. Research indicates that red (660 nm) and blue (450 nm) wavelengths are optimal for plant growth and chlorophyll synthesis (Darko et al. 2020). Compared to conventional lighting, LED systems consume 50–70% less energy, have a longer lifespan, and enable indoor agricultural production (Junge et al. 2017). Studies have shown that LED-supported cultivation systems can increase plant biomass by 20–25% and chlorophyll content by 15% (Bittsanszky et al. 2016).

While previous studies have examined the general effects of LED lighting in aquaponic systems, there is a lack of experimental research comparing LED-supported and non-LED-supported environments specifically in peppermint (*Mentha piperita L.*) cultivation. This study addresses this gap by providing a detailed analysis of plant growth, chlorophyll content, and morphological characteristics under both conditions.

The application of digital technologies such as the Internet of Things (IoT), artificial intelligence, and sensor-based monitoring systems is becoming increasingly prevalent in agriculture (Anaz et al. 2023). Automation in aquaponic systems allows real-time monitoring and control of water quality, temperature, pH, and nutrient levels (Shamshiri et al. 2018). Artificial intelligence, data analytics, and predictive modeling play a vital role in optimizing agricultural processes (Liakos et al. 2018). These technologies accelerate disease detection, optimize plant growth, and reduce resource consumption (Kamilaris and Prenafeta-Boldú 2018; Jha et al. 2019). Furthermore, digital systems promote environmental sustainability by conserving energy and water (Mohapatra et al. 2019).

Digital technologies used in aquaponic systems offer remote monitoring and control capabilities, simplifying system management. Through web-based platforms and mobile applications, users can monitor real-time data on water quality, plant growth, and fish health, making necessary adjustments when needed. Remote monitoring systems provide several advantages, including real-time data tracking and analysis, instant alerts for critical conditions, and centralized management of processes such as automatic water changes, nutrient supplementation, and temperature regulation.

Recent advances in aquaponic farming have highlighted the role of IoT-enabled systems in improving environmental monitoring, automation, and crop management (Goddek et al. 2021; Zamnuri et al. 2024). Integrating sensors and microcontrollers in aquaponic setups has been shown to enhance water use efficiency, ensure stable nutrient cycles, and reduce manual labor requirements.

Therefore, the integration of automation systems and digital technologies in aquaponic farming not only improves productivity but also plays a crucial role in ensuring environmental sustainability. These technologies minimize human intervention, providing a more predictable, reliable, and sustainable production process. This study presents the development of a portable system designed for use in indoor environments such as homes and offices, evaluating its performance with and without LED support.

Materials and methods

In this study, a portable aquaponic system equipped with automation was designed to evaluate its performance in peppermint cultivation. The research was conducted in the laboratories and workshops of Tekirdağ Namık Kemal University, Faculty of Agriculture. Tilapia fish were fed in the system, serving both as a protein source and as a supplier of organic fertilizer to meet the nutrient requirements of the plants.

Peppermint (*Mentha piperita L.*) was selected as the model plant in this study due to its widespread use in the pharmaceutical, cosmetic, and food industries, as well as its high economic value. It is a fast-growing, herbaceous plant that is well-suited for controlled environment agriculture and hydroponic or aquaponic systems. Peppermint's sensitivity to environmental conditions, especially light quality and nutrient availability, makes it an ideal candidate for evaluating the effectiveness of controlled lighting and nutrient delivery in aquaponic setups. Furthermore, improvements in its growth parameters—such as chlorophyll content, biomass, and leaf coloration—are directly relevant to its commercial quality and marketability, which aligns with the goals of sustainable and high-efficiency production in small-scale, indoor farming systems.

The designed aquaponic system is based on a natural cycle consisting of fish, plants, and bacteria. The main components of the system include a frame, fish tank, plant beds, LED lighting, and automation systems. The system was examined in three primary stages: prototype design, cultivation, and measurements.

In the aquaponic system, fish waste was biologically converted into plant-available nutrients through natural nitrification processes. The water from the fish tank, containing ammonia-rich waste, was circulated through biofilters where beneficial bacteria converted ammonia into nitrite and then into nitrate—a primary nutrient for plant growth. Nitrate levels were monitored weekly to ensure they remained within the optimal range (60–80 ppm). When nitrate concentrations exceeded 100 ppm, water supplementation and filter cleaning were performed to prevent nutrient imbalances. This approach ensured that peppermint plants received a stable and sufficient nutrient supply throughout the experiment.

