

Design and performance assessment of a PLC based automation system for controlled environment multi-layer hydroponic horticulture

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Abstract

Horticulture factory farms, having controlled environment hydroponic setups used to produce fresh and nutritious vegetative near consumption areas, serve as transformative solution to food security challenges. Manual control in such farms leads to variability and human error, ultimately compromising yield and sustainability. To address this, PLC based automation solution is proposed in this work. A novel architecture incorporating network of sensors and actuators, is specifically designed for multilayer hydroponic farms. Based on proposed design, a functional prototype was developed in laboratory, with precise control over light intensity, temperature, humidity, nutrient flow, pH, and EC. The effectiveness of the automation and prototype is monitored by growing various leafy horticultural plants, under different treatments. Among the several experiments performed, detailed statistical growth analyses of Basil (*Ocimum basilicum*) is recorded and compared with other studies. The result demonstrated that the plant height and biomass remained within the ranges, while leaf count showed a noticeable increase compared against manually controlled farms. Autonomously varying controlled parameter and its effect on plant growth was also evaluated by varying light intensities across different sections of the prototype. The assessed high F-values in ANOVA for leaves count (63.75), buds (90.70), leaf length (16.92) and plant height (7.73) confirms the significant differences on the growth. Result showcase designed system's ability to handle multiple treatments simultaneously in a single prototype, which is challenging under manual operation. Technical robustness and sustainability of proposed automation is evaluated by comparing the specifications with similar automation systems indicates, PLC automation is more preferred for factory farm environment. The presented automation design contributes toward Agriculture 4.0 for sustainable food production and supports UN Sustainable Development Goal 2 (Zero Hunger), ensuring safe and nutritious food for current and future generations.

Key words: Automation, Agriculture 4.0, factory farming, horticulture, hydroponics, PLC.

Introduction

Over the past decade, the global food crisis has become severe due to rising populations, climate change and the uncertainties in the traditional farming methods (Knorr *et al.*, 2018; Mc Carthy *et al.*, 2018). The decline in the availability of skilled manpower from 61.5% in 2019–20 to 58.4% in 2022–23 (Govt. of India, 2025), possess a critical constraint for an agrarian economy like India (Rathour and Badal, 2025).

In response to these challenges the World Government Summit - 2018, in collaboration with the Food and Agriculture Organization (FAO) of the United Nations, highlighted the need to integrate automation, digitalization and smart technologies into the agricultural sector. This collaborative initiative formally introduced the concept of Agriculture 4.0 (Beluhova-Uzunova and Dunchev, 2022). Agriculture 4.0 has introduced a range of advanced engineering alternatives to enhance efficiency and sustainability in crop production, including precision farming, IoT-based monitoring systems, drone assisted crop management, AI-driven decision support and smart technologies. (Santos Valle, 2020; Abbasi *et al.*, 2022). Here, the presented study focuses on factory farm automation, a key component of Agriculture 4.0.

Factory farming offers a sustainable and space efficient alternative to traditional farming which enables large-scale production,

consistent fresh food supply and optimised resource management (Eigenbrod and Gruda, 2015). This farming method offers solution to the rising demand for fresh and hygienic vegetative in densely populated cities, thereby, reducing transportation costs, minimizing land use and ensuring year-round availability (Kozai, 2019; Wang *et al.*, 2023). In the factory farming, hydroponics and vertical farming methods are preferred (Dharani *et al.*, 2025), which is a soilless cultivation technique that utilizes nutrient-enriched water solutions to deliver essential minerals directly to plant roots (Gericke, 1945; Santosh and Gaikwad, 2023). This technique enables precise control over growth parameters, leading to improved resource efficiency and higher crop yields in controlled environment (Barbosa *et al.*, 2015; Reyna-Avila *et al.*, 2025).

Automation in factory farm, ensures real-time control over variables, thereby improving accuracy and yield. Here, Programmable Logic Controller (PLC) is used to integrate the field sensors to control various parameters. Whereas, Human-Machine Interfaces (HMIs) and Supervisory Control and Data Acquisition (SCADA) systems provide easy visualization and access to historical trends, facilitating decision making. In this work, automated system is designed and implemented on

horticulture based factory farming prototype to evaluate its operational efficiency and productivity. The objective of this research is to upgrade the existing automation framework, by integrating with an industrial grade controller and validate its performance and technical effectiveness.

