



## IoT-Based Nitrogen, Phosphorus, and Kalium Nutrient Control for Improving Morphological and Physiological Quality of *Brassica rapa L.*

Eko Noerhayati<sup>1\*</sup>, Soraya Norma Mustika<sup>2</sup>, Siti Asmaniyah Mardiyani<sup>3</sup>, Mohamad Jasa Afroni<sup>4</sup>,  
Wahyu Mulyo Utomo<sup>5</sup>, Shipun Anuar Hamzah<sup>5</sup>

<sup>1</sup> Department of Civil Engineering, Universitas Islam Malang, Malang 65144, Indonesia

<sup>2</sup> Faculty of Applied Science and Technology, Universitas Negeri Malang, Malang 65145, Indonesia

<sup>3</sup> Faculty of Agriculture, Universitas Islam Malang, Malang 65144, Indonesia

<sup>4</sup> Department of Electrical Engineering, Universitas Islam Malang, Malang 65145, Indonesia

<sup>5</sup> Department of Electrical Engineering, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat 86400, Malaysia

Corresponding Author Email: [eko.noerhayati@unisma.ac.id](mailto:eko.noerhayati@unisma.ac.id)

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### ABSTRACT

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*IoT-based fertigation, Brassica rapa L., nutrient stability, solar-powered agriculture, precision ecological engineering, sensor drift mitigation, rhizosphere homogenization*

Precision agriculture through Internet of Things (IoT) integration offers a transformative approach to sustainable food production. This study evaluated a solar-powered IoT system designed for automated Nitrogen, Phosphorus, and Kalium (NPK) nutrient control in *Brassica rapa L.* cultivation. Unlike conventional systems, the proposed framework utilized industrial-grade RS485 Modbus sensors to ensure signal stability and minimize sensor drift. Data were analyzed using box-and-whisker plots and mean  $\pm$  standard deviation to assess nutrient distribution homogeneity between inlet and distal nodes. The results demonstrated that the IoT-regulated environment successfully homogenized the rhizosphere, maintaining Nitrogen ( $58.2 \pm 14.12$  mg/kg) and Phosphorus ( $81.67 \pm 19.85$  mg/kg) levels within optimal ranges. This stable resource provision triggered a significant shift in energy allocation, reducing root biomass while enhancing photosynthetic efficiency. Furthermore, the system's energy autonomy and modular design confirm its deployment portability for diverse agricultural scales and remote climates. This research provides a robust framework for precision ecological engineering, demonstrating that biological efficiency can be optimized through intelligent system control rather than input intensification.

## 1. INTRODUCTION

### 1.1 Background

Within the framework of functional food security, crop quality is increasingly gauged not just by yield but by nutritional efficacy. Spinach (*Spinacia oleracea*) is a prime example of a leafy vegetable whose commercial and health value derives from a critical synergy: its morphological vitality must be underpinned by robust biochemical integrity [1, 2]. Therefore, quality assessment now prioritizes internal physiological markers, particularly chlorophyll and ascorbic acid (Vitamin C) content, as these directly determine photosynthetic capacity and nutrient density. These attributes, in turn, are key drivers of consumer preference and market competitiveness [3-5].

Attaining this superior quality profile is fundamentally dependent on the precise management of essential macronutrients—Nitrogen (N), Phosphorus (P), and Potassium (K) [6-8]. Nitrogen acts as the cornerstone for chlorophyll formation and vegetative growth, phosphorus is central to energy metabolism, and potassium governs critical

functions from cellular turgor to post-harvest durability. Prevailing agricultural practice, however, often adheres to fixed application schedules and uniform dosages. This conventional strategy inherently fails to accommodate the dynamic nutrient demands of the crop and the spatial heterogeneity of soil, commonly resulting in inefficient resource use, nutrient leaching, and a destabilized rhizosphere microenvironment. The consequence is a suboptimal phytochemical profile in the harvested crop [9].