The aquaponic system was equipped with a digital automation setup utilizing an Arduino Uno microcontroller. Sensors for water temperature (DS18B20), pH (analog pH sensor kit), water level (ultrasonic HC-SR04), and

ambient light (photoresistor) were installed. Data from these sensors were continuously transmitted to the controller, which activated auxiliary systems (e.g., LED lighting and water pump) based on pre-defined threshold values. The entire setup allowed semi-autonomous operation of the system with real-time environmental feedback. Initially, the system was designed in a virtual environment, and the dimensions of the cultivation area were calculated by considering the living conditions of fish and peppermint plants. Two separate plant beds were designed for the comparison of artificial and natural lighting: the upper section was produced without LED support, while the lower section was equipped with LED lighting. The structural part of the system was mounted on a wheeled chassis, making it portable. The technical specifications of all system components are provided in Fig. 1.

In the plant beds, 6–12 mm pumice stones were used alongside a filtration system to facilitate both biological and physical filtration. The biological waste produced by the fish was converted into nitrates by nitrifying bacteria, providing nutrients for the plants. Water was pumped from the fish tank to the plant beds and returned via a siphon system, creating a continuous ecosystem cycle.

The LED lighting system installed on the second level of the aquaponic system aimed to enhance the photosynthetic capacity and efficiency of plants. Red (660 nm) and blue (450 nm) wavelengths were selected as the optimal spectra for plant growth (Darko et al. 2020). The upper plant bed was exposed to ambient light, while the lower plant bed was subjected to LED lighting from 18:00 to 21:00 in addition to ambient and daylight. This design optimized energy efficiency while significantly enhancing plant size and chlorophyll synthesis (Bittsanszky et al. 2016). The LED lighting and natural light were provided simultaneously in the LED-supported platform. In contrast, the non-LED platform relied solely on natural light. Both conditions were applied during the same experimental period under identical environmental conditions.

A fish tank was placed at the bottom level to serve as the habitat for the fish. The entire system was mounted on a wheeled chassis, and an automation system was installed to monitor and control the system's performance.

Tilapia (*Oreochromis niloticus*) was selected as the fish species in the aquaponic system due to its high adaptability to varying water conditions, rapid growth rate, and efficiency in nutrient recycling. For this purpose, 20 fish were added to the system. As a key component of the aquaponic cycle, tilapia contributes to the system by producing ammonia-rich waste, which is converted by nitrifying bacteria into plant-available nutrients such as nitrites and nitrates. This biological nutrient source supports plant growth without the need for synthetic fertilizers, making tilapia an essential element in maintaining a sustainable, closed-loop aquaponic ecosystem.

Component	Specification
Chassis Dimensions	650 × 450 × 1300 mm
Roof Profile	Square profile, 400 × 400 mm
Wheels	4 wheels, Ø100 mm
Piping System	16 mm water pipes, 50 mm PE pipe
Plant Beds (2 units)	- Dimensions: 600 × 400 × 120 mm - 6 mm glass thickness - 28.8 L total water capacity - Filled with 16.2 L of water
Fish Tank	- Dimensions: 600 × 600 × 400 mm - 6 mm glass thickness - 144 L total water capacity - Filled with 72 L of water
Automation System	Pump: SEAFLO-SFDP1-020-030-33 (DC 22V ~ 26V, 12A), - Maximum head: 21 m - Pressure: 2.1 bar - Flow rate: 7.6 L/min
Communication Protocol	RS485
Microcontroller	Arduino ATmega 2560
Sensors	EC Sensor pH Sensor: Feegow-2413667047, 5V, range: 0-14, operating temperature: 0-60°C Temperature Sensor: DS18B20 Digital, 3-5V, warning system TDS Sensor: Input voltage: DC 3.3 ~ 5.5V, range: 0 ~ 1000 ppm, accuracy ± FS (25°C) Dissolved Oxygen Sensor: Operating voltage: 3.3-5V, detection range: 0-20 mg/L
Light Sensor	-No name
Level Sensor	AZ 86031 Combo
Display	Nextion HMI touch TFT LCD, 5"
LED Lighting	SOL LED plant growth lamp - 200W, PAR value equivalent to 180W HPS - 900 × 600 mm illumination area - Fusion reflector
Plant Species	Peppermint (*Mentha piperita L.*)

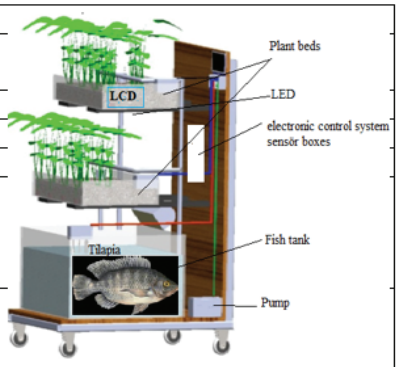

Figure 1. Prototype Chassis Specifications and System Components.

