DEVELOPMENT AND EVALUATION OF AN ENHANCED SMALL-SCALE HYDROPONIC SYSTEM FOR INDOOR SEEDLING PRODUCTION

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РАЗРАБОТВАНЕ И ОЦЕНКА НА ПОДОБРЕНА МАЛКА ХИДРОПОННА СИСТЕМА ЗА ПРОИЗВОДСТВО НА РАЗСАД НА ЗАКРИТО

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ABSTRACT

This study presents the development and evaluation of an enhanced, modular, IoT-based hydroponic system for indoor seedling production. Designed to be low-cost and scalable, the system integrates automated lighting, irrigation, and environmental monitoring with cloud-based control. Its performance was validated using two tomato varieties, achieving 94–96% germination without added nutrient solution. A cost-benefit analysis indicated a payback period of under two years. While promising, the system has not yet been tested with other plant species, substrates, or nutrient solutions. Future research will focus on these variables to assess broader applicability and optimize performance.

РЕЗЮМЕ

Това проучване представя разработването и оценката на подобрена, модулна, базирана на интернет на нещата хидропонна система за производство на разсад на закрито. Проектирана да бъде нискобюджетна и мащабируема, системата интегрира автоматизирано осветление, напояване и мониторинг на околната среда с облачен контрол. Нейната производителност е валидирана с помощта на два сорта домати, постигайки 94–96% кълняемост без добавен хранителен разтвор. Анализът на разходите и ползите показва период на възвръщаемост под две години. Макар и обещаваща, системата все още не е тествана с други растителни видове, субстрати или хранителни разтвори. Бъдещите изследвания ще се фокусират върху тези променливи, за да се оцени по-широката приложимост и да се оптимизира производителността.

INTRODUCTION

One of the most pressing challenges for modern agriculture is ensuring food security for a rapidly growing global population. According to the *United Nations (2022)*, the world population is projected to exceed 10 billion by 2100, placing significant pressure on agricultural systems. This challenge is exacerbated by changing climatic conditions and limited arable land availability (*Rosenzweig and Tubiello, 1996; NOAA, n.d.; Peters et al., 1971; Wing et al., 2021; IPCC, 2021*).

Simultaneously, intensive agricultural practices are degrading soil quality and increasing the risk of contaminants entering food crops, with potential health consequences (*Alengebawy et al., 2021; Adil et al., 2023; Hossain et al., 2022*). Urbanization further compounds these issues, reducing the agricultural workforce and complicating food distribution networks (*United Nations, 2018*).

Given these combined pressures, new sustainable and space-efficient food production systems are required. Vegetable cultivation, particularly in urban settings, faces rising costs and declining feasibility due to climate variability and land limitations (*Hartwell et al., 2024; Rockström and Sukhdev, n.d*.). Urban agriculture solutions such as hydroponics and vertical farming have emerged as promising alternatives, offering optimized space utilization and resource efficiency (*Eigenbrod and Gruda, 2015*).

Hydroponic cultivation enables continuous, high-density vegetable production independent of soil and outdoor conditions. This method also facilitates automation and reduces reliance on manual labor (*van Delden et al., 2021; Cardoso et al., 2018; Alam et al., 2023; Ma et al., 2023; Chadwick et al., 2023*).

Recent advances integrate Internet of Things (IoT), computer vision, and mobile technologies to improve monitoring and control in hydroponic systems (*Nikolov et al., 2023; Hanafi et al., 2025; Duangpakdee* *and Thananta, 2024; Perara et al., 2024; Yessenamanova et al., 2023*). Smart hydroponic systems designed for home or urban use have demonstrated the potential to enhance yield, water efficiency, and user accessibility (*Kushawaha et al., 2024; Stevens et al., 2024; Kim et al., 2024*). Examples include modular towers, intercropping setups, and crop-specific nutrient optimization (*Patel et al., 2004; Maucieri et al., 2017; Woznicki et al., 2021; Pieters et al., 2024; Elmulthum et al., 2023; Gutiérrez-Chávez et al., 2025; Luthuli et al., 2024; Ulas et al., 2024*).

Despite these innovations, many small-scale hydroponic systems remain either oversimplified or prohibitively expensive, lacking adaptability or full automation. Existing home solutions often fail to deliver adequate productivity or user control, while industrial systems are unsuitable for domestic use due to complexity and scale (*Khadijah et al., 2024; Hostalrich et al., 2022; Tatas et al., 2022; Lakshmiprabha and Govindaraju, 2019; Li et al., 2018*).

To address this gap, the present study aims to design and develop an enhanced version of a small, adaptive, high-tech hydroponic system suited for growing seedlings and vegetables in domestic environments. The system is modular, low-cost, and constructed from readily available components. It incorporates automated lighting, climate, irrigation control, cloud-based data logging, and video monitoring, offering users remote access and real-time adjustments.

It is anticipated that this system will provide an affordable and sustainable option for home-based food production, particularly in urban environments. The modular structure allows independent operation of units, enabling diverse crop cultivation. The present study seeks to validate the system's functionality, productivity, and economic viability through controlled experiments using tomato seedlings.

By bringing forward the research objective and clearly outlining the novel aspects of the developed system—including its affordability, modularity, and full IoT integration—this study contributes a practical solution to the challenges of small-scale urban agriculture.