This challenge presents a clear opportunity for ecological engineering, which aims to design systems that harmonize agricultural productivity with environmental stewardship. A promising pathway is the adoption of Internet of Things (IoT) technology, which enables a paradigm shift from static management to adaptive, data-driven precision agriculture [10, 11]. Through the integration of in-situ soil sensors, wireless communication networks, and automated delivery mechanisms, IoT platforms facilitate real-time monitoring and responsive fertigation [12, 13]. This approach allows for interventions that are precisely synchronized with the plant's immediate physiological needs. Conceptually, the IoT system functions as an intelligent ecological regulator, actively

maintaining rhizosphere stability and nutrient distribution homogeneity, thereby buffering crops against the stochastic stressors of open-field environments.

The stabilized growing conditions enabled by such a system are theorized to be foundational for consistent, high-quality production. By providing precise nutritional inputs, IoT-driven fertigation supports not only uniform phenotypic traits—such as plant architecture and leaf development—but also the integrity of the core metabolic pathways that synthesize chlorophyll and vital antioxidants like Vitamin C [14, 15]. While the capacity of IoT to improve input efficiency is well-established in the literature, most studies have been limited to technical proofs-of-concept or confined, controlled greenhouse trials.

## 1.2 Research novelty and objectives

A significant gap remains in empirically connecting IoT-mediated Nitrogen, Phosphorus, and Kalium (NPK) fertigation to a holistic, multivariate crop response—encompassing morphological, physiological, and biochemical dimensions—under the variable and often stressful conditions of a tropical open-field ecosystem. This study addresses this gap by evaluating the performance of a novel, solar-powered IoT smart fertigation system designed to optimize the quality of *Spinacia oleracea*. Using a suite of bio-indicators, including plant height, leaf count, chlorophyll content, and Vitamin C concentration, this research aims to generate robust evidence on how such digital integration can enhance agricultural product quality. Ultimately, this work seeks to demonstrate a practical application of ecological engineering principles, contributing to the development of more sustainable and resilient agroecological systems.

## 2. LITERATURE REVIEW

### 2.1 The evolution of precision agriculture through the Internet of Things

A central component of this paradigm is the IoT, which utilizes wireless sensors and communication networks to gather high-accuracy micro-environmental data. Consequently, agronomic decision-making has transitioned from being reactive, based on manual observation, to being data-driven, thereby supporting more efficient resource management [16, 17]. Contemporary literature positions IoT-based systems not merely as automation tools, but as instruments for optimizing agricultural inputs, such as water and nutrients. For instance, research by Noerhayati and Mustika demonstrates the implementation of an IoT-integrated drip irrigation system utilizing soil sensors to enhance water and nutrient use efficiency in lettuce (*Lactuca sativa*). Their findings illustrate how IoT enables the adjustment of irrigation and fertilization schedules based on the plant's actual requirements, directly impacting both crop productivity and quality [18, 19]. IoT is also widely reported to reduce human error in monitoring agronomic parameters—such as soil temperature, moisture, and pH—making cultivation decisions more precise and responsive to environmental fluctuations [10, 20, 21]. This automated, periodic measurement aligns with the needs of farming systems that must adapt to dynamic field microclimates. Furthermore, the implementation of IoT in contexts like urban farming and small-scale agriculture has

gained significance, as spatial and resource limitations demand more efficient and sustainable cultivation systems. Through connected environmental monitoring and centralized data computation, IoT helps maximize the biological efficiency of plants per unit area, a critical aspect in supporting urban food security.

Collectively, the integration of IoT within precision agriculture provides a technological foundation enabling a shift from conventional practices toward more efficient, adaptive, and environmentally considerate cultivation systems [22, 23]. This evolution aligns with the principles of sustainability and resource optimization in modern agriculture.

### 2.2 The dynamics of smart fertigation and specific nutrient management

Building on its role in data acquisition, the IoT has empirically proven capable of mitigating subjectivity and human error in agronomic management. Through integrated smart sensors, edaphic parameters such as soil temperature, moisture, and pH can be monitored via high-resolution telemetry, yielding cultivation decisions that are both precise and adaptive to microclimatic fluctuations. The synchronization of this data into a central system optimizes the biological efficiency per unit area, a fundamental prerequisite for strengthening local food resilience. From a holistic perspective, IoT integration in precision agriculture facilitates a socio-technical transition from conventional methods toward sustainable agroecological systems, where resource optimization is aligned with the principle of minimizing environmental impact [24, 25].