The paper aimed to develop and validate a robust automation system for a multi-layered factory-farm based hydroponic horticulture system using an industrial-grade controller. The plant growth-related parameters were continuously monitored and regulated, the controlled experimental conditions were autonomously simulated, and the efficiency of the system was assessed by statistical, agronomical and engineering analyses for horticulture research.

Materials and methods

Nutrient Film Technique (NFT) based customized hydroponic prototype of a factory farm was design and fabricated in the laboratory. This setup consists of 5 vertical layers with capacity to adopt 120 plants per layer. The nutrient rich water timely circulated over the plant roots providing oxygen and nutrients required for plant growth. Full spectrum LED based artificial lighting is employed for artificially simulate sunlight. Environmental parameters, temperature and humidity are precisely controlled using air conditioner and humidifier. A stable microclimate is created and maintained to support plant growth and maximize photosynthesis efficiency.

Automation: The integration and implementation of a PLC based automation system in the farm prototype, enable real-time monitoring and control of essential environmental and growth parameters. This system include three main subsystems: Input interface, Output Interface and Controller (Fig. 1). The parameters governing artificial lighting, air conditioning, humidification and nutrient delivery are monitored and controlled by the PLC. Moreover, Electrical Conductivity (EC) and pH of the nutrient solution are also precisely controlled using predefined recipes which is timely circulated within the system.

System architecture: In the automated factory farm, the PLC serves as the central control unit for regulating key parameters. Field deployed sensors continuously monitor critical process variables, including temperature, relative humidity, level, flow rate, EC and pH, which are transmitted as analog or digital signals to the PLC (Fig. 2). Based on real time sensor inputs, the PLC actuates final control elements such as pumps, motors, solenoid valves, humidifiers, heating/cooling systems and artificial lighting units, to maintain precise environmental and growth conditions. A computer based system is employed for controller programming and SCADA interface. Here, system is used for supervision, real time data acquisition, historical trend analysis and adjustment of nutrient recipes, temperature setpoints, lighting schedules etc. To monitor plant growth and identify nutrient deficiencies or diseases, robotic vision systems are often recommended (Shastri and Thakker, 2023). These systems timely capture images of the plants at regular intervals, enabling image processing for growth analysis and early detection of issues.