MATERIALS AND METHODS

2.1. Architecture of the Hydroponic System

In this study, a hydroponic system was developed, whose architecture is summarized in Figure 1. The general management of all periphery is implemented by the control system, which operates according to predefined rules and assignments that were preliminary set by an operator. The control system receives feedback about its actions from several systems.

Microclimate monitoring system – collects data about the temperature and relative humidity of air inside the hydroponic system.

Water monitoring system – includes pH, electric conductivity (EC), and temperature sensors, used to monitor the key parameters of the water substrate.

Video monitoring system – provides a live stream so that the operator can change the system's operating parameters based not only on the abovementioned sensors but also on remote visual observations.

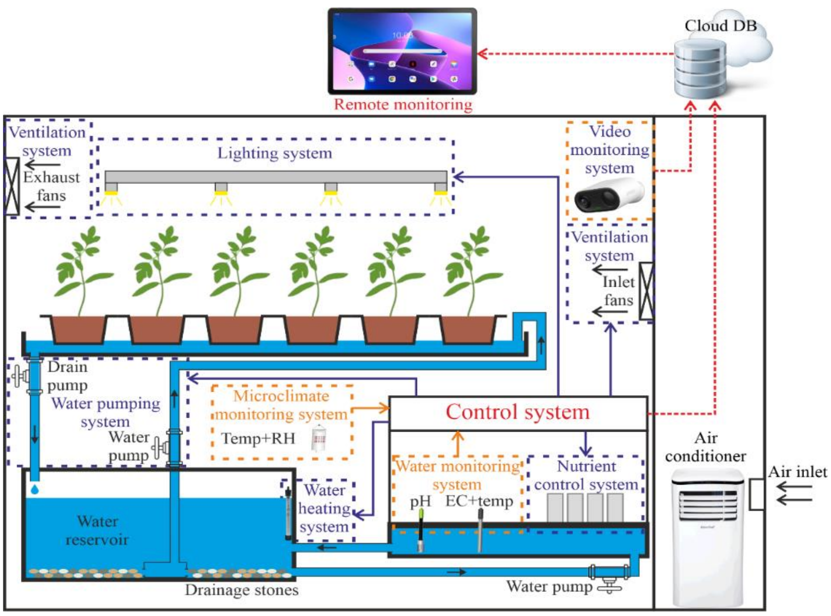

Fig. 1 - Architecture of the developed hydroponic system

The control system ensures the hydroponic system operates properly using several actuator subsystems:

a) Nutrient control systems – responsible for maintaining the fertilizer parameters following the operator-set requirements.
b) Water heating system – used to keep the water substrate temperature within acceptable boundaries.
c) Water pumping system – pumps the water through the different components of the hydroponic installation and includes at least three pumps: the first one is responsible for pushing the water through the nutrient system; the second one transfers the water from the reservoir to the plants; and the third one drains the water back to the reservoir. Furthermore, the water goes through drainage stones to ensure additional cleaning.
d) Lighting system – provides the plants with the necessary imitation of solar energy.
e) Ventilation system – used to replace the air inside the hydroponic installation and includes several parts:
   - an air conditioner is installed in a separate chamber of the system. It makes sure the air parameters in the chamber correspond to the necessary agro-technical requirements;
   - inlet fans for suctioning in the preliminary heated/cooled air from the air conditioner inside the chamber with the plants.;
   - exhaust fans – used to remove air from the plants' chamber.

All collected data, as well as the current states of all actuators, are stored in a remote cloud-based database and can be observed by an operator via a tablet device with the appropriate application installed. Naturally, the live stream from the video monitoring system is also accessible online.

To support a clearer understanding of the system architecture and the interconnections between sensors, actuators, and control elements, Table 1 summarizes the key components of the developed hydroponic system and their primary functions.

Table 1

Key components of the hydroponic system and their functions

System / Component	Function
Control Unit (NIDO ONE)	Central controller; manages irrigation, lighting, climate control, and data collection.
Microclimate Monitoring System	Measures air temperature and humidity; provides real-time data for environmental control.
Water Monitoring System	Monitors pH, EC, and temperature of the nutrient solution.
Video Monitoring System (WiFi Camera)	Enables visual inspection and remote system supervision.
Lighting System (Valoya LED L28)	Provides artificial light (16h/day); ensures proper photoperiod for seedling growth.
Irrigation System (GMAX Water Pump)	Delivers nutrient solution to trays; ensures even distribution across all levels.
Drainage System (Giant Drainage Pumps)	Removes excess water; recirculates it to the reservoir; ensures efficient water use.
Nutrient Control System	Maintains optimal concentration and composition of the nutrient solution.
Water Heating System (Water Master Heater)	Maintains optimal root zone temperature for nutrient uptake.
Aeration System (BOYU Pump & Air Stone)	Oxygenates nutrient solution to support root respiration and prevent pathogens.
Ventilation System (Blauberg Fans)	Provides fresh air; maintains uniform microclimate on all levels.
Air Conditioning Unit (AEG Comfort)	Controls air temperature; integrated into a separate chamber for optimal air handling.
Exhaust Fans (DF Extractor)	Removes warm/moist air; prevents condensation and maintains air quality.
Cloud Database & Tablet App	Stores sensor/actuator data; allows remote monitoring and control via app interface.
Cultivation Trays (Danish Trays)	Hold the plants; optimized size for productivity and ease of maintenance.