### 2.3 Energy sustainability through off-grid photovoltaic systems

The synergy between renewable energy and smart agricultural architecture is a fundamental prerequisite for decarbonizing the agricultural sector, particularly for digital, IoT-dependent cultivation systems. In such ecosystems, integrating off-grid photovoltaic (PV) systems serves not merely as an alternative power source but as an instrument for achieving energy independence. It ensures the continuous operation of sensors and actuators without reliance on the stability of conventional power grids. Literature by the study [26] affirms that transitioning to solar power within fertigation mechanisms can integrate circular economy principles into nutrient management, where long-term operational cost efficiency aligns with a reduced carbon footprint. In the context of urban farming in regions characterized by microclimatic fluctuations and primary energy infrastructure challenges, such as Indonesia, solar energy utilization provides additional systemic resilience. This approach shifts the paradigm of agricultural technology from a mere productivity tool to an adaptive ecological engineering solution. By leveraging centralized data computation powered by clean energy, smart farming systems can maintain high precision under dynamic environmental conditions [27, 28]. This simultaneously supports local and global Sustainable Development Goals (SDGs).

### 2.4 Physiological response and morphological plasticity in spinach (*Spinacia Oleracea*)

Spinach (*Spinacia oleracea*) is a physiologically sensitive

crop whose growth trajectory and root system architecture are directly influenced by the dynamics of nitrogen (N) availability and soil moisture [29, 30]. In environments with high and consistent resource supply, such as those created by IoT-based precision fertigation, plants exhibit significant morphological plasticity as an adaptation mechanism to microclimatic stability [31].

Referring to the Optimal Partitioning Theory, plants adopt biomass allocation strategies based on the principle of efficiency toward the limiting growth factor [32]. When water and nutrients are abundantly and homogeneously available in the root zone, the plant's need to develop an extensive root system for exploration is reduced [33]. This phenomenon explains why smart fertigation systems often result in lower root mass compared to conventional methods, without compromising above-ground growth traits. In this context, reduced root biomass is not an indicator of nutrient stress but rather a reflection of metabolic optimization. The plant reduces its energetic investment in nutrient-foraging organs and reallocates resources to maximize the function of photosynthetic organs (leaves) [34]. This adaptive strategy demonstrates that precise environmental control can enhance a plant's biological efficiency through a more productive distribution of biomass.

## 2.5 Identification of research gaps

Although discourse on IoT applications in agriculture has accelerated, the majority of literature remains focused on large-scale industrial implementations or rigidly controlled laboratory environments. This has created a disconnect between theory and empirical evidence regarding the performance of IoT systems in dynamic, open-field conditions at small-to-medium scales, particularly in tropical regions. This study identifies three critical research gaps in the current literature:

(1) **Spatial Validation:** Limited data exist on the extent to which nutrient distribution homogeneity and microclimatic stability can be maintained within a single cultivation bed under external environmental fluctuations.

(2) **Morphological Trade-off:** There is a lack of understanding regarding the impact of input efficiency on biomass allocation plasticity, specifically the phenomenon of reduced root biomass in *Brassica rapa L.* under precision fertigation regimes.

(3) **Energy Autonomy:** The effectiveness of off-grid solar systems in ensuring the continuity of real-time soil nutrient (NPK) telemetry for local farmer applications requires further evaluation.

This study aims to address these gaps by evaluating the performance of a solar-powered smart fertigation system through a comparative analysis of agronomic parameters and micro-environmental stability. This approach was expected to provide a significant empirical contribution toward developing a framework for precision agriculture that is adaptive, efficient, and aligned with global sustainability targets in real-world farming ecosystems.

## 3. MATERIALS AND METHODS

### 3.1 Experimental site and system architecture

To empirically address the research gaps identified

earlier—specifically the need for validated performance in dynamic, open-field tropical settings—a field experiment was established in Blimbing, Malang, Indonesia (7°56' S, 112°38' E). Located at an elevation of approximately 460 meters above sea level, the site was chosen to replicate the characteristic microclimatic variability and environmental stressors faced in tropical urban agriculture. Conducting the research within this authentic East Javanese cultivation context ensures that the findings possess direct practical relevance for real-world agroecological implementation.