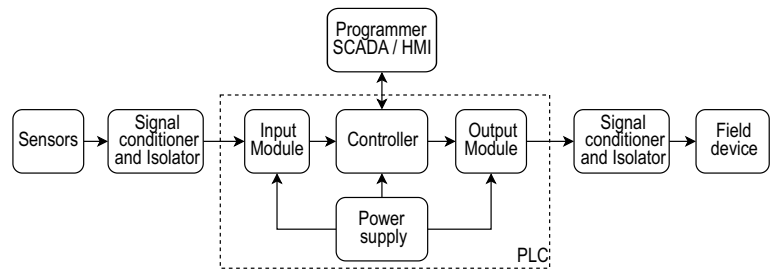


Fig. 1. PLC-based integration of field devices

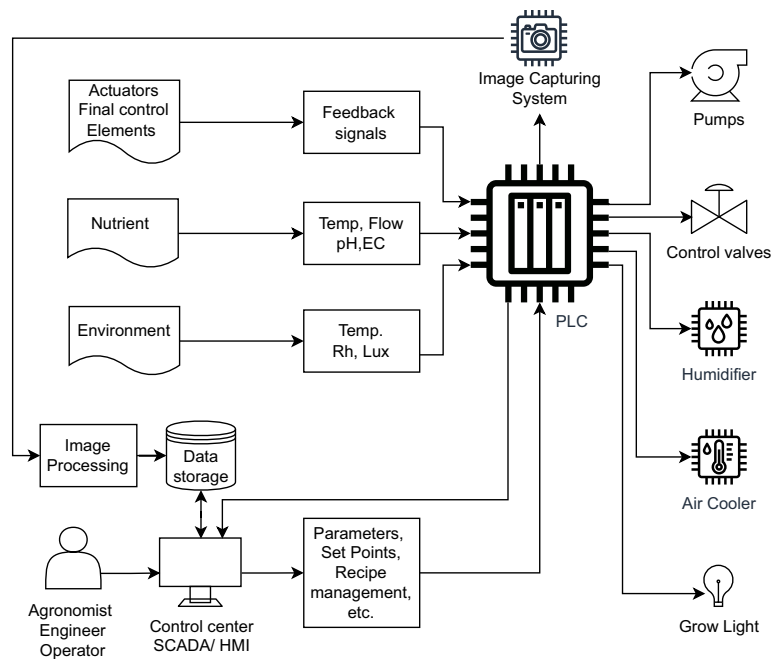


Fig. 2. Architecture of system

Nutrient management: Plant needs 17 essential micro and macro elements (Kumar *et al.*, 2021) and its management is the key parameter for healthy plant growth and yield (Ali *et al.*, 2008; Selim, 2020). Based on the chemical composition and nature, they are combined in two different stock solution commonly known as nutrient A and B (Hochmuth and Hochmuth, 2018). High concentration nutrient A and B which are stored in the separate tank, subsequently they are mixed and diluted with RO water in the main nutrient tank (Fig. 3). All tanks were equipped with level sensors, while the main tank was additionally fitted with EC and pH sensors. Based on the measured level, EC and pH values, the nutrient recipe was prepared and adjusted accordingly. A temperature sensor–heater assembly was integrated into the nutrient tank, to regulate solution temperature, which plays a critical role in crop yield (Al-Rawahy *et al.*, 2019; Yan *et al.*, 2012). Using the controller's Real Time Clock (RTC) nutrient circulation is timely executed. In current system 3 minutes circulation at 4 hours interval at 100 LPH flow is configured. Turbine flow sensor is used for precise flow control, as excess flow will waste the resources and under flow will slant the plant growth (Baiyin *et al.*, 2021).

Environment management: Environmental control in factory farming enables year-round production, reduces dependence on external climate and enhances plant growth, yield and quality (Allen *et al.*, 1978)(Bange *et al.*, 1997). By maintaining specific temperature and humidity levels, many pests and pathogens can be prevented (Quesada-Moraga *et al.*, 2024). Air temperature, circulation and humidity were regulated through the PLC system, using domestic air conditioner, fans and ultrasonic humidifier. Light intensity and photoperiod were carefully regulated, which is needed for the healthy plant growth and development (Mao *et al.*, 2014). Plant lighting needs, vary by species and growth stage; for instance, green and blue light stimulate compact, leafy development (Razzak *et al.*, 2022), and

