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Flow-verified ESP32 fertigation control for efficient polybag spinach cultivation

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ABSTRACT

Spinach cultivation in polybags supports urban food production, but limited substrate volume makes root-zone moisture and nutrient delivery sensitive to manual dosing errors. Many internet of things (IoT) irrigation systems monitor environmental conditions without verifying the volumes of water and fertilizer delivered. This study developed and evaluated an ESP32-based closed-loop irrigation and flow-verified fertigation system for polybag spinach. The platform integrated capacitive soil-moisture sensing, air and root-zone temperature measurement, Hall-effect flow sensors, relay-driven pumps, an organic light-emitting diode (OLED) display, and Blynk supervision. Irrigation used 60% and 80% moisture thresholds with hysteresis, while fertigation stopped when cumulative flow reached the prescribed dose. A 30-day experiment compared IoT-controlled silica-NPK fertigation, IoT-controlled conventional NPK, and manual conventional NPK using three polybags per treatment. The controller maintained mean soil moisture at 68.5%, responded locally within two seconds, and achieved 97.9% uptime during a 168-hour validation period. Soil-moisture error was 1.92%, temperature errors were 0.52 °C and 0.36 °C, and flow accuracy exceeded 90%. Compared with manual cultivation, IoT control reduced water use by 28.7%, while silica-NPK treatment reduced delivered fertilizer by 38.1%. These findings demonstrate a practical embedded architecture for traceable and resource-efficient irrigation and fertigation.

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1. INTRODUCTION

Urban and peri-urban vegetable production must be carried out on limited land and with limited water and labour, while maintaining stable root-zone conditions. Polybag cultivation is ideal for small spaces such as yards and rooftops [1]-[4]. However, its small substrate volume means that moisture and nutrient conditions can change rapidly. Manual watering is therefore susceptible to uneven application, delayed response to plant demand, excessive drainage, and operator-dependent dosing. These limitations necessitate a compact, embedded system that can measure the cultivation state, make local control decisions, verify the volume of liquid delivered, and remain observable both on-site and remotely [4], [5].

Spinach (*Amaranthus sp.)* was chosen as a test crop because of its short cultivation cycle and sensitivity to water and nutrient stress [6]-[8]. Water deficit restricts leaf expansion and biomass formation, whereas root-zone aeration can be reduced and nutrient loss increased by excessive watering. The requirement for a technically credible system is the display of more than just sensor values: maintenance of a defined

moisture band, prevention of unstable pump switching, quantification of water and fertilizer delivery, and demonstration of the accompaniment of engineering performance by measurable resource-use and plant responses.

An Espressif Systems 32-bit (ESP32) can be used for capacitive soil moisture sensing, measuring air and root zone temperatures, acquiring Hall-effect flow data, driving relay-controlled pumps, displaying information on a local organic light-emitting diode (OLED) screen and supervising wireless fidelity (Wi-Fi) connections [9]-[11]. However, assembling familiar components does not constitute a scientific contribution in itself. The engineering question is whether local control of moisture and flow can form a fertigation platform that can be checked and is able to deal with problems in a test of growing plants [12], [13]. Table 1 compares the suggested work with other studies on irrigation control, managing nutrients, soil monitoring, and research on nanofertilizers. The system-level innovation lies in the combination of calibrated multi-sensor acquisition with local two-threshold feedback and pulse-based verification of water and fertilizer delivery. The three-treatment evaluation separates the shared automation response (Groups A and B compared to Group C) from the formulation-dependent response (Group A compared to Group B). The contribution is therefore an embedded-control architecture that can be reproduced and an integrated proof-of-concept evaluation, rather than the individual use of ESP32, Blynk, sensors, or silica.