The study's central technological intervention was a self-contained smart fertigation system, built upon a dedicated IoT architecture. Consistent with the sustainability objectives discussed in the literature review, the system was powered entirely by an off-grid PV array. This renewable energy foundation guarantees continuous sensor operation and automated control, eliminating dependence on the conventional power grid and enhancing the system's resilience and applicability in settings with limited or unstable infrastructure.

The IoT framework was specifically designed to automate irrigation and nutrient (NPK) delivery with high precision, targeting the stabilization of the critical soil-root interface (rhizosphere). *Brassica rapa L.* served as the model crop for this investigation. Its rapid growth cycle and well-documented physiological sensitivity to variations in water and nutrient availability make it an excellent bio-indicator for evaluating the efficacy and responsiveness of the precision fertigation regime.

To critically assess the proposed system's agronomic and ecological benefits, a comparative experimental design was employed, pitting the IoT-driven treatment against conventional cultivation practices. This side-by-side comparison enables a rigorous evaluation of how digital integration modulates both the rhizosphere micro-environment and the subsequent morphological and biochemical response of the crop under naturally fluctuating field conditions.



**Figure 1.** Open-field cultivation of *Brassica rapa L.* at the experimental site in Malang, Indonesia, showing integrated drip irrigation and fertigation infrastructure

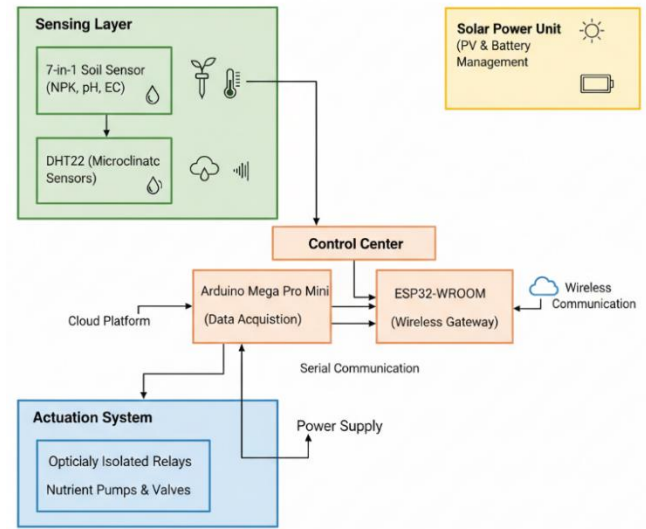
The spatial layout of the experimental setup, as shown in Figure 1, demonstrates the direct integration of an automated distribution network within the open-field environment. This configuration was designed to ensure balanced resource delivery to the ten *Brassica rapa L.* plants in each cultivation bed. By embedding the hydraulic infrastructure directly into

the soil profile, the system maintains a consistent spatial distribution of water and nutrients. This design minimizes localized environmental variability, establishing the controlled baseline required to objectively assess the IoT system's capacity to sustain resource homogeneity—A core theoretical premise outlined earlier in this study.

### 3.2 Hardware architecture and embedded system

The hardware system utilizes a modular dual-controller architecture designed to ensure data integrity and low latency, where an Arduino Mega Pro Mini manages high-frequency sensor sampling while an ESP32-WROOM-32U module serves as a dedicated wireless gateway for cloud data transmission. For environmental monitoring, the system integrates an industrial-grade 7-in-1 soil probe using the RS485 Modbus protocol to measure NPK, pH, EC, temperature, and moisture, supplemented by DHT22, ultrasonic, and flow sensors for microclimate and fluid dynamics tracking. The actuation mechanism employs optically isolated relays and contactors to manage heavy-duty pumps while safeguarding the microcontrollers against inductive voltage spikes. To achieve complete off-grid autonomy, the entire setup was powered by a 200 Wp monocrystalline solar panel regulated by an MPPT charge controller and a 12 V 50 Ah VRLA battery; however, detailed electrical schematics have been moved to the supplementary material to maintain focus on the system's operational logic (Figure 2).

To ensure the reliability of the real-time data acquisition, the performance metrics of the integrated sensors, including their measurement range, accuracy, and observed signal stability during field operation, were summarized in Table 1. These parameters define the precision framework used to maintain optimal nutrient levels throughout the cultivation period.