Tilapia (*Oreochromis niloticus*), native to East Africa, was selected as the fish species. The fish were raised under optimal water quality and temperature conditions, maintained between 27–30 °C during the growth period (Bittsanszky et al. 2016). Tilapia were fed a diet consisting of both protein-based and plant-based feed (Bodur and Okudur 2017).

A sensor network employing the RS-485 protocol was established for monitoring and controlling the system. Sensors measuring electrical conductivity (EC), pH, temperature, total dissolved solids (TDS), dissolved oxygen, light, and water level were integrated into an Arduino platform, enabling real-time data tracking. Water temperature was maintained between 25–28 °C (Bittsanszky et al. 2016), and a TDS sensor monitored the mineral content of the water.

An automatic feeding system was employed, utilizing an Arduino Nano, 28BYJ-48 step motor, and ULN2003A driver. Fish were fed daily, and their weight and size were measured every 10 days (Love et al. 2015).

To support nitrifying bacteria colonization, volcanic stones were used in the plant bed. Water circulation was sustained through a pump and siphon system, and iron (Fe) supplementation was provided to maintain water quality. All water parameters were measured daily using a nitrate test kit.

The nitrification process involved *Nitrosomonas europea* bacteria converting ammonia into nitrite, followed by Nitrobacter bacteria converting nitrite into nitrate, which plants absorbed as nutrients.

Measurements

After the water was added to the system and the necessary parameters were stabilized, 20 fish were introduced into the system. The number of fish was determined based on the study by Love et al. (2014), which suggested that maintaining a fish-to-plant ratio of 0.5 ensures sustainable and optimal yield. Therefore, 20 fish were used to support the growth of 40 plants in the system. Fish were fed daily, and their growth was monitored by measuring their length and weight every 10 days.

To maintain the water temperature at 28 °C ± 1 °C, a 300 W heater was used in the fish tank. A total of 20 juvenile Nile tilapia, with an initial average weight of 3.35 ± 0.18 g, were introduced into the tank. The natural waste produced by the fish was utilized in the aquaponic system. After stabilizing the ammonium level, volcanic stones were placed in the plant beds, and peppermint seedlings were planted. This process prepared the system for operation.

Pumice stones were added to the plant beds to support nitrifying bacteria colonization and ensure balanced water circulation between the fish tank and plant beds through a timer-controlled pump. Mint seedling were sown into rockwool, which was mixed with peat and transferred into seedling trays. After germination in a climate-controlled room, peppermint seedlings were transplanted into the system. Each plant bed contained 20 plants, making a total of 40 plants. Measurements were taken daily, as shown in Table 1.

Results

The chassis, which is capable of moving on four wheels, was equipped with two plant beds and a fish tank, with automation and lighting systems integrated into the prototype. The power requirement was supplied from a 220V mains electricity source.

In the room where the system was placed, four fluorescent lamps were kept on from 08:00 to 18:00, ensuring constant lighting for both levels. Additional LED lighting was applied to the lower level for 4 hours at night. Curtains were kept open throughout the day to allow natural daylight into the room.

An Arduino board was used to achieve system automation. RS-485 communication protocol was employed for the design. This protocol prevents data collisions in multi-node systems and ensures coordination among sensors. A code was written to represent a master node system designed to collect temperature data from multiple nodes using the RS-485 communication protocol. It performs tasks such as reading data from temperature sensors, communicating with nodes, and processing the data. The communication protocol provides bidirectional communication capability to ensure reliable data exchange among multiple nodes.

The system utilizes a DS18B20 temperature sensor for temperature measurements, which are read through the DallasTemperature library. Data read by the master node is included in messages sent to the nodes, transmitting temperature information. Each message is formatted to include the target node address and temperature data, and is transmitted via RS-485. During transmission, a control pin is used to switch between sending and receiving operations.

In each cycle, the master node sequentially sends messages to all nodes and awaits responses. The responses are parsed into message format, extracting the node address and sensor values. If the responses are successfully parsed, the sensor data from each respective node is stored in an array. For nodes that do not respond, the sensor value is set to zero by default. This approach enhances system reliability by facilitating the detection of error states.