2.2. Hardware Implementation of the Hydroponic System

The improved version of our multifunctional small-scale hydroponic system was developed to address the constructive and technological shortcomings identified in the prototype small-scale hydroponic system for indoor sustainable farming of leafy vegetables, which was proposed in *Nikolov et al. (2023*). The general scheme of the improved hydroponic system is presented in Figure 2. Its key components are integrated into a structurally optimized external frame, which consists of three metal racks. Each rack includes supporting rails, measuring 1400 mm in length, on which trays for crop cultivation are arranged across three levels. A key improvement in the upgraded system is the increased tray size. The previous trays, measuring 600 mm in length and 400 mm in width (*Nikolov et al., 2023*), were replaced with new Danish trays (manufacturer: Danish Trays, China) with dimensions of 1100 mm in length and 630 mm in width. This modification enhanced the system's productivity by enabling the simultaneous distribution of nutrient solutions to plants at all levels, resulting in a simplified design and easier maintenance during operation.

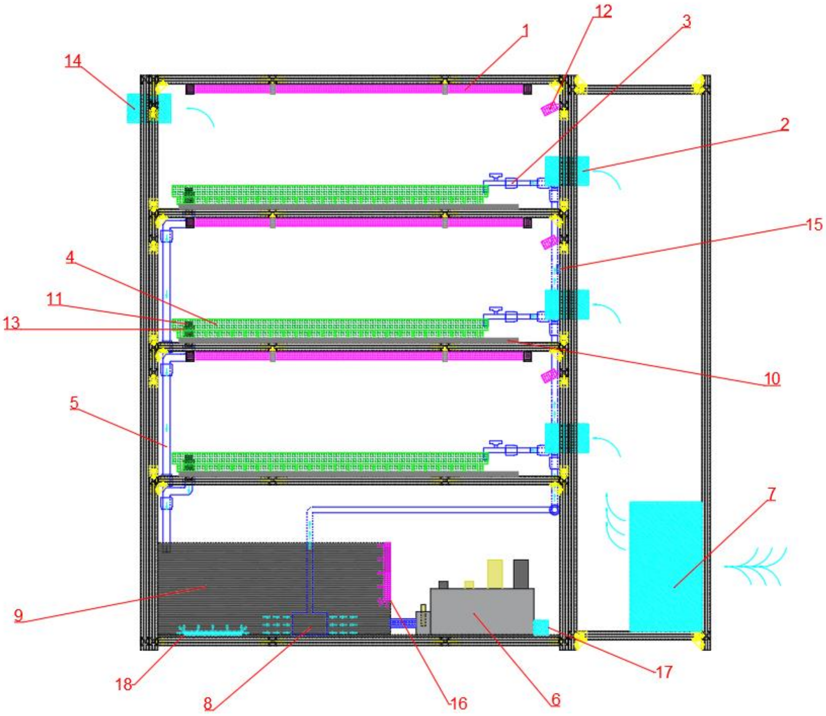

Fig. 2 - Scheme of the improved version of the multifunctional small-scale hydroponic system:
1) Full Spectrum led growing lights for vertical farming; 2) Inlet fans; 3) Irrigation system; 4) Growing trays; 5) Drainage system; 6) Computer NIDO ONE; 7) Mobile air conditioner; 8) Water pump; 9) Nutrient solution tank; 10) Plate for supporting and leveling the tray; 11) Drain head; 12) Surveillance camera; 13) Drainage pump; 14) Exhaust fan; 15) Temperature and humidity sensor; 16) Heater; 17) Air pump; 18) Air stone.

The nutrient solution is supplied to the trays by a GMAX Model Q400122 pressure water pump (manufacturer: GMAX Bulgaria) with a maximum flow rate of 9 m³/h, a maximum head of 8 m, and an installed power of 0.4 kW. A significant advantage of this pump is its ability to ensure uniform nutrient distribution across all levels of the system. Additionally, its operating parameters allow for future expansion of the prototype without requiring a more powerful pump. The lighting system is facilitated by LED lights from the Finnish company Valoya Ltd (Helsinki, Finland), specifically the Model L28, which has a power rating of 28 W and features the AP67, AP673L, G2, and NS12 spectra. These lights are positioned at 318 mm above each tray containing the cultivated plants. Artificial lighting was implemented for a specific photoperiod of 16 hours per day to simulate optimal day length conditions for seedling development.

An innovative feature of the constructed small-scale hydroponic system is the installation of three drainage pumps manufactured by Giant Electric Tech Inc. (Shenzhen, China) on each level of the system. These pumps have the following specifications: operating voltage of DC 6-12 V (maximum 1 A), IP68 grade, a maximum water column height of 3 m, a maximum static flow rate of 240 l/h, and dimensions of 54.4 mm in length, 52 mm in width, and 40.8 mm in height. Both the inlet and outlet have an outer diameter of 8.5 mm. These drainage pumps facilitate the remote and simultaneous drainage of all three levels.