**Figure 2.** Functional block diagram of the IoT-integrated fertigation control system and power management

**Table 1.** Performance metrics and signal stability of integrated sensors

Sensor Parameter	Measurement Range	Resolution	Manufacturer Accuracy	Observed Signal Deviation (Field)
Soil NPK	0 – 1999 mg/kg	1 mg/kg	± 2.0% F.S	< 1.5%
Soil pH	3 – 9 pH	0.1 pH	± 0.05 pH	± 0.02 pH
Electrical Conductivity (EC)	0 – 10000 µs/cm	1 µs/cm	± 3.0% F.S	< 1.2%
Soil Moisture	0 – 100%	0.1%	± 3% (0-50% range)	± 0.5%
Air Temperature (DHT22)	-40 – 80 °C	0.1 °C	± 0.5 °C	± 0.2 °C
Relative Humidity (DHT22)	0 – 100% RH	0.1% RH	± 2% RH	± 0.8%
Water Level (HC-SR04)	2 – 400 cm	0.3 cm	± 1.0%	± 0.5 cm

### 3.3 Computational logic and control modeling

To execute the automated fertigation accurately, the IoT system's control logic was computationally modeled based on a closed-loop feedback mechanism. The microcontrollers continuously process real-time sensor data variables (denoted as  $S_t$ ) encompassing soil moisture and NPK levels. The computational algorithm evaluates  $S_t$  against predefined optimal agronomic thresholds ( $T_{opt}$ ).

The decision-making process for the actuation layer was governed by a conditional logic matrix. The state of the fertigation water pump ( $P_a$ ) can be mathematically modeled as a discrete function:

$$P_a = \begin{cases} 1(ON), & \text{if } S_t < (T_{opt} - \delta) \\ 0(OFF), & \text{if } S_t \geq T_{opt} \end{cases}$$

where,  $\delta$  represents the hysteresis margin (acceptable error tolerance). The inclusion of this hysteresis parameter in the computational model was critical to prevent hardware oscillation (rapid switching of the relays) when sensor readings fluctuate marginally around the threshold. This logic ensures that the automated system operates with high computational stability and precision before delivering the

physical agricultural outcomes.

## 4. RESULT AND DISCUSSION

### 4.1 Experimental design and data acquisition

The system was deployed in a field-scale *Brassica rapa L.* cultivation bed to evaluate its capability in maintaining environmental homogeneity and nutrient stability. To rigorously test the distribution efficiency of this smart fertigation system, monitoring was conducted using two sensor nodes positioned at opposite extremes: the Inlet (U1) near the primary pump, and the Distal End (U2) at the furthest point. By comparing soil parameters, including pH, temperature, EC, and NPK levels at these two opposite nodes, the study aimed to quantify the IoT system's capacity to prevent spatial imbalances and ensure uniform resource delivery to all plants.

The experimental setup was carefully designed to ensure valid statistical power. This study was conducted in a Completely Randomized Design (CRD) with 2 treatment groups. To ensure reliability, each treatment was replicated 3 times, resulting in a total of 6 independent experimental plots

(beds). Each bed contained 30 *Brassica rapa L.* plants, meaning a total of 180 plants were planted during the study. From each plot, 10 plants were selected as samples for observation of plant growth and yield variables. The reported morphological and physiological values represent statistical averages across replicated plots for each treatment, not from a single bed, thus validating the statistical significance of plant responses to the IoT-based fertigation system.

#### 4.2 Statistical analysis: Spatial uniformity assessment

To determine the statistical significance of the observed data and validate the hypothesis of nutrient distribution uniformity, a one-way analysis of variance (ANOVA) was employed. This statistical framework was utilized to identify whether significant deviations existed between the environmental readings at the inlet (U1) and the distal terminal (U2).

Statistical analysis was performed using a one-way ANOVA based on a CRD. Prior to the analysis, the fundamental assumptions of parametric statistics were tested. Data normality was verified using the Kolmogorov-Smirnov test, while the homogeneity of variance was assessed using Levene's test. Results indicated that all datasets satisfied these assumptions ( $p > 0.05$ ). For variables showing significant differences, a Tukey's HSD post-hoc test was applied at a 95% confidence interval ( $\alpha = 0.05$ ) to evaluate the specific differences between the IoT-integrated and conventional fertigation treatments.