After collecting sensor values from the nodes, the system displays this information to the user on a touch screen in the form of a report.

The sensor node code is designed to measure various environmental parameters and transmit data to a master node via the RS-485 communication protocol. The code reads, processes, and transmits data from analog signal-generating sensors in a specific protocol format. The code developed for the TDS sensor can be adapted for other sensors with similar structures, including EC, pH, dissolved oxygen, light, and water level sensors.

Each sensor node is assigned a unique address within the RS-485 communication network. Incoming messages are processed if they match the node's address. If the message format is correct and the target address is valid, the sensor measurement process is initiated. The analog

Table 1. "Methodology for Plant Parameter Measurements.

Parameter	Measurement Method
Leaf Number	The number of leaves longer than 2 cm was counted at the harvest stage.
Leaf Weight	Leaves exceeding 2 cm in length were weighed using a precision balance with a sensitivity of 0.1 g.
Leaf Thickness	During each growth stage, the thickness of the best-developed leaf was measured using a caliper at a point as close as possible to the midrib, between two secondary veins. In this study, the term "beginning" refers to the initial stage of plant development after the peppermint seedlings were transferred into the aquaponic system. Measurements were taken following a short acclimatization period, typically within the first 2–3 days. This phase corresponds to the early vegetative growth stage of *Mentha piperita L.*
Leaf Area	The area of leaves longer than 2 cm was determined using a scanner, followed by image analysis with computer software according to the methods of Kraft (1995) and Deveci et al. (2006).
Fresh and Dry Weight Determination	To assess the impact of stress treatments, two plants were randomly selected from each plot. Their fresh weights were recorded using a precision balance. The samples were then dried in an oven at 65 °C for 48 hours, and their dry weights were measured (Öztekin 2009).
Plant Height	Plant height was determined by measuring the vertical distance between the soil surface and the highest point of the aerial plant organs.
Root Depth	Root depth was measured by determining the maximum depth reached by the roots at the harvest stage.
Color Measurements	The color properties of the plant material were assessed using a HunterLab D25LT colorimeter (Hunter Associates Laboratory Inc., Virginia, USA). The measured color parameters included brightness (L*) and color coordinates (a* and b*). The L* value ranges from 0 (black) to 100 (white). The a* coordinate represents the red-green axis, where positive values indicate red, and negative values indicate green. The b* coordinate represents the yellow-blue axis, where positive values indicate yellow, and negative values indicate blue (Açıkgöz et al. 2015). Measurements were taken from three randomly selected plants per plot, focusing on the most developed leaf of each plant, with at least three replicates per leaf.
Leaf Stomatal Conductance	Stomatal conductance was measured on four randomly selected leaves per plot using a Decagon SC-1 portable porometer at 10:00–11:00 AM (Fischer et al. 1998).
Leaf Temperature Determination	Leaf temperature was measured using an infrared thermometer (IRT) (Raynger ST8 model). This technique is based on the principle that transpiration lowers leaf surface temperature. When water uptake is limited, stomatal resistance increases, transpiration decreases, and leaf temperature rises (Ödemiş and Bastug 1999). At the harvest stage, temperature measurements were taken at different regions of leaves from three randomly selected plants per plot, with 3–4 replicates per leaf.
Chlorophyll Content Index	Chlorophyll content was assessed using a "Konica Minolta SPAD-502" portable chlorophyll meter on four randomly selected plants at the harvest stage. Measurements were taken from two regions of the leaf, near the midrib (Geravandi et al. 2011).
Nitrate Measurement	Nitrate levels were determined using a nitrate test kit. A 5 ml sample of aquarium water was placed in a container, followed by the addition of 6 drops of Nitrate-A reagent and 2 microspoons of Nitrate-B powder. The sample was allowed to stand for 7 minutes, after which 1 microspoon of Nitrate-C powder was added, mixed until dissolved, and left to stand for 4 minutes. The resulting color was compared with a standard color chart to determine the nitrate concentration. Measurements were conducted over seven weeks, with two measurements per week, except for the final week.

data obtained from the measurement is first converted to voltage units and then processed using a specific mathematical formula for each sensor to obtain a meaningful measurement value (e.g., ppm for TDS). This data is converted into a text message and transmitted to the master node via RS-485.