Table 1. A review of strengths and weaknesses of previous studies

Year	Author	Research focus	Method	Strengths	Weaknesses	Relevance to this study
2022	Atmaja and Nico [14]	Automatic nutrient control in hydroponic cultivation	Fuzzy logic control for deep flow technique hydroponics	Demonstrates that automatic control can regulate nutrient concentration effectively.	Focuses on hydroponic water media, not soil/polybag cultivation; does not integrate drip irrigation or nanoparticle fertigation.	Shows the potential of control systems for agricultural automation.
2023	Ding *et al*. [15]	Nanofertilizer development and nutrient efficiency	Review of nanofertilizer properties and applications	Explains the potential of nanofertilizers to improve nutrient use efficiency through small particle size and controlled release.	Review-based study; does not implement internet of things (IoT) fertigation or evaluate crop growth using sensor-actuator control.	Supports the use of nanoparticle fertilizer in precision fertigation.
2024	Ali *et al.* [16]	IoT-based soil moisture monitoring	Capacitive soil moisture sensor with IoT-based real-time monitoring	Strong emphasis on sensor calibration and field validation; capacitive sensors are suitable for long-term soil monitoring.	Mainly focuses on monitoring, not integrated fertilizer dosing, flow measurement, or comparative plant growth evaluation.	Supports the use of capacitive soil moisture sensors for reliable irrigation control.
2025	Aisyah *et al*. [17]	ESP32-based smart irrigation for water efficiency	ESP32, soil moisture sensor, temperature-humidity sensor, and Blynk platform	Closely related to IoT irrigation, low-cost ESP32, and Blynk implementation for water-efficient irrigation.	Limited to water control; does not include nanoparticle fertilizer, flow-based fertigation, OLED local display, or comparison with manual cultivation.	Provides direct technical reference for ESP32-Blynk irrigation automation.
2026	**Proposed method**	Embedded IoT sensor-actuator control for drip fertigation and spinach cultivation in polybags	Capacitive soil moisture sensor, flow sensors, OLED display, and Blynk IoT dashboard	Integrates irrigation control, nanoparticle fertigation, multi-sensor monitoring, flow-based dosing, local display, and remote control in one compact system. Evaluates both technical performance and crop growth.	Still limited to one cultivation cycle and small-scale polybag testing, long-term durability, larger-scale implementation, economic feasibility, and backup power integration need further study.	Becomes the proposed contribution by combining embedded electrical engineering, IoT automation, and precision fertigation for urban farming.

The suggested way of doing things is to combine electrical engineering, IoT automation, watering plants at the right times, and using a special type of fertilizer made from very small silica particles to grow spinach in polybags. Previous studies looked at different things, as shown in Table 1, including automated nutrient solution regulation in hydroponic systems [14], mixing nutrients [15], monitoring soil [16], and using

nanofertilizers on their own [17]. This new method combines several different technologies. It uses an ESP32-based sensor-actuator control, checks the moisture and temperature of the soil all the time, and delivers water and fertilizers based on the flow of water. It also has an OLED display and can be monitored remotely using Blynk. Finally, it uses nano silica from rice husks as a way to carry nutrients. The integration of these elements enhances the system's responsiveness, optimizes water and fertilizer use, and boosts crop growth performance. Additionally, it fosters sustainable urban farming by repurposing agricultural waste as a functional nanomaterial.

2. METHOD

2.1. Research design

An ESP32-based closed-loop irrigation and flow-monitored fertigation platform for spinach grown in polybags was evaluated in a 30-day experimental engineering study. Three treatments were each allocated nine polybags, with three polybags being measured and allocated separately for each treatment. Group A received IoT-controlled irrigation with silica-nitrogen, phosphorus, and potassium (silica-NPK) fertigation; Group B received the same IoT-controlled irrigation with conventional NPK; and Group C received manual irrigation with conventional NPK. The polybag was the experimental unit, and the following were held constant: variety, polybag dimensions, growing medium, cultivation site, and initial plant condition. Table 2 summarizes the treatment structure. As n=3 per treatment provides limited inferential power, the primary evidence is engineering operation and resource use, while crop responses are interpreted as descriptive findings at prototype scale.

Table 2. Research design

Group	Treatment	Description
A	IoT+NPK+nanoparticle fertilizer	Automatic drip irrigation and scheduled nanoparticle fertigation controlled by ESP32
B	IoT+NPK fertilizer	Automatic drip irrigation controlled by ESP32 with conventional fertilization
C	Manual watering+NPK fertilizer	Conventional manual watering and fertilization without IoT control

2.2. Preparation of nano silica material

Rice husks were meticulously washed, desiccated at temperatures ranging from 100 to 105 °C, and subsequently incinerated in a furnace at temperatures between 700 and 800 °C for a duration of 2 to 4 hours, thereby yielding silica-rich ash. The ash was subjected to acid leaching to reduce metallic impurities, then rinsed with distilled water until the pH was neutral, and finally dried before undergoing alkaline extraction [18]-[20]. These temperature and cleaning steps were controlled because if something is not completely burned, it can leave a bit of carbon behind. But if it is heated too much, it can change the silica structure and how it sticks to other things.