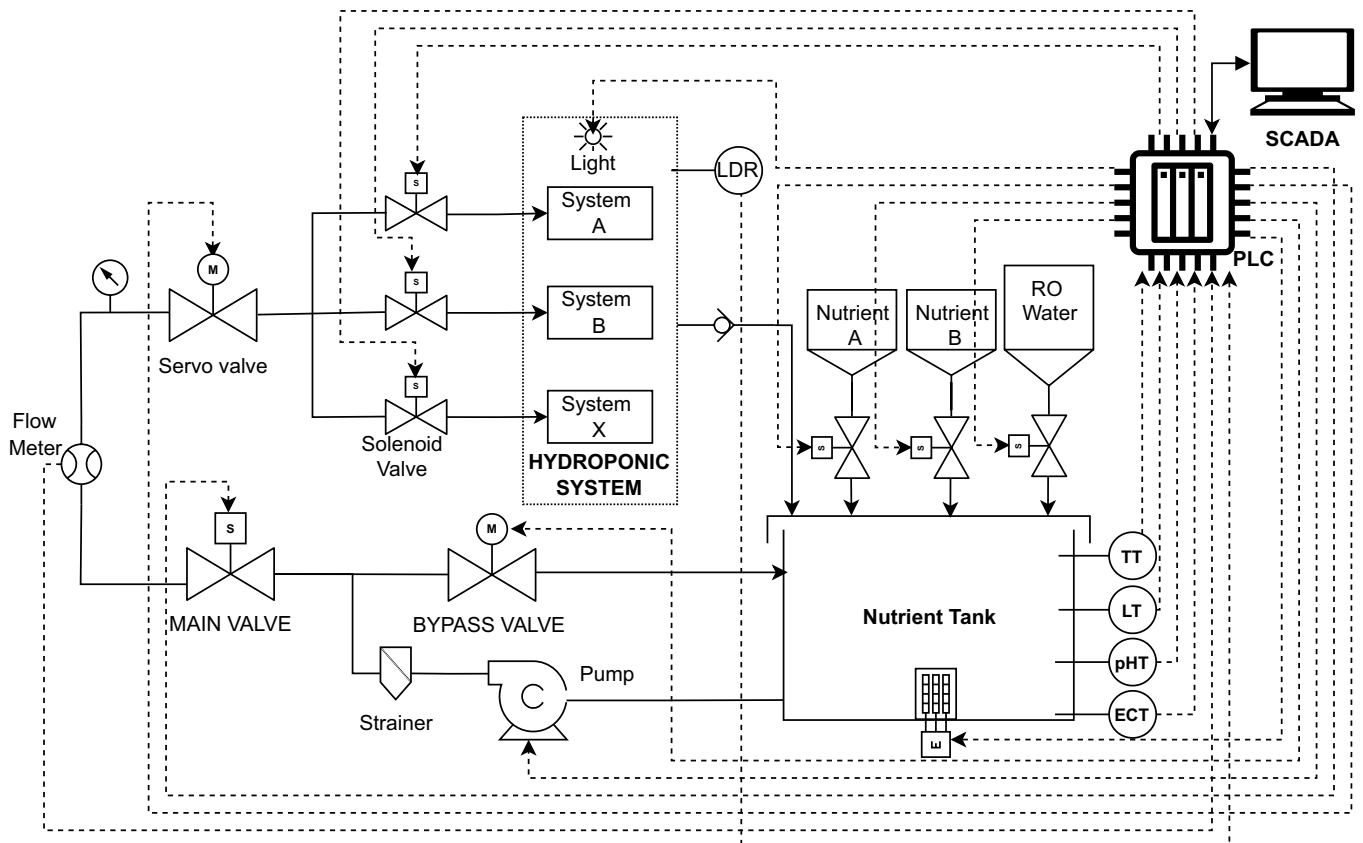


Fig. 3. Process and Instrumentation diagram of plant demonstrates integration of field inputs and controlled outputs with PLC

red light stimulates flowering and fruiting (Nanya *et al.*, 2012). In this work, a full spectrum 400–700 nm grow light is used, to provide balanced wavelengths for photosynthesis (Verma *et al.*, 2025). Uniform light distribution is achieved by appropriate placement of lights, as excessive direct light intensity can cause leaf scorching and browning (Shibaeva *et al.*, 2023). Though, dark period is also essential for proper plant development, so the PLC's RTC was programmed in such way that, grow lights on time are not more than 16 hours per day (Arthur and Harvill, 1937).

Implementation: The automation system was implemented and tested on a factory farm prototype deployed within the research laboratory environment. This hydroponic setup consist of 5 vertical layers having total capacity of 600 plants. In this automated setup, a variety of leafy plants and herbs were cultivated and grown for horticulture research. For the automation, Siemens S7-1200 1214 series PLC is used, while programming is done in Siemens Total Integration Automation Portal (TIA) which also integrates PLC with SCADA and HMI. SCADA continuously gathers data from the PLC (e.g., temperature, pressure, flow rate) and displays it to operators in real-time. It provides a graphical trends, alarms and process diagrams, helping operators to understand the system performance and status.

Results and discussion

Automation system was designed, developed and successfully deployed on a laboratory scale prototype (Fig. 4). The system supported in cultivation of multiple horticultural crops, such as Lettuce (*Lactuca sativa*), Mint (*Mentha spicata*), Basil (*Ocimum basilicum*), Oregano (*Origanum vulgare*), Spinach (*Spinacia oleracea*) and Kale (*Brassica oleracea*). All of which progressed successfully to maturity and harvest.

Among the cultivated species, the growth characteristics of basil

(*Ocimum basilicum*) is evaluated across their entire ontogenetic development, from transplant to harvest. The growth parameters, including number of leaves, number of buds, leaf length and plant height, were measured and analysis of variance (ANOVA) revealed a highly significant F-value ($P < 0.05$) (Table 1). The consistent rise in mean values across age intervals confirms that plant growth parameters showed a significant positive correlation with age, reflecting active morphological development during the observed period. The results confirm that our proposed automation architecture was successfully implemented to achieve the desired plant growth. The parameter values of light intensity, temperature, humidity and EC, which are controlled by PLC are mentioned (Table 2).

The data represent mean values of the measured growth parameters and its comparison with findings from related hydroponic cultivation studies (Table 3). The positive deviations in leaf count and plant height were recorded, while fresh and dry weights found within the range, under controlled parameters using automation.

Developed system's performance was evaluated by monitoring the plant growth in different environment conditions simulated by PLC at different sections of the setup. Experiments were conducted on basil to study the effect of various light intensity on the plant growth. Five distinct light zone (30000 to 120000 Lux) were created, and simultaneous growth of plants in each zones are recorded. One way ANOVA analysis revealed that light intensity had a considerable effect on all measured traits: number of leaves, number of buds, leaf length and plant height with F-values exceeding the critical limit ($F_{0.05} \approx 3.35$) (Table 4). This result showed capability of our design to control environmental parameter to achieve desired growth of the plant.