Some sensors, such as light and level sensors, do not use temperature data from the master node, whereas others, such as EC and pH sensors, may apply temperature-based corrections. This flexibility allows the integration of different sensor types using the same basic code structure. By centralizing common functions such as analog signal processing, sensor data validation, and data transmission, the code provides a modular framework for sensor nodes.

Additionally, the automatic feeding system was operated using the following code. The system completes 10 rotations every 12 hours, dispensing 1 g of feed per rotation, resulting in a total of 10 g of feed.

Plant measurement results

The measurements specified in the methods section were conducted periodically while the system was in operation, and harvesting was carried out when the plants reached maturity. Upon analyzing the process, it was observed that peppermint plants are typically harvested within approximately 2–2.5 months. However, in the prototype study, the production without LED application took 50 days, whereas the production with LED application reached harvest in 40 days. Harvest evaluations were conducted for all measured plants at 40 days. In the non-LED environment, some selected plants were not harvested to observe their development until harvest maturity, and measurements were taken accordingly. The results are described below. During this process, as LED-supported plants reached harvest earlier, the process was completed, and measurements were finalized.

When LED was applied to peppermint plants, the harvested plants had an average of 19 leaves, whereas plants in the non-LED environment had 14 leaves. The number of leaves increased by 20% in the LED-applied system. This increase demonstrates that LED light supports photosynthetic capacity, contributing to the formation of more leaves.

When LED was applied, the average leaf weight of the harvested plants was 11.2 g, whereas this value was 9.4 g in the non-LED application (Table 2). In the LED-supported cultivation system, fresh leaf weight increased by 15%, and dry weight increased by 12% (Fig. 2). This result also reflects an increase in the plant's water retention capacity.

Table 2. Comparison table LED supported and non-LED system.

Parametreler	LED supported	Non LED	Change (%)
CCI	27,175	21	29
Leaf Number	19	14	35,7
Fresh weight (g)	11,2	9,4	19,1
Dry weight (g)	1,2	1	20
Leaf thickness (mm)	0,32	0,31	3,2
Leaf area (cm^2)	140	91	53,8
Planth height (cm)	27,5	23,2	18,5
Root lenght (cm)	14	11	27,3
Stomatal conductance ($mol/m^2/s$)	1,16	0,97	19,6
Max. Fresh weight (g)	50,1	40,2	24,6
Max. Dry weight (g)	12	9,8	22,4
L*	48,7	45,2	7,7
a*	10	8,2	21,9
b*	23,3	18,8	23,9

Leaf thickness was measured as 0.29 mm at the beginning. In plants grown under LED application, maximum thickness (0.32 mm) was reached after the 30th day, and this thickness was maintained until harvest (Fig. 2). In non-LED plants, maximum thickness (0.31 mm) was achieved on the 35th day (Table 2). The thickening effect of blue light on the epidermal tissue explains these results.

At the beginning of the application, the average total leaf area was 25 cm^2. By the 40th day, the leaf area was 91 cm^2 without LED application, whereas it increased to 140 cm^2 with LED application. Leaf area in LED-supported plants was 25% larger (Fig. 2). This outcome maximized the photosynthetic potential of the plants and led to an increase in biomass.

When maximum fresh weights were examined, plants grown in the LED-supported system reached a maximum of 50.1 g, while those in the non-LED system reached 40.2 g (Table 2). Additionally, the maximum dry weight was 12.0 g in the LED group and 9.8 g in the non-LED group. On average, fresh weight was 37.4 g in the LED-supported system compared to 32.8 g in the non-LED system, reflecting an 18% increase. Similarly, the average dry weight was 7.9 g under LED lighting and 7.0 g without LED, corresponding to a 12% improvement. These results indicate that nutrient uptake and biomass accumulation were enhanced under the influence of LED light.

When the average heights of the plants were examined after 40 days, the maximum height in the LED-supported environment was 27.5 cm, whereas it was 23.2 cm in the non-LED environment (Fig. 2). Plants under LED application were 15% taller compared to those in the non-LED system. This increase may be associated with the stimulating effect of light on plant height.

Peppermint seedlings in the experiment initially had root lengths between 2–5 cm. By the time of harvest, root length ranged between 13–15 cm in the LED-supported environment, whereas it was 10–12 cm in the non-LED system (Fig. 2). Root depth was 10% greater in the LED-supported system. Root length contributed to increasing the plant's capacity for water and nutrient uptake.