The purified ash was reacted with sodium hydroxide to form sodium silicate, which was then filtered and acidified with hydrochloric acid until silica gel formed. Following ageing, washing, drying at 100–110 °C and milling, the product was characterized using energy-dispersive X-ray analysis and nitrogen adsorption-desorption. Brunauer-Emmett-Teller (BET) analysis was used to quantify the specific surface area, while Barrett-Joyner-Halenda (BJH) analysis was used to estimate the pore volume and pore size distribution [18], [21], [22]. While the measured surface and pore properties establish mesoporosity and potential carrier functionality, they do not prove nanoscale particle size or controlled nutrient release by themselves.

2.3. System architecture

The system comprised four functional layers. The sensing layer included a capacitive soil moisture probe, a digital humidity and temperature (DHT22) air temperature/humidity sensor, a DS18B20 root zone temperature sensor, and separate Hall effect flow sensors for water and fertilizer. The processing layer used an ESP32 for data acquisition, calibration, conversion, threshold evaluation, pulse counting, actuator command generation and Wi-Fi communication. The actuation layer comprised 12-V DC water and fertilizer pumps driven by relays, as well as reservoirs, pipes and drip emitters. The application layer comprised an SH1106 OLED display and a Blynk dashboard. Essential feedback control was executed locally, whereas Blynk provided asynchronous supervision and manual override to prevent network latency or temporary internet loss from affecting the primary irrigation loop [23]-[25].

The suggested system was created as a control system that is built into the machine and can sense things and actuate them. The ESP32 microcontroller functioned as the primary controller, receiving input from

soil and environmental sensors, processing the data in accordance with threshold logic, and actuating the water and fertilizer pumps via relay modules [23]-[25].

The controller used two different service routines: one that was triggered by moisture and one that was triggered by a schedule. Automatic irrigation was evaluated on every control cycle. The initiation of a fertigation event was contingent upon the fulfilment of its predetermined schedule. Thereafter, the fertilizer pump functioned under the aegis of cumulative-flow supervision until the stipulated volume was attained. The two routines used separate pumps, reservoirs, flow sensors, and state variables. The exact pump-priority or mutual-exclusion rule must be the same as the firmware that has been deployed, and this is shown for author confirmation in Table 3. The Blynk commands that were used by hand were in charge of the system, while the OLED screen showed the sensor values, the pump's status, and the connection status.

Table 3. Irrigation and fertigation controller parameters

Parameter	Symbol/state	Value or implementation
Lower moisture threshold	M_L	60%
Upper moisture threshold	M_H	80%
Moisture hysteresis	M_L-M_H	20 percentage points; previous pump state retained inside band
Fertigation trigger	S_{due}	Programmed schedule event; interval must be inserted from deployed firmware
Fertilizer target volume	V_{set}	Insert target mL per event from deployed firmware
Dose termination	$V_f >= V_{set}$	Fertilizer pump OFF; pulse counter/event reset
Irrigation-fertigation interaction	Interlock	Confirm from firmware: mutually exclusive, deferred, or simultaneous operation
Flow-fault protection	N=0 while pump ON	Confirm timeout and shutdown value from firmware
Controller sampling/update	Delta t	Insert local sampling period; Blynk update was 45-60 s

2.4. Hardware design

The prototype incorporated an ESP32, a capacitive soil moisture sensor, a DHT22 sensor, a waterproof DS18B20 sensor, two Hall-effect flow sensors, a two-channel relay module, two 12 V DC pumps, an SH1106 OLED display, a regulated power supply, reservoirs, tubing, and drip emitters. The soil moisture probe and the DS18B20 were installed in the root zone, while the DHT22 was mounted above the canopy to protect it from direct wetting. One flow sensor was installed in each liquid line. The relay modules connected the ESP32 logic level to the pump loads, and the water and fertilizer paths were separated to prevent cross-contamination of the reservoirs.

Each drip emitter discharged near the root zone to limit conveyance and evaporation losses. The ESP32 counted the flow pulses using an interrupt-based acquisition method and converted them into a cumulative volume using an experimentally calibrated pulses-per-volume coefficient. The installation depth and probe orientation were kept unchanged throughout the cultivation period. The moisture thresholds, flow coefficients and controller logic were maintained throughout the 30-day experiment. The fertilizer schedule, target dose and irrigation-fertigation interlock are firmware parameters that must be reported numerically from the deployed programme rather than being inferred from total consumption.