Another novel element in the improved hydroponic system is the addition of three axial fans manufactured by Blauberg Ventilatoren GmbH (München, Germany) to supply fresh air to each level. Each fan has a capacity of 105 m³/h.

Additionally, the aeration system includes a BOYU Air Pump S-1000, which has a capacity of 252 l/h, operates at 3 W, and generates a pressure greater than 0.014 MPa. The outlet diameter is 1 x 4 mm, and it is equipped with a round ceramic air stone with a diameter of 200 mm manufactured by Guangdong BOYU Group Co., Ltd. (Chaozhou, Guangdong, China).

The primary purpose of the added BOYU Air Pump and Volume Air Round Ceramic Air Stone is to enrich the nutrient solution with oxygen, thereby supporting active root respiration in the plants and reducing the risk of mold and pathogen development. The exhaust air from the system is removed via exhaust ventilation, using a DF Extractor with a capacity of 350 m³/h, manufactured by Secret Jardin (Manage, Belgium). The airflow is heated by a mobile air conditioner model AEG Comfort 6000 BTU 9000, manufactured by AEG (Berlin, Germany). To optimize nutrient solution assimilation by the plant root system and maintain the solution at an optimal temperature, a Calentador Water Master heater (100W), manufactured by Guangzhou City Werierma Electrical Co., Ltd. (Guangzhou, Guangdong, China), was added inside the tank of the improved hydroponic system. For remote monitoring and control of plant vegetation at each level of the system, WiFi cameras, model IMOU Cell Go, with a microSD slot for storing video data up to 128GB, were installed. These cameras are manufactured by Hangzhou Huacheng Network Technology Co., Ltd. (Hangzhou, China). The air temperature and humidity monitoring is conducted using a combined sensor, manufactured by Nido S.r.l. (Carpineti, Italy).

The automation process relies on the NIDO ONE hydroponic controller system, manufactured by the Italian company Nido S.R.L. (Carpineti, Italy). The NIDO ONE controls the automatic regulation of nutrient solutions in hydroponic systems and manages climatic parameters in indoor cultivation environments. The NIDO control unit is also responsible for manipulating the lighting system via the NIDO Plug. Cloud and IoT technologies enable remote plant monitoring and facilitate the management of individual measurement parameters.

Nutrient solution monitoring is conducted using two types of sensors. The pH sensor measures acidity within a range of 4 to 10, with a resolution of 0.01 pH and an accuracy of 0.1 pH. The EC sensor measures electrical conductivity (EC) within a range of 0 to 5.0 mS/cm, with a resolution of 0.01 mS/cm and an accuracy of 0.1 mS/cm. Additionally, the EC sensor has an integrated temperature sensor used for EC/TDS temperature compensation.

The following main dimensions of the hydroponic system could be mentioned:

- Main chamber (where the seedlings are positioned): 2000 mm height, 1400 mm width, and 700 mm depth;
- Air conditioning chamber (where the air conditioner is kept): 2000 mm height, 435 mm width, and 700 mm depth;
- Distance between the lighting systems and the soil surface: 318 mm.

The assembly of the hydroponic system followed a logical sequence that ensured proper integration of all subsystems. The process included the construction of the supporting metal frame, installation of lighting, trays, irrigation and drainage systems, sensors, ventilation and air conditioning units, as well as the NIDO ONE control unit. The design emphasized modularity and ease of maintenance, enabling future upgrades and expansion.

2.3. Verification of the Functional Suitability of the System and Organization of the Experimental Investigations

To establish the functional suitability of the improved version of the designed system, experimental studies were conducted involving the cultivation of seedlings from two tomato varieties commonly used in Bulgaria: Florida F1 and Aleno Surtse. No nutrient solution was used during the seedling cultivation. Before the start of the experiment, the system was filled with 150 liters of clean spring water obtained from a local water source. Each tray contained 7 liters of water.

The sowing of seeds for all tomato varieties was carried out in nutrient cubes made from organic matter, with integrated fertilizer manufactured by HGA International B.V.- Eazy Plug (HJ Goirle, The Netherlands). The manufacturer did not disclose the specific ingredients of the nutrient component due to proprietary reasons. The nutrients present in the cubes are sufficient to support seedling growth for 15 days. For longer growing periods, it is necessary to replace the irrigation water with a nutrient solution, tailored to the specific needs of the cultivated crop.

The experiment took place from 01.08.2024 to 14.08.2024 and involved testing the system's performance with two tomato varieties - *Florida F1* and *Aleno Surtse*. Each variety was placed in a separate tray on a distinct level of the system.

Before initiating the experiment, the system was prepared by filling the water tank and checking all major components—irrigation, drainage, lighting, ventilation, sensors, and internet connectivity. Once verified, the trays were loaded with seeded nutrient cubes, and the automated control program was configured. The irrigation-drainage technological program for seedling cultivation was then launched. The irrigation-drainage technological protocol for seedling cultivation was established based on preliminary assessments of the substrate's physical properties, particularly its water retention capacity and drainage behavior (*Raviv et al., 2004*). The program parameters were defined to ensure optimal moisture conditions for seedling development under controlled environment cultivation. In this protocol, trays containing nutrient cubes are filled with water for 5 minutes to achieve field capacity without oversaturation. The timing was set based on the substrate's water absorption kinetics, ensuring sufficient hydration without waterlogging. After irrigation, trays are drained for 5 minutes to eliminate excess water, prevent hypoxic conditions, and enhance water-use efficiency (*Jones, 2013*). The collected surplus water is recirculated to promote resource conservation. Irrigation and drainage cycles are performed daily, with a total duration of 10 minutes. The protocol was uniformly applied to both tomato varieties to assess the functional suitability and adaptability of the constructed hydroponic system for varieties and species with differing vegetative requirements.