Similar kind of automation have been developed by other

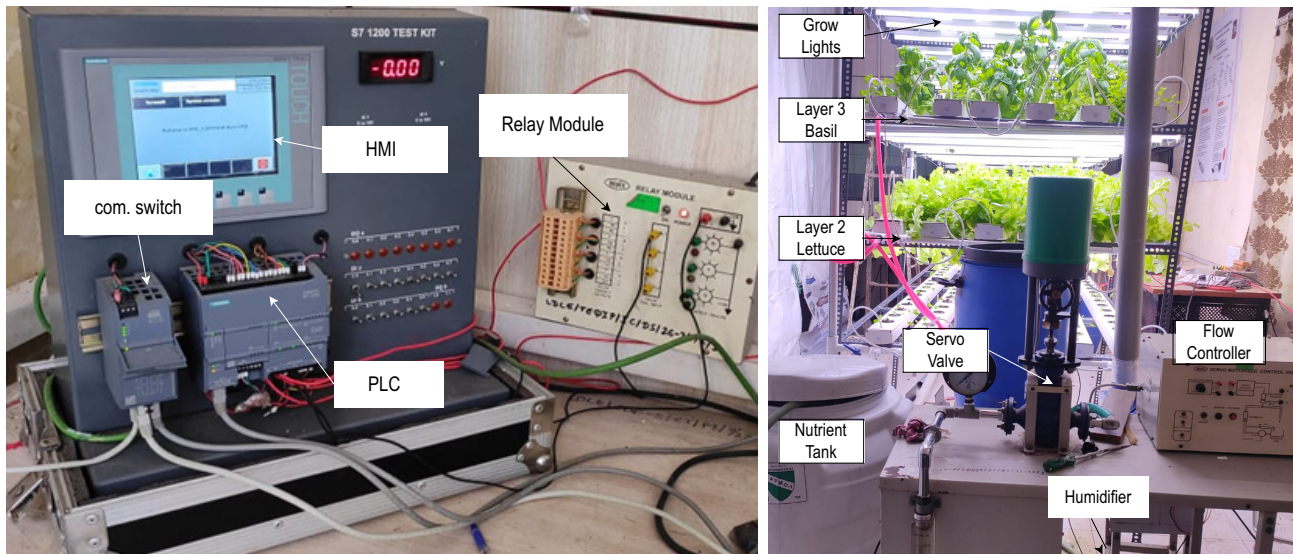


Fig. 4. Automation system, setup and plant growth

Table 1. Growth characteristics of Basil (*Ocimum basilicum*) in automated factory farm prototype

Parameter	Leaf count	Number of buds	Leaf length (cm)	Plant height (cm)
DAT 10	4±0	2.0±0	2.9±0.22	3.2±0.44
DAT 20	7.2±1.09	1.8±0.44	1.9±0.96	3±1.17
DAT 30	10.8±1.09	4±0	5.8±0.75	10.4±2.88
DAT 40	28.4±4.56	8.6±0.54	8±1.22	23.2±4.14
DAT 70 (Harvest)	106±4.3	47.2±3.63	9.8±0.83	60±4.69

F-values: no. of leaves (147.92), number of buds (623.60), leaf length (97.91), and plant height (90.77) were found to be highly significant ($P < 0.05$).

The parameter values of light intensity, temperature, humidity, flow, pH, and EC, which controlled by PLC are mentioned (Table 2).

Table 2. Plant parameter setpoints

Temperature	Humidity	Flow	Light	EC (mS/cm)	pH
26±2°C	70±3%	100±10 LPH	8–10 K Lux 10 h	0.5/0.75/1 -1.2/1.5	6.3±0.2

Nutrient circulation time : 3 min at every 4 hours at 100 LPH, lighting duration: 10 hours

researcher, mostly using cost effective control boards like Arduino and Raspberry Pi (Bua *et al.*, 2024; Leiwai *et al.*, 2020; Lukito and Lukito, 2019). The control strategies implemented on such embedded type systems are user friendly, flexibility and economical for small-scale projects (Awal *et al.*, 2025).