In LED-supported plants, color values from the beginning to harvest varied as follows: L* values ranged between 48.7–50.1; a* values ranged between 10–15; and b* values ranged between 23.3–25.2. In the non-LED system, these values were as follows: L* values ranged between 45.2–46.6; a* values ranged between 8.2–13; and b* values ranged between 18.8–19.9.

Stomatal conductance measurements at the end of 40 days showed that the maximum stomatal conductance was 1.16 mol m^{-2} s^{-1} in the LED-supported application (Table 2). Stomatal aperture increased by 12% in the LED-supported system, whereas this value was 0.97 mol m^{-2} s^{-1} in the non-LED application (Fig. 3).

Leaf temperatures in the LED-supported system were found to be 1 °C higher compared to the non-LED system. This difference may be attributed to increased metabolic activity.

The SPAD (Soil Plant Analysis Development) value is an indicator that indirectly measures the chlorophyll content in leaves. Regular CCI measurements provide valuable information for monitoring plant nutritional status and optimizing fertilization programs. Chlorophyll content offers insights into the photosynthetic capacity and overall health of the plant. The CCI value was found to be 15% higher in the LED-supported system, indicating an increase in chlorophyll concentration in the leaves (Fig. 3).

At the end of the experiment, a fish weight of 12.81 ± 1.35 g was obtained. A total of 10 Nile tilapia (*Oreochromis niloticus*) was used in the aquaponic system. The fish were fed twice daily with a commercial feed containing 56% crude protein. Feeding was calculated based on 10% of the Nile tilapia biomass until satiation (Silva et al. 2020), and the feeding amount was adjusted weekly according to fish weight. Due to water loss through evaporation, a water replenishment program was carried out twice a week.

Nitrate measurements taken over seven weeks are shown in Fig. 3. From the beginning to the end, nitrate balance in the system was stabilized and maintained in the range of 60–80 ppm. When nitrate levels reached 100 ppm during measurements, water supplementation and filter cleaning were performed.

Discussion and conclusion

In this study, a portable aquaponic system was designed, and the effects of LED-supported and non-supported systems on peppermint plants (*Mentha* spp.) were examined. Growth parameters such as chlorophyll content, leaf brightness and color coordinates, fresh and dry weights were evaluated. Our findings confirm that LED lighting significantly enhances plant growth and pigmentation, as plants grown in the LED-supported system exhibited 29% higher chlorophyll content, along with a 14% and 30% increase in fresh and dry biomass, respectively.