A total of 450 seed pots were used per variety. The reported germination percentages are based on this fixed number and correspond to the actual number of seedlings that emerged.

The selection of tomato seedlings (*Florida F1* and *Aleno Surtse*) as the test crop in this study was not intended for the production of fruiting plants, but rather to evaluate the functional suitability of the hydroponic system for seedling cultivation. Tomato seedlings were chosen due to their relatively high sensitivity to environmental conditions and nutritional requirements during early growth stages, making them a suitable model for assessing the system's performance, flexibility, and reliability. While leafy vegetables such as lettuce or spinach are more commonly used in hydroponic cultivation, tomatoes were intentionally selected to demonstrate the versatility of the system and its potential applicability to a broader range of crops in controlled environment agriculture.

Both tomato varieties used in the experiment were certified commercial seeds obtained from reputable suppliers. The germination degree was not independently measured before the experiment, as the manufacturer guarantees a germination rate exceeding 95% following international seed certification standards.

Throughout the 14-day test period, no functional faults or interruptions were observed. All components of the system—including pumps, aeration devices, lighting, and environmental sensors—operated autonomously and continuously under the control of the NIDO ONE unit. The modular structure of the system allowed for easy access to each component, and no maintenance interventions were required during the experimental phase. These results support the system's operational reliability for domestic or small-scale seedling production.

RESULTS

3.1. Experimental Measurements

After the initial checks and preparation of the system for operation, the cubes with the sown seeds were placed in the constructed improved small-scale hydroponic system Figure 3.

(a) (b)

Fig. 3 - Different views of the implemented small-scale hydroponic system for indoor vegetable growing

The measured germination rates (94–96%) reflect the effectiveness of the system in maintaining suitable microclimatic and water conditions during the seedling phase. Temperature and humidity variations, shown in Figures 4–6, align with the expected biological response of tomato seedlings under controlled cultivation and were obtained from the NIDOPRO software product (Nido S.r.l., Carpineti, Italy). The presented results are from the 1st to the 14th day after the tomato seeds were sown.

Figure 4 illustrates the variations in ambient temperature throughout the seedling cultivation period. From the first to the sixth day after sowing, the temperature fluctuated between 19°C and 44°C. It should be noted that even though an air conditioner was planned for the hydroponic system, it was still not installed during the experiment, which explains the high-temperature fluctuations. During the study, the minimal ambient temperatures (outside the container) varied between 18 and 23 °C, and the maximal ones between 28 and 34 °C. Considering that the hydroponic installation was placed inside a container heated by the sun, the maximal room temperatures were even higher, as seen from the experimental data.

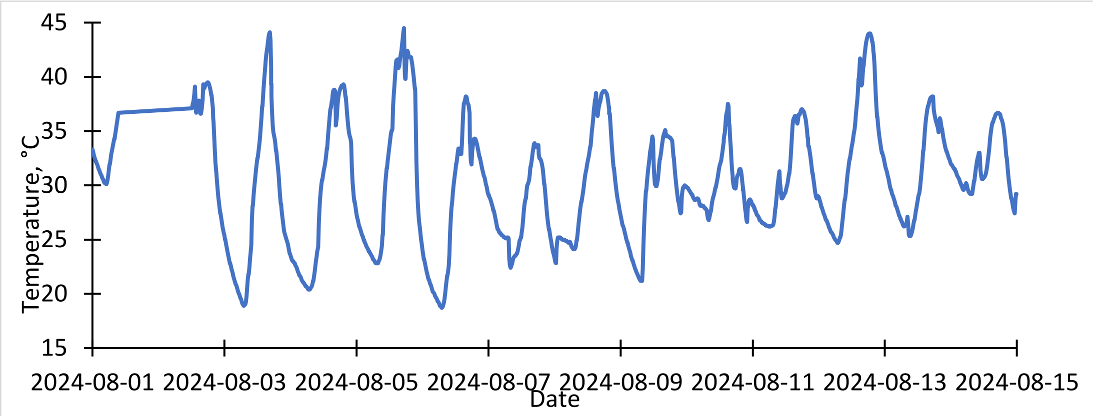

Fig. 4 - Time series of the ambient temperature

Maintaining elevated air temperatures during this initial phase is crucial, as it accelerates seed germination and enhances early seedling development. Optimal germination temperatures for tomatoes typically range between 20°C and 30°C, with higher temperatures promoting faster emergence but posing a risk of thermal stress if excessively high. However, considering that at the beginning of the period the plants were in the initial vegetation stage, the measured high temperature did not adversely affect their development. From the seventh day onward, the average temperature was around 30.4°C, though it varied significantly, following the environmental fluctuations. These observations show that having an air conditioning system that supports cooling is mandatory for the meteorological conditions in Bulgaria. It would allow for optimizing the temperature control and could help minimize extreme variations, reduce potential stress factors, and improve overall seedling uniformity and growth efficiency.