2.5. Sensor calibration and control algorithm

Before integration, the moisture sensor was calibrated using dry and wet references in the actual growing medium. The DHT22 and DS18B20 were then compared with a reference thermometer, and both flow sensors were verified against known volumes collected in a graduated vessel. For each measurement (xi) and its respective reference $(x(r,i))$, the percentage error was calculated as $|x_i - x(r,i)|/x(r,i)\ x\ 100\%$. Mean sensor accuracy was reported as 100% minus the mean absolute percentage error. Temperature error was reported in degrees Celsius. Flow volume was estimated using the formula $V = N/K_f$, where N is the accumulated pulse count, and K_f is the calibrated pulses-per-volume coefficient. The original records available for this revision do not specify the number and range of calibration points. These should be added from the laboratory log before final submission.

The irrigation system used two thresholds: the pump was switched on when the measured moisture level $(M(k))$ was less than 60% and switched off when $M(k)$ was greater than or equal to 80%. It retained its previous state inside the 20-percentage-point band. This hysteresis reduced relay chatter near a switching boundary. Fertigation followed an event-and-volume state machine. When a scheduled dose was due and the activation/interlock conditions were met, the controller reset the fertilizer pulse counter, started the pump, and updated the cumulative volume V_f. Delivery stopped when $V_f \geq V(set)$ or a safety condition occurred, after which the event flag was cleared. The same control parameters were used throughout cultivation. Table 3 summarizes the implemented values and highlights firmware parameters that require author confirmation before resubmission.

2.6. Internet of things monitoring and user interface

The Blynk control panel exhibited environmental metrics, aggregate water and fertilizer consumption, and pump status [26], [27]. Local and remote response times were measured from the detection of a command or threshold to the observed change in the actuator state [28], [29]. During the 30-day cultivation experiment, the system's reliability was checked continuously for 168 hours. This was done using the same hardware, firmware, control settings, sensors, network, and operating conditions. The experiment ran for seven consecutive days. Uptime was calculated as the ratio of correct operating time to the 168-hour observation period.

2.7. Cultivation procedure and outcome measurements

Following calibration and bench testing, the firmware, dashboard, drip network, pumps, relays, and emitters were inspected to ensure they were free from leaks and operating consistently. Similar spinach seedlings were planted and acclimatized before the treatment was activated. Groups A and B used the same moisture-control algorithm, whereas Group C was watered manually. Group A received scheduled, flow-terminated silica-NPK fertigation, Group B received conventional NPK under the same IoT irrigation, and Group C received manual irrigation and conventional NPK. At each fertigation event, the controller verified the enabling conditions, reset the cumulative fertilizer flow, activated the fertilizer pump, and stopped it either when the set value was reached or after a safety timeout. It then returned to moisture control supervision. Sensor values, pump events, accumulated volume, response time, communication behaviour, and fault events were logged. Plant height was measured at 10-day intervals, leaves were counted, and leaf area was estimated using the formula length × maximum width × 0.6. Fresh and oven-dried mass were measured at harvest for each polybag.

2.8. Resource-use data collection

Water and fertilizer consumption in Groups A and B was accumulated from calibrated flow measurements, whereas the volumes applied manually in Group C were measured using graduated containers. The water saved relative to manual cultivation was calculated as $\{(W_C - W_I)/W_C\} \times 100\%$, where W_C is the consumption in Group C and W_I is the corresponding consumption in the IoT group. Fertilizer savings were calculated similarly. These metrics quantify the delivered input rather than the operating time of the pump, thereby accounting for changes in pump output, supply voltage, line pressure and emitter resistance.

2.9. Statistical and uncertainty analysis

The performance of the engineering system was summarized using some metrics, including sensor error and accuracy, the response times of the actuators and communication components, the accuracy of the flow, the amount of water and fertilizer used, and the system's uptime. For the cultivation analysis, each polybag was treated as an independent experimental unit, providing three replicates per treatment. The harvest results were reported as the mean±standard deviation and were compared using a one-way analysis of variance, with the only factor being the treatment. The analysis reported the *F*-statistic, degrees of freedom, exact *p*-value, omega-squared effect size and 95% confidence interval. When differences among treatments were found, Tukey-adjusted comparisons were used to compare groups A–B, A–C, and B–C. The results included mean differences, adjusted *p*-values, 95% confidence intervals and Hedges' g. Repeated measurements from the same polybag were not counted as additional replicates. As each treatment contained only three polybags, the statistical results should be interpreted as preliminary evidence from a small prototype experiment [30], [31].