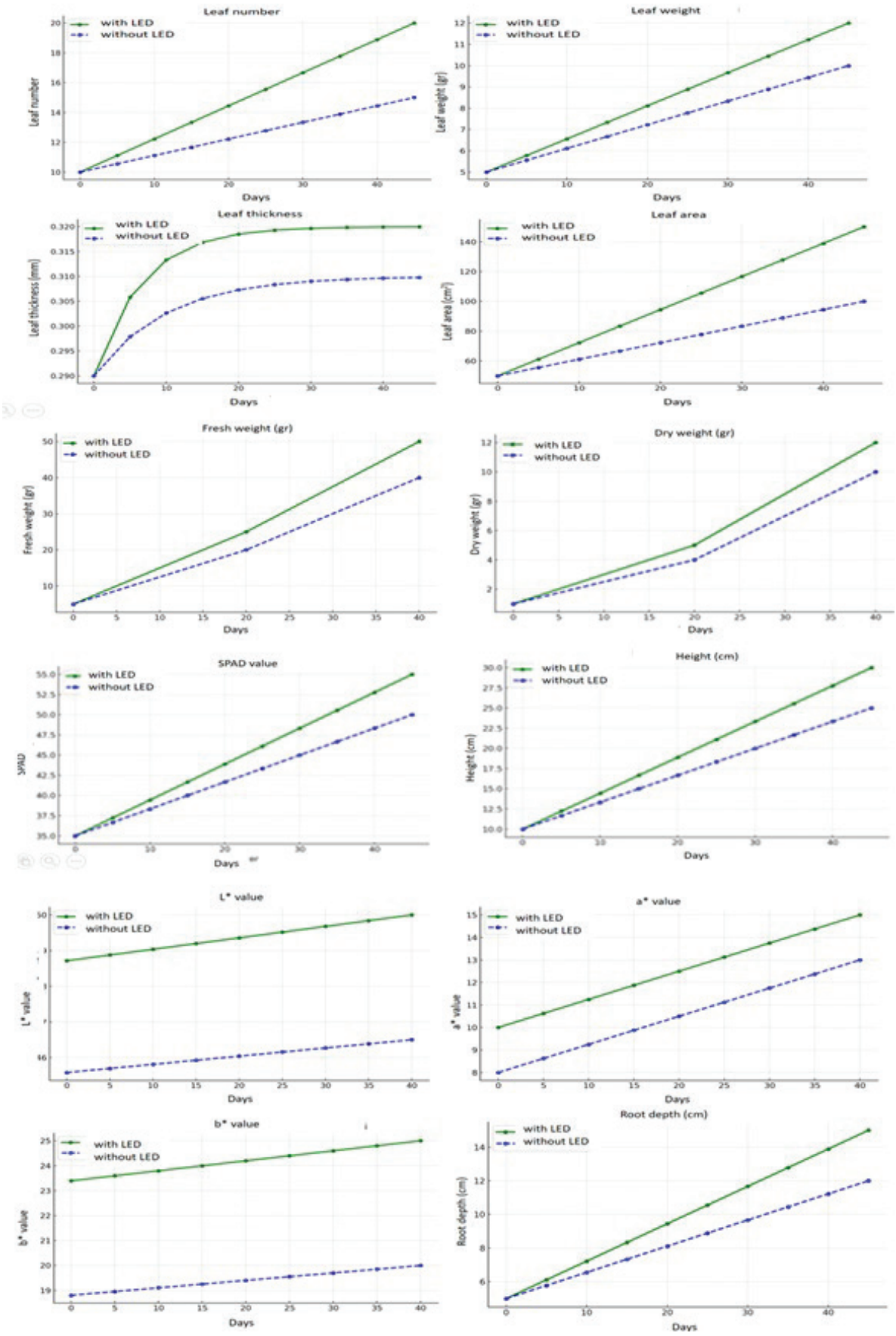

Figure 2. Measurement results.