The time series of relative air humidity is shown in Figure 5. It exhibits variation throughout seedling cultivation. During the initial period, from sowing to the sixth day, high air temperatures led to intensive water evaporation, causing relative humidity to peak at 95.9% at nighttime when the temperatures were lower. This high humidity is typical during the early stages of vegetation when moisture levels are predominantly influenced by evaporation.

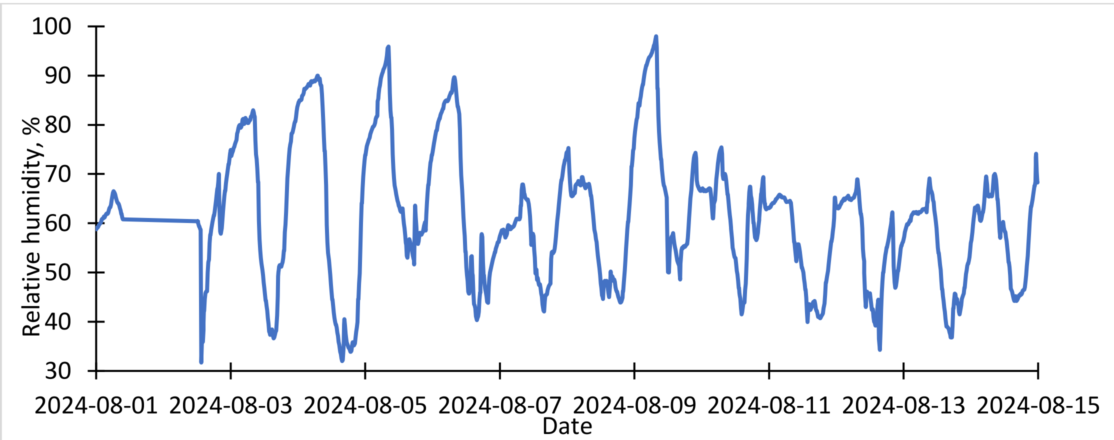

Fig. 5 - Time series of the air's relative humidity

From the seventh day onwards, the relative humidity in the system varied around an average value of 60.7 % with daily fluctuations following the air temperature variation. This moderate humidity level is more conducive to seedling growth, as excessive levels can encourage fungal diseases and hinder proper air circulation around the plants.

The regulation of air humidity within the system is implemented with ventilation holes incorporated into the enhanced prototype of the hydroponic system. These ventilation openings allow the expulsion of excess moisture from the air and improve overall air exchange, ensuring that humidity levels are kept within the optimal range for plant health. By controlling the airflow, the system helps maintain a balanced microclimate that supports the healthy development of seedlings.

During the entire cultivation period, the average water temperature in the system was 26.3 °C, with recorded values ranging from a minimum of 21.3 °C to a maximum of 32 °C (Figure 6).

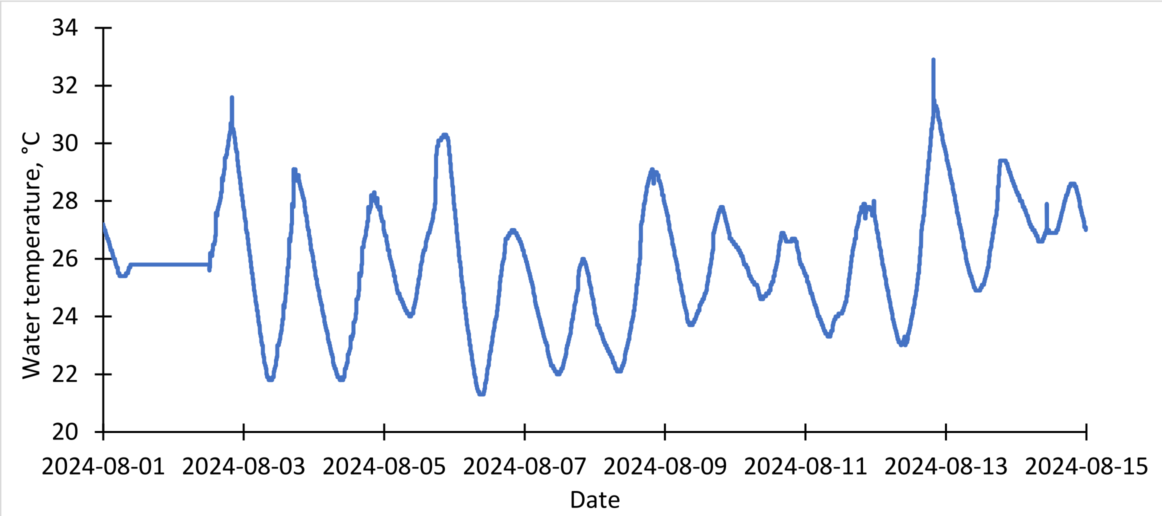

Fig. 6 - Time series of the temperature of the water

The variation in water temperature closely followed fluctuations in ambient air temperature, which served as the primary factor influencing thermal dynamics within the system. This passive heating and cooling mechanism effectively regulated the water temperature without the need for active intervention. The elevated water temperature had a positive effect on root system development, contributing to favorable growth conditions. As a result, no additional water heating was required during the experiment.