2.10. Performance evaluation

The evaluation linked three levels of evidence. Engineering performance: measurement error, flow accuracy, actuator and cloud response, update interval, and uptime. Resource performance: delivered water and fertilizer volume. Biological response: height, leaf number, leaf area, fresh mass, and dry mass. The 168-hour reliability window was evaluated separately from the 30-day cultivation experiment. A short reliability test cannot be generalized to the full cultivation period if this hierarchy is in place. The same goes for reliable electronics, which cannot be treated as proof of agronomic superiority. The same is also true of a crop difference, which cannot be attributed to mesoporous silica without considering irrigation control and nutrient formulation.

3. RESULTS AND DISCUSSION

3.1. Rice-husk-derived silica characteristics

Figure 1 illustrates the process of preparing the silica-rich product from cleaned rice husk, involving drying and milling. Controlled combustion at temperatures between 700 and 800 °C produced the ash precursor

by removing most of the organic matter while retaining a structure that is suitable for alkaline extraction. The thermal stage required precise control to prevent residual carbon from incomplete combustion lowering the purity and to avoid excessive heating altering the silica phase and adsorption behaviour.

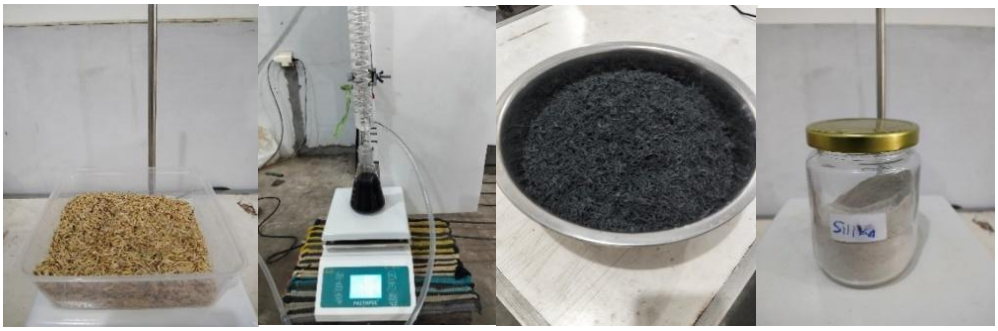


Figure 1. Nano silica process

Figure 2 shows the nitrogen adsorption-desorption results used to quantify the porous texture. BET analysis yielded the following values: a specific surface area of 314.254 m^2/g; a total pore volume of 0.727 cm^3/g; and an average pore diameter of approximately 9.254 nm. The pore size is between 2 and 50 nanometers, which suggests there are internal surfaces and diffusion pathways that may support nutrient interaction. BET and BJH are not concerned with establishing the morphology of particles, the efficiency of nutrient loading, or the release kinetics. Consequently, material results exclusively support mesoporosity, while the primary conclusions pertain to embedded control and measured delivery.

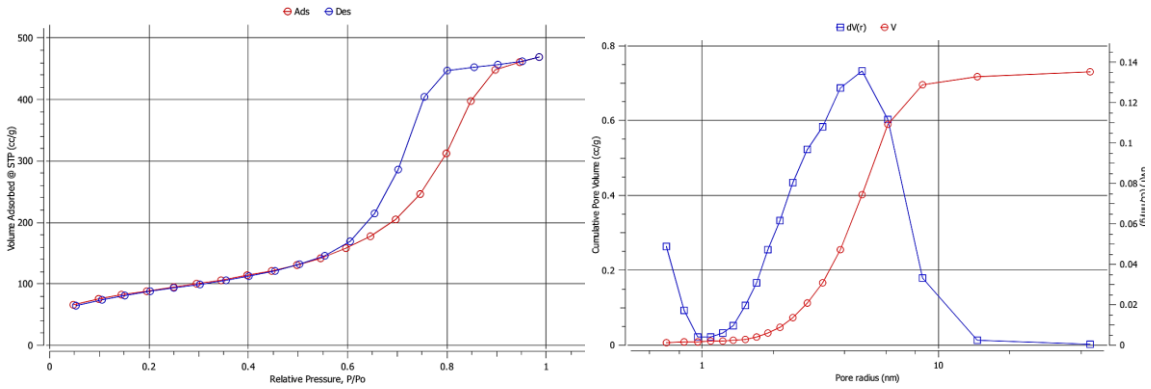


Figure 2. BET multi-point

The BJH analysis confirmed that the rice-husk-derived silica had a well-developed porous structure, which is an important finding given the potential applications of this material. The adsorption and desorption surface areas were found to be 347.557 and 427.517 m^2/g, respectively, and the corresponding pore volumes were found to be 0.731 and 0.775 cm^3/g, respectively. The material's potential use as a nutrient carrier is supported by the many possible interaction sites provided by these high surface areas and pore volumes. Table 4 summarizes its oxide composition and Figure 3 shows the compositional spectrum and analyzed micrograph. However, the current results only confirm the material's composition and porous characteristics. They do not fully establish its particle morphology, nanoscale size distribution, crystallinity, surface functional groups, nutrient-loading capacity, or release behaviour.