The stability of soil nutrients and environmental parameters was monitored daily to evaluate the system's performance in ensuring resource uniformity. Table 2 presents the statistical summary of the collected data, expressed as mean values  $\pm$  standard deviation (SD), to demonstrate the consistency of the IoT-based fertigation. The results indicate a high degree of correlation between the inlet and distal nodes, with minimal deviations, confirming that the automated control logic successfully maintained nutrient concentrations within the optimal growth range for *Brassica rapa L.*

**Table 2.** Average soil nutrient and environmental stability during the cultivation period

Parameter	Unit	Control Node (Inlet/U1)	Distal Node (End/U2)
Nitrogen (N)	mg/kg	58.23 $\pm$ 14.12	45.42 $\pm$ 11.55
Phosphorus (P)	mg/kg	81.67 $\pm$ 19.85	63.85 $\pm$ 16.24
Potassium (K)	mg/kg	163.54 $\pm$ 39.71	127.85 $\pm$ 32.55
Soil pH	pH	5.34 $\pm$ 0.45	5.28 $\pm$ 0.38
Soil Moisture	%	47.12 $\pm$ 7.23	36.45 $\pm$ 6.88
Electrical Conductivity (EC)	$\mu$ s/cm	821.5 $\pm$ 185.4	645.2 $\pm$ 142.1

By assessing the variance across these critical points, the ANOVA provides a quantitative measure of the system's precision in maintaining a stabilized micro-environment. A summary of the resulting statistical metrics, including the distribution of macronutrients and physical soil parameters, is presented in Table 1.

The statistical analysis provides robust empirical validation of the system's core functionality. As summarized in Table 3, all monitored parameters exhibited no statistically significant variation between the inlet (U1) and distal terminal (U2) of the cultivation bed, with P-values consistently exceeding the 0.05

threshold. This finding, clearly illustrated by the overlapping confidence intervals in Figure 2, confirms that the automated system effectively eliminated the spatial heterogeneity typically inherent in open-field fertigation, establishing a uniform rhizosphere environment across the experimental unit.

**Table 3.** Summary of one-way ANOVA results assessing the spatial homogeneity of edaphic and nutrient parameters between the inlet (U1) and distal (U2) monitoring nodes

Parameter	F-Value	P-Value	Interpretation
Nitrogen (N)	2.13	0.1501	Homogeneous ( $P > 0.05$ )
Phosphorus (P)	2.12	0.1506	Homogeneous ( $P > 0.05$ )
Potassium (K)	2.13	0.15	Homogeneous ( $P > 0.05$ )
Soil pH	0.02	0.9034	Homogeneous ( $P > 0.05$ )
Soil Temperature ( $^{\circ}$ C)	0	0.9793	Homogeneous ( $P > 0.05$ )
Electrical Cond. (EC)	2.15	0.1498	Homogeneous ( $P > 0.05$ )

Note: ANOVA = analysis of variance

#### 4.2.1 Precision in spatial nutrient distribution

The system demonstrated exceptional precision in macronutrient delivery. As detailed in Table 1, concentrations of nitrogen (N), phosphorus (P), and potassium (K) remained consistent along the entire longitudinal axis of the bed, a uniformity graphically depicted in Figure 3. This result was critical, as conventional systems often exhibit a decline in nutrient concentration with distance from the injection point due to factors like sedimentation and pipeline friction losses. The observed homogeneity indicates that the logic-driven control mechanism successfully compensated for these hydraulic dynamics, ensuring equidistant plants received an identical nutrient solution. This precision directly supports the ecological engineering objective of maximizing improved nutrient uptake while preventing the localized stress responses caused by nutrient imbalances.

#### 4.2.2 Homogeneity of soil physicochemical conditions

A parallel uniformity was observed in key soil physicochemical properties. Parameters including pH, temperature, and electrical conductivity (EC) show no significant spatial gradients between the monitored nodes (Table 1). This consistency indicates that the IoT framework effectively regulated the irrigation regime to buffer the rhizosphere against the patchy wet-dry cycles characteristic of manual watering. By ensuring even water distribution, the system maintained a stable and predictable soil environment, which was fundamental for optimal root function and microbial activity.