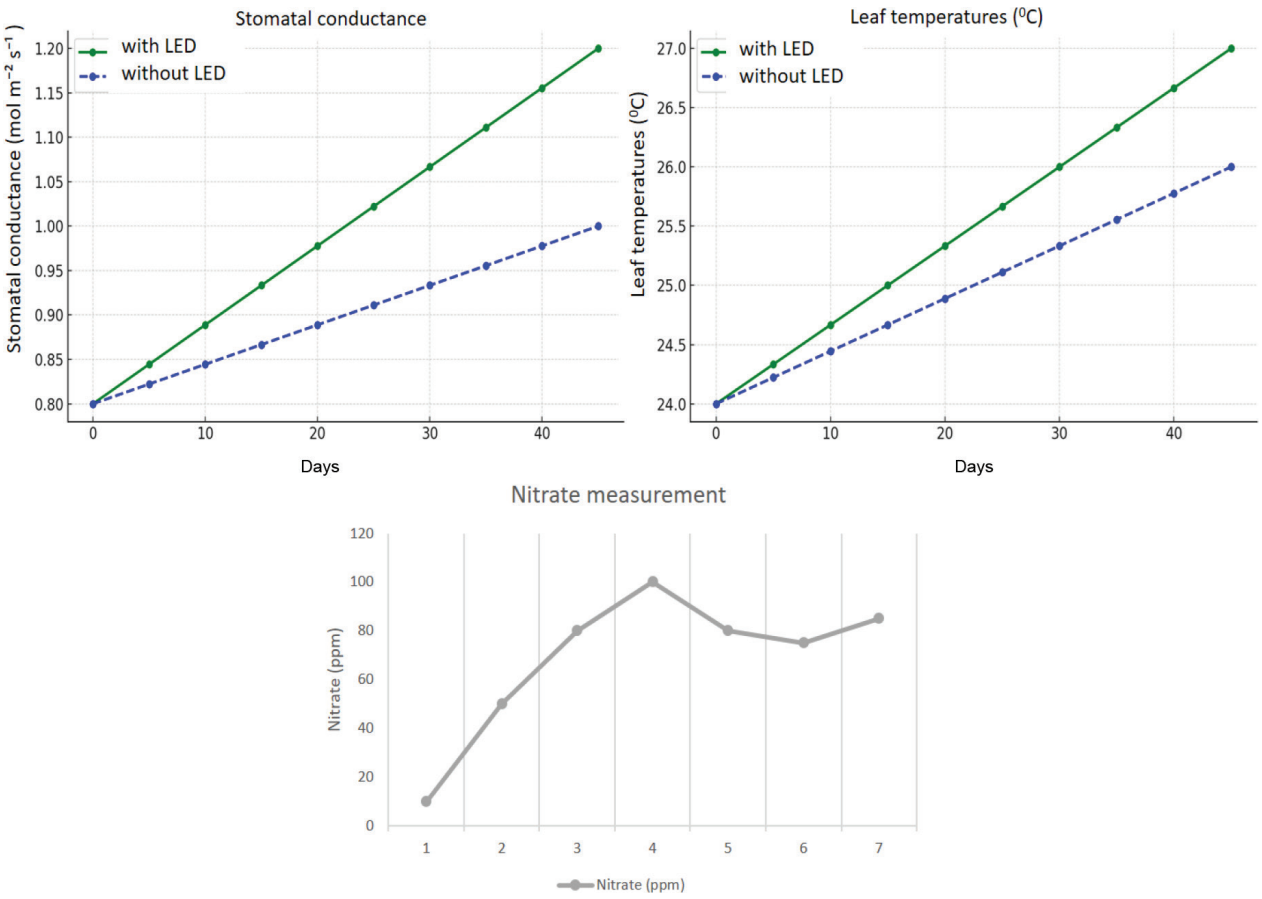

Figure 3. Measurement results.

These results align with the findings of Massa et al. (2008) and Zheng and Labeke (2017), who demonstrated that red (660 nm) and blue (450 nm) LED spectra enhance chlorophyll synthesis and biomass accumulation. Additionally, our findings regarding leaf pigmentation (L*, a*, and b* values) are consistent with those of Son and Oh (2013), who observed improved coloration under optimized LED illumination. However, in contrast to Kong and Nemali (2021), who reported potential chlorophyll degradation under prolonged LED exposure, our study observed sustained chlorophyll enhancement, suggesting that spectrum composition and photoperiod optimization play a crucial role in plant response.

The physiological improvements observed in LED-supported plants can be attributed to enhanced stomatal conductance and optimized photosynthetic efficiency under red and blue light conditions. The balanced light conditions provided by LEDs are known to accelerate plant metabolism by influencing the expression of key photosynthetic genes (Olle and Viršilė 2013). This mechanism supports the observed increase in biomass and pigmentation, reinforcing the potential of LED technology in controlled agricultural environments.

Despite these promising results, some limitations should be considered. Future research should focus on evaluating the energy efficiency and cost-effectiveness of LED-supported aquaponic systems on a larger scale. Additionally, comparative studies involving different plant species and alternative light spectra, such as full-spectrum LEDs or UV-enhanced lighting, could provide deeper insights into the optimization of aquaponic lighting systems.

Overall, this study highlights the potential of LED-supported aquaponic systems to enhance agricultural productivity while supporting environmental sustainability. By improving photosynthetic efficiency and plant growth parameters, these systems offer a viable solution for urban and controlled-environment agriculture. Future research should investigate the long-term economic and ecological impacts of LED technologies and explore novel strategies for further optimizing energy consumption and plant growth efficiency.

The results demonstrate that LED lighting significantly enhances chlorophyll concentration and biomass accumulation in peppermint plants. Unlike previous studies that often focus solely on growth or light spectra, this study provides a comprehensive comparison involving color parameters and physiological responses, which has not been extensively explored in the literature.

This study contributes to the existing literature by experimentally validating the positive impact of red and blue LED lighting in portable aquaponic systems, specifically for peppermint production. The findings offer a basis for optimizing controlled-environment agriculture practices in urban settings.

Previous studies have primarily focused on the integration of IoT technologies and automation in aquaponic systems. For instance, Jacob (2017) developed a smart and portable aquaponic system featuring remote control of watering and lighting cycles, live video monitoring, overflow detection, and temperature tracking of the aquarium. Similarly, Bajeh et al. (2017) proposed a conceptual design for a self-regulating indoor aquaponics system that utilizes sensors and feedback loops to monitor water quality and manage system operations. However, neither of these studies experimentally assessed the effects of different lighting strategies on plant physiological development. In this context, our study fills a critical gap in the literature by conducting a comparative evaluation of peppermint (*Mentha piperita* L.) growth under LED-supported and natural-light-only conditions. The research includes quantitative analysis of physiological parameters such as chlorophyll content, color indices (L*, a*, b*), fresh and dry biomass, and stomatal conductance, offering a more comprehensive understanding of plant response in automated aquaponic environments.

The images related to the design and implementations carried out within the scope of the study are presented in Fig. 4.

Figure 4. Prototype images.

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