The measured environmental parameters demonstrated that the system maintained conditions generally favorable for tomato germination. For example, the average water temperature during the cultivation period was 26.3 °C, which aligns with optimal root-zone temperatures promoting rapid germination and root activity. Although ambient air temperatures exhibited higher fluctuations, germination was not adversely affected, and system productivity remained above 94%. These observations support the positive correlation between controlled water temperature and seedling emergence under hydroponic conditions.

This approach helped to avoid the temperature-related drawbacks observed in the previously designed system (*Nikolov et al., 2023*), where environmental influences affected the temperature of the working solution. According to *Yaling et al. (2015*), when growing tomatoes in soil, the temperature in the root zone should be maintained around 23°C to optimize root development and nutrient uptake. Additionally, *Miao et al. (2023*) have demonstrated the negative effects of low temperatures in the root zone on CO_2 assimilation and photosynthesis. Once again, the temperature variation shows that an air conditioner is mandatory for the meteorological conditions in Bulgaria if precise microclimate conditions are to be maintained within the hydroponic system.

To reduce the observed fluctuations in relative humidity and water temperature, future improvements will include precise microclimate control and better insulation of the nutrient tank. These upgrades aim to stabilize both parameters and maintain them within optimal ranges for plant growth.

In the implemented hydroponic system, the risk of pathogen development and reduced oxygen absorption by the roots, potentially caused by excessive temperatures in the root zone, is mitigated by the installed air stone. This ensures adequate oxygenation of the root zone, further promoting healthy root growth and minimizing the risks associated with high water temperatures.

A photo from the first day after sowing the seeds is shown in Figure 7. Mass germination of the tomato seeds was recorded on the 7th day of sowing, as shown in Figure 8. The recording was done on each shelf and tray for each tomato variety. After counting the successfully germinated seeds, it was found that the *Florida F1* hybrid had a 94% productivity of the hydroponic system. Promising results of 96% productivity were achieved for the *Aleno Surtse* variety.

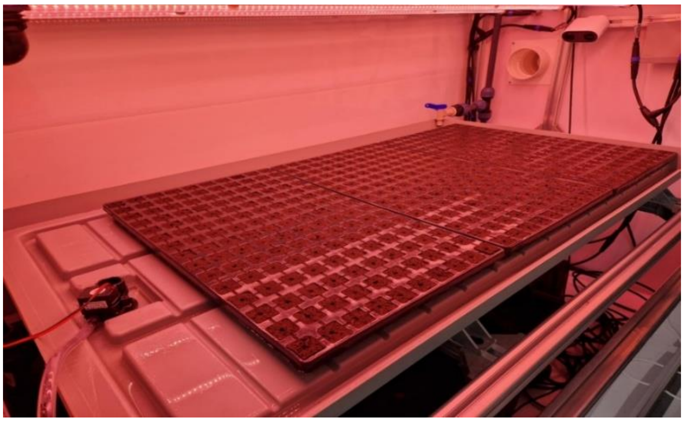

Fig. 7 - Tomato seeds on day 1 from sowing

The productivity of the hydroponic system was evaluated based on the percentage of successfully germinated seeds relative to the total number of seeds sown—an established metric for assessing seedling cultivation efficiency under controlled environmental conditions (*Bugbee and White, 1984*). Although no external reference system (e.g., conventional soil-based cultivation or an alternative hydroponic setup) was included for direct comparison, the observed germination rates were assessed against standard benchmarks reported for optimal tomato seedling production in hydroponics, which typically exceed 90% under ideal conditions (*Resh, 2012*). The germination performance of the tomato hybrids *Florida F1* and *Aleno Surtse* was comparable to or surpassed these reference values, indicating effective system functionality.

Fig. 8 - Germination of tomato seeds on day 7 from sowing

An intermediate reading of the viability of the seedlings was carried out on the tenth day after sowing the seeds. It was established that all the growing plants developed well, as shown in Fig. 9.

Fig. 9 - Germination of tomato seeds on day 9 from sowing

A fourth reading was carried out at the end of the growing period (Figure 10). It showed that all the sprouted tomato plants had retained their viability and were suitable for growing in a permanent place. The cultivation of tomatoes is not economically justified at a later stage in the hydroponic system due to its small volume and productivity.

Fig. 10 -The condition of tomato seedlings 15 days after sowing the seeds

3.2. Economic Evaluation of a Small-Scale Hydroponic System for Indoor Vegetable Growing

The economic evaluation is based on the observed seedling productivity, which serves as a proxy for functional system efficiency and potential income. The implementation costs of the prototype of the small-scale hydroponic system for indoor vegetable growing are summarized in Table 2. The total price of the facility is 9593 BGN or approximately 4900 EUR.