Table 4. Contents in 1 gram of silica nanomaterial

Compound	SiO_2	CaO	Cr_2O_3	MnO	Fe_2O_3	NiO
Conc	97.7	1.98	0.024	0.038	0.19	0.004
Unit	%	%	%	%	%	%

3.2. Embedded internet of things system implementation

Figure 4 shows the platform that has been implemented, including local OLED monitoring, the Blynk dashboard, the ESP32 sensor-actuator hardware, and the deployment in a polybag. The prototype completed the intended sensing-decision-actuation cycle by acquiring moisture and temperature signals, counting water and fertilizer flow pulses, executing local pump logic, displaying system status, and transmitting supervisory data. This design goes beyond monitoring-only designs because the measured state triggered the actuator commands and the delivered liquid was estimated independently from the flow pulses. Separating local control from cloud supervision also enabled irrigation to continue during temporary connectivity loss.

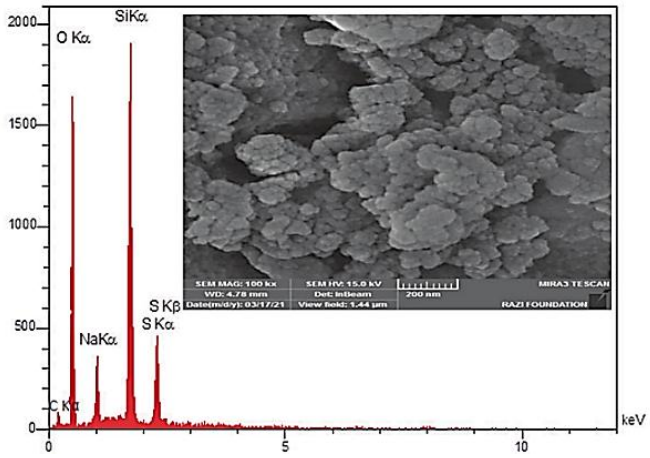


Figure 3. Silica nanomaterial content

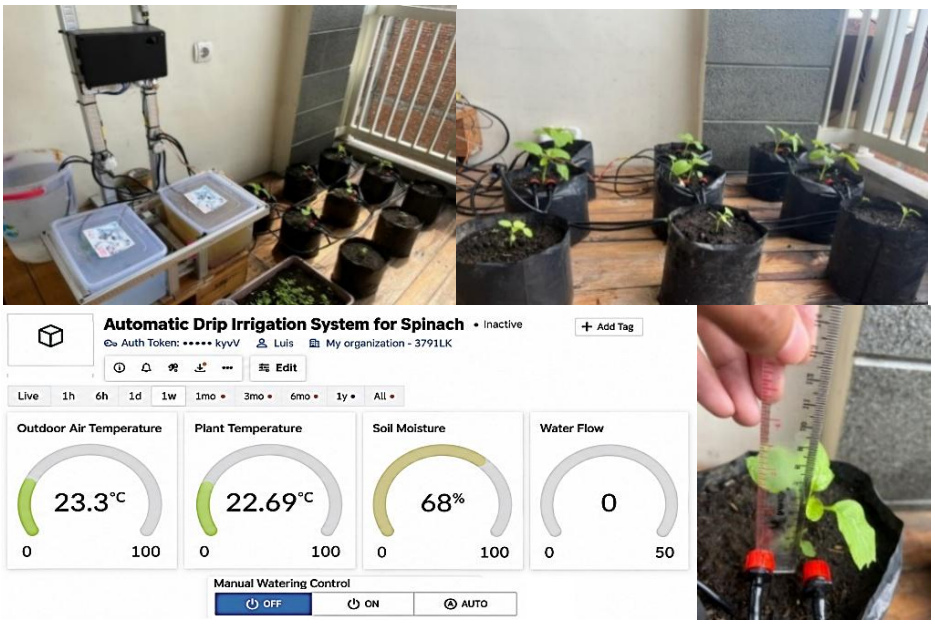


Figure 4. Embedded IoT system

The ESP32 provided the prototype with sufficient analogue and digital interfaces, interrupt capability, Wi-Fi connectivity and processing capacity. Relay isolation enabled the low-voltage controller outputs to switch the 12 V pump loads without routing the actuator current through the microcontroller. The separate water and fertilizer paths and flow sensors made the delivery process auditable at the line level. However, future field deployment should also quantify emitter uniformity and pressure variation among outlets.