Table 5. Comparative technical specifications and reliability metrics of industrial PLCs and popular microcontroller-based boards

Device	Operational Temperature °C	Operational Relative humidity	MTBF	Protection level	Approvals	Reference
PLC (Siemens SIMATIC S7-1200 -1214AC/DC)	-20 to 60 °C	95%	≈21-48 Years * product specific	IP20 & EMC 6-8 KV	CE, CSA, UL, cULus, FM, RCM, Marine	(Siemens, 2025a, 2025b)
PLC (Arduino Opta)	-20 °C to +50 °C	Standard industrial ambient	≈ 87 years	IP20	EU, UKCA, FCC, IC, cULus	(Arduino S.r.l, 2025)
Arduino Uno- R3	-40 °C to +85 °C ¹	Not Available	Not Available	Open board (no IP rating)	EU, RoHS & REACH	(Arduino UNO R3, 2025)
Raspberry Pi 4 Model B	0 °C to +50 °C	RH not published ²	≈ 25 years	Open board (no IP rating)	CE, FCC and others	(Raspberry Pi Ltd, 2025)
ESP32 (WROOM / WROOM-32 modules)	40 °C to +85 °C	MSL 3 (168 hours 30 °C-60%RH)	Not Available	Open board (no IP rating)	FCC/CE-RED/IC/TELEC/KCC/SRRC/NCC	(Espressif Systems, 2016)

EEPROM, voltage regulator, and the crystal oscillator, might not work as expected as mention in datasheet

Disclaimer: All values are derived from the latest available datasheet or official technical documentation at the time of compilation (Oct-2025), it is subjected to vary based on the specific model number, country specific product variants and periodic updates by the respective manufacturers.

Table 3. Comparative study of basil growth parameters

Plant height (cm)	Leaf count	Fresh weight (gm)	Dry weight (gm)	References
57.83 ± 7.42	-	139.02 ± 10.19	32.36 ± 0.68	(Khater <i>et al.</i> , 2021)
-	76-88	65.3-67.0	9.9-11	(Raimondi <i>et al.</i> , 2006)
-	36.12 ± 2.89	38.05 ± 1.67- 46.67 ± 3.49	1.16 ± 0.07 - 3.26 ± 0.27	(Modarelli <i>et al.</i> , 2023)
49.38 ± 4.22	-	-	6.48 ± 0.72	(Aghamirzaei <i>et al.</i> , 2024)
60 ± 4.69	106± 4.3	70.5 ± 5	5.809 ± 1.57 ¹	Prototype Result ²

¹ Samples were dried in a hot-air oven at 65°C for 72 hours, ²Age: 70 DAT, Light:8000 lux, Temperature: 25°C, Humidity: 80%RH

Table 4. Growth parameters of basil (*Ocimum basilicum*) measured under varying light-intensity treatments

Parameter	Number of leaves	Number of buds	Leaf length (cm)	Plant height(cm)
3K	13.2±1.10	5±0.71	6±0.71	21.2± 2.17
5K	14.8±1.10	5.6±0.55	6.3±1.14	20± 5.70
7K	36.4±6.54	9.8±0.45	8.3± 0.45	34.2± 4.27
9K	44±7.62	14.4±2.07	8.8± 0.45	32± 6.63
120K	62.4±8.05	17.4±1.67	9.8± 0.22	32.4± 7.27

F-values: Number of leaves (63.75), number of buds (90.70), leaf length (16.92), and plant height (7.73) confirming significant differences among treatments ($P < 0.05$).

However, comparing technical specification, they lack industrial grade reliability and lower MTBF (Mean Time Before Failure). Humidity promotes the plant growth (Taticharoen *et al.*, 2023), but it is also the main cause of electronics failure. Although, the non marine approved controllers are unsuitable for high humid horticulture farms. Here selected PLC controller proved to be the most suitable automation platform for hydroponic factory farming because of its reliability, high humidity tolerance (up to 95%) and industrial grade protection.

Looking ahead, advancements in smart sensors and intelligent field devices are likely to eliminate extensive hard wiring, enabling more flexible and modular automation systems. The system can also be integrated with artificial intelligence and machine learning for predictive maintenance (Karimzadeh *et al.*, 2025) and optimization (Sharmin *et al.*, 2025).

The work demonstrates that the integration of industrial automation into hydroponic horticultural systems enables precise environmental and nutrient control, achieving efficient plant growth and productivity in line with Agriculture 4.0 principles. Plant growth analyses and yield outcomes validate the effectiveness of the automation system for large scale factory farming. It highlights the potential for scalable, resource-efficient food production systems to address food security.

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