The operating costs in our study are based only on the production of tomato seedlings of the experimental varieties. The productivity of the hydroponic system is 1350 tomato seedlings in 15 days. From this productivity, 5% losses were observed due to the non-germination of the plants. The selling price of one plant is 1.00 BGN, and the system is expected to operate 120 days a year. The expected number of monthly plants is about 2700 minus 5% losses, with the price of integrated fertilizer being 0.18 BGN per plant, and the cost of purchasing tomato seeds for a single 15-day production cycle is 270 BGN. The price of electricity in Bulgaria is 0.23988 BGN/kWh daily rate and 0.14122 night rate. The daily electricity consumption is 5.219 kWh. The price of water is 0 BGN because it is from a self-owned source. Furthermore, no salary costs were foreseen for servicing the system because it was operated by the owner.

Table 2

Costs for constructing a small-scale hydroponic system for indoor vegetable growing

Product	Count, pcs	Price, BGN
Profile 30x30 with a length of 2000 mm	12	380.42
Profile 30x30 with a length of 1460 mm	8	188.00
Profile 30x30 with a length of 1400 mm	12	271.06
Profile 30x30 with a length of 700 mm	27	322.87
Profile 30x30 with a length of 435 mm	24	190.40
Profile 30x30 with a length of 405 mm	6	61.04
Corner connectors 30x30 with slot 8 nuts and bolts	206	526.78
IMOU Cell Go cameras	3	747.00
Nido One computer	1	2 223.98
Lighting Set Valoya L28 Clear AP673L	1	2 050.19
Drainage pump DC6-12V + Power supply	3	78.00
Irrigation pump GMAX Model Q400122	1	135.22
Ventilation Inlet - Axial fan 105 m^3/h, 100 mm	3	120

Product	Count, pcs	Price, BGN
Exhaust Ventilation – Secret Jardin DF Extractor T 150/250/350/ m^3/h	1	294
Scream parts 1		77.9
Scream parts 2		78.36
Danish tray 1100x630 mm	3	216
Total for planes and panels		530
WiFi Adapter 3840W	7	202.3
Tank: growTANK Food Tank 150 l.	1	129
Air pump + air stone: BOYU Air pump S-1000 252l/h +VolumeAir Round Ceramic Airstone 200mm - Aeration stone		63
Solution heater: CALENTADOR WATER MASTER 100W	1	22
Blum AVENTOS HL16 door mechanisms	3	686.28
Total All:		9593.8

A summary of all costs and benefits is presented in Table 3. The results of the economic analysis show that the small hydroponic system for growing tomato seedlings is cost-effective and can generate stable income for the owner. With a planned workload of 120 working days per year, the system is expected to produce approximately 10260 plants after adjusting for losses. The annual revenue from selling seedlings for 1 BGN per plant amounts to 10260 BGN (5245.85 EUR), while the total costs, including the costs of fertilizer, seeds, and electricity, are 4126.14 BGN (2109.66 EUR). This results in an annual net profit of 6133.86 BGN (3136.19 EUR).

The initial investment for the system is BGN 9593.80 (4905.23 EUR). At current revenues and expenses, the payback period is approximately 1.6 years (or about 19 months). This means that the system will start generating net profit in a relatively short period. Furthermore, assuming a depreciation period of 5 years, the annual depreciation costs will be around BGN 1918.76 (981.05 EUR), which further increases the predictability of financial results.

The profit will increase significantly once the investment is paid off, as depreciation costs will be eliminated. Furthermore, the profitability of the system can be improved by increasing the number of working days per year, including the production of seedlings of other vegetable crops, as well as the production of leafy vegetables, or by optimizing the production process, which would allow better resource management and reduction of losses.

Table 3

Results of economic evaluation of a small hydroponic system

Indicators	Value
Monthly number of plants	2565, pcs
Annual number of plants	10260, pcs
Monthly sales revenue	2565, BGN
Annual sales revenue	10260, BGN
Monthly fertilizer costs	461.7, BGN
Annual fertilizer costs	1846.8, BGN
Annual seed costs	2160, BGN
Monthly electricity cost	29.83, BGN
Annual expenses for electricity consumption	119.34, BGN
Total annual costs	4126.14, BGN
Annual profit	6133.86, BGN
Annual depreciation (assuming a 5-year term)	1918.76, BGN
Redemption period	≈19 months

The investment in this hydroponic system appears economically justified and has a high potential for return within less than two years. It provides an opportunity for a sustainable and profitable business model, especially for small producers who use self-owned water resources and can manage the system independently, without additional labor costs.

CONCLUSIONS

This study presented the design, development, and experimental validation of a modular, IoT-enabled hydroponic system intended for seedling cultivation in indoor environments. The system demonstrated high operational reliability and achieved a germination rate of 94–96% for two certified tomato varieties without the use of nutrient solution. These results confirm the system's ability to maintain favorable environmental and substrate conditions during early plant development.

While the study focused primarily on germination as a functional indicator, the observed environmental parameters—such as stable water temperature and controlled humidity—showed a positive correlation with seedling emergence. However, no detailed statistical analysis or phenological tracking was conducted, which limits the biological conclusions. These aspects will be addressed in upcoming studies with diverse crops and extended growth cycles.

The innovation of this system lies in its compact, modular structure, cloud-based control, and low-cost design, making it accessible for domestic users, urban gardeners, and small-scale producers. Its adaptability for different crops and potential for integration into home-based food production systems offer a practical solution for resilient agriculture in urban settings.

Further development will focus on refining environmental control, expanding biological monitoring, and evaluating long-term productivity and sustainability.

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