3.3. Measurement performance

The capacitive soil-moisture sensor had a reported mean error of 1.92% compared to the reference procedure. This was considered small in relation to the 20-point hysteresis band and was therefore deemed adequate for making prototype threshold decisions. However, capacitive readings are still sensitive to substrate density, salinity, placement, temperature, and drift. Consequently, calibration in the actual growing medium and fixed probe placement were essential. The absence of calibration-point counts and dispersion measures in the laboratory records limits uncertainty assessment and should be corrected.

The DHT22 and DS18B20 showed mean temperature errors of 0.52 °C and 0.36 °C, respectively. Flow accuracy exceeded 90%, and fertilizer flow error was approximately 1.56%. While these results support low-cost monitoring and volume-terminated dosing, they do not demonstrate long-term stability. Future validation should therefore include repeated calibration across the operating flow range, drift analysis, and uncertainty intervals.

3.4. Closed-loop response and moisture regulation

The system was found to be capable of activating the water pump in less than 2 seconds in response to a drop in soil moisture below a certain threshold, as demonstrated by the actuator response test. Specifically, the pump started working within about 0.8 seconds and stopped working within about 1.2 seconds once the target condition was reached. The effectiveness of the ESP32 control loop, relay switching, and pump activation as a closed-loop control system is demonstrated by this fast response.

The Blynk remote control took about 3.5 seconds to connect. This delay is more protracted than local control because the signal must pass through the Wi-Fi network and cloud server before returning to the device. But this is still fine for irrigation because soil moisture changes slowly and doesn't need to be controlled to the millisecond. The Blynk data refresh time was around 45-60 seconds, with a mean of 52 seconds, which is adequate for real-time farming observation.

In Table 5, groups A and B used 18.5 and 18.3 L of water per polybag, respectively, compared with 25.8 L in the manual group. The mean IoT consumption of 18.4 L corresponds to a 28.7% reduction relative to Group C. The near-identical water use of Groups A and B is consistent with their shared moisture-control logic and suggests that the saving arose primarily from feedback irrigation rather than fertilizer formulation. Group A used 1,950 mL fertilizer per polybag versus 3,150 mL in Group C, a 38.1% reduction; Group B used 2,420 mL. These are delivered-volume comparisons, not nutrient-use-efficiency measurements, because tissue nutrient concentration, leaching, and residual substrate nutrients were not quantified.

Table 5. Water and fertilizer volumes delivered during the 30-day experiment

Group	Irrigation system	Fertilizer	Water use (L/polybag)	Fertilizer use (mL/polybag)
A	IoT automatic	NPK+silica treatment	18.5	1,950
B	IoT automatic	NPK	18.3	2,420
C	Manual	NPK	25.8	3,150

At 30 days after planting, as shown in Table 6, Group A had the greatest mean height (80 cm), leaf number (47), and estimated leaf area (69.3 cm^2), followed by Group B (73 cm, 38 leaves, and 46.1 cm^2), and Group C (55 cm, 22 leaves, and 22.3 cm^2). The common advantage of both IoT groups over manual cultivation is consistent with more stable moisture availability. The additional canopy expansion in Group A is compatible with a formulation effect, but the small sample and absence of replicate-level uncertainty prevent a causal claim. Group B produced the greatest fresh and dry biomass (184 g and 16.01 g), exceeding Group A (153 g and 12.39 g) despite Group A being taller and having more or larger leaves. Several nonexclusive physiological mechanisms could explain this divergence: Group A may have produced thinner leaves or longer, less dense tissues; dry matter may have been partitioned differently among leaves, stems, and roots; the silica-associated nutrient formulation may have released nutrients more slowly or altered nutrient balance during the short 30-day cycle; and larger leaf area does not necessarily translate into greater carbon gain if leaf thickness, photosynthetic rate, or nutrient status is limiting. Because biomass concentration, specific leaf area, tissue nutrients, root mass, and release kinetics were not measured, these explanations remain hypotheses. Practically, the result shows that Group A favored canopy morphology, whereas conventional NPK under the same IoT irrigation produced the highest harvest mass; nano silica dosing therefore requires optimization rather than being described as universally superior.

3.5. Statistical interpretation

While the treatment means demonstrate significant differences in direction, statistical significance cannot be verified based on the information reported in the source manuscript. Therefore, the previous

statements of $p<0.01$ and $p<0.05$ were removed, as no test statistics, degrees of freedom, confidence intervals, standard deviations, or replicate-level observations were available. With only three polybags per treatment, the Shapiro–Wilk and Levene tests also have limited ability to diagnose assumptions. The present results should therefore be regarded as exploratory prototype evidence rather than as confirmatory agronomic inference.

Table 6. Descriptive spinach growth and biomass outcomes at harvest (n=3 polybags per treatment)

Parameter	Group A	Group B	Group C
Plant height at 30 DAP (cm)	80	73	55
Number of leaves	47	38	22
Leaf area (cm²)	69.3	46.1	22.3
Fresh weight (g)	153	184	83
Dry weight (g)	12.39	16.01	7.51

DAP: days after planting. Values are treatment means; replicate-level dispersion and confidence intervals were not available in the source manuscript.

A defensible confirmatory analysis requires the original values for every polybag. The preferred report would present the mean and standard deviation, along with 95% confidence intervals. This would be followed by a one-factor treatment comparison with assumption diagnostics and multiplicity-adjusted post hoc contrasts. However, a permutation or exact nonparametric alternative may be more appropriate if the model assumptions are not credible. Effect sizes should accompany *p*-values. Until this analysis is provided, the evidence only supports engineering feasibility, differences in resource use, and descriptive biological trends.

3.6. Integrated engineering contribution and limitations

A coherent engineering chain was formed by the results: stable threshold decisions were supported by calibrated sensing; rapid switching was prevented by explicit hysteresis; local actuation was made fast relative to soil dynamics; and the delivered volume was made observable by pulse-based dosing. Local control reduced reliance on cloud latency, and the dedicated 168-hour test quantified short-term availability without generalizing to the full 30-day trial. This chain was associated with a 28.7% reduction in water use and improved growth outcomes compared to manual treatment. However, the exact values of the fertilizer schedule, target volume, safety timeout, and pump interlock must be recovered from the deployed firmware for full reproducibility. The trial included one cultivation cycle and one site. It included nine polybags. Silica characterization did not measure particle morphology, nutrient loading, release kinetics, tissue nutrients, or root biomass. Therefore, the findings demonstrate the feasibility of prototype engineering rather than the complete validation of materials or the generalized superiority of agronomy.

4. CONCLUSION

This study successfully developed and evaluated an ESP32-based fertigation prototype. This prototype integrated calibrated soil-moisture and temperature sensing. It also had hysteretic local irrigation control. Event-scheduled and flow-terminated fertilizer delivery was another feature. Relay-driven pumps were also included. The prototype had OLED visualization. Blynk-based supervision was a final feature. The system maintained a mean soil moisture level of 68.5% within the target range of 60–80%, producing a local actuator response of less than 2 seconds. During the 168-hour observation period, the system achieved 97.9% uptime. Reported soil moisture error was 1.92%, DHT22 temperature error was 0.52 °C, and DS18B20 temperature error was 0.36 °C. Flow measurement accuracy exceeded 90%. Compared with manual cultivation, water consumption was reduced by 28.7% by feedback-controlled irrigation, while the delivered fertilizer volume was reduced by 38.1% by Group A. The results show that using feedback control and flow-verified dosing at the local level can enhance the precision, reliability, and efficiency of a fertigation system built with standard embedded hardware.

The plant's response differed depending on the indicator measured. The greatest plant height, leaf number, and leaf area were produced by the silica treatment, whereas the greatest fresh and dry biomass was produced by IoT-controlled conventional NPK. The primary contribution of this study lies in the proposed integrated sensing–control–delivery architecture, rather than demonstrating the superiority of mesoporous silica in all instances of growth or yield indicators. As each treatment contained only three polybags, the results for the plants should be interpreted as exploratory evidence from a prototype-scale experiment. The following should be included in future studies: the morphology of silica particles and the release of nutrients over time should be characterized; reliability should be monitored continuously throughout the cultivation period; backup power and offline data storage should be integrated; the uniformity of flow among emitters should be evaluated; and the experiment should be repeated using more polybags, randomized treatment allocation, and multiple cultivation cycles.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [initials: GP], upon reasonable request.

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