In synthesis, the data presented in Table 1 move beyond technical validation to demonstrate a substantive agroecological benefit. The IoT-based fertigation system proved to be a fundamental tool for imposing micro-environmental equilibrium. The achieved homogeneity was a prerequisite for synchronized crop development and physiological stability within a cultivation unit, thereby enhancing both yield predictability and the overall resilience of the production system.

### 4.3 Visualization of microclimate homogeneity

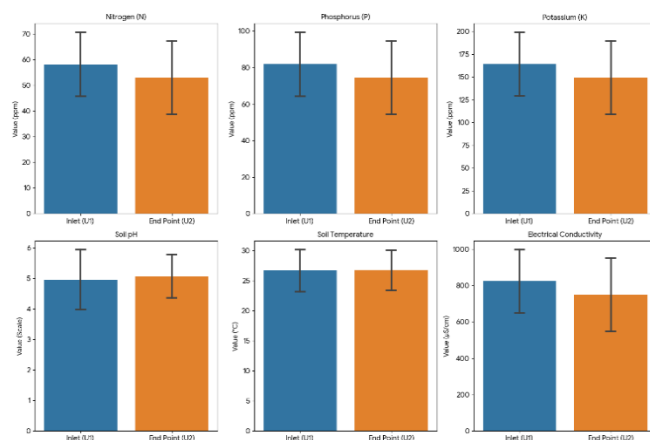
This visualization effectively illustrates the homogeneity achieved by the smart fertigation system across the cultivation bed.

U (N, P, and K) monitored over the 30-day period were visualized in Figure 3 using box-and-whisker plots. This visualization provides a clear statistical comparison between the inlet (U1) and distal node (U2). The data show that the Nitrogen (N) levels at the inlet remained stable with a median of 58.2 mg/kg, while the distal node exhibited a slightly lower but consistent distribution. The narrow interquartile range (IQR) across all parameters confirms the precision of the IoT-based fertigation system in maintaining nutrient homogeneity, which was essential for the uniform growth of *Brassica rapa L.*

### 4.4 Comparative assessment of plant morphological and agronomic responses

To evaluate whether the precision of the IoT system confers tangible agronomic advantages, a comparative assessment of key morphological markers—plant height, leaf count, and root biomass—was conducted against conventional cultivation methods. The statistical summary of these parameters was

provided in Table 4, with visual comparisons presented in Figure 3.

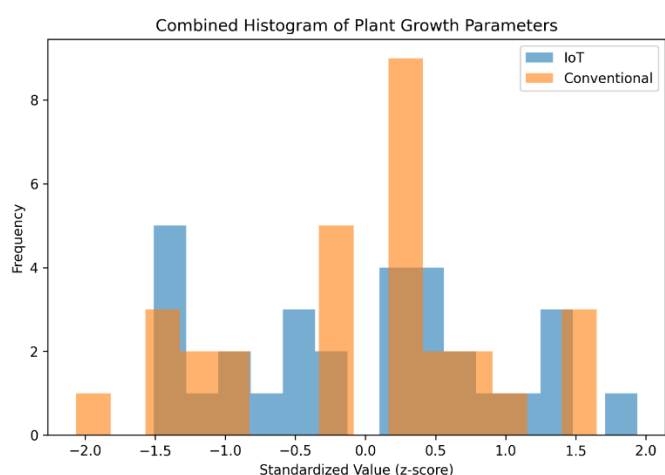


**Figure 3.** Comparative analysis of mean  $\pm$  standard deviation (SD) for six key environmental parameters: Nitrogen (N), Phosphorus (P), Potassium (K), soil pH, soil temperature, and electrical conductivity (EC). Blue bars represent the inlet position (U1), while orange bars represent the end-point position (U2)

**Table 4.** Comparative statistics of plant growth parameters between Internet of Things (IoT)-based and conventional systems

Parameter	IoT (Mean $\pm$ SD)	Conventional (Mean $\pm$ SD)	F-Value	P-Value	Interpretation
Plant height (cm)	9.30 $\pm$ 0.95	9.47 $\pm$ 1.63	0.014	0.907	Not significant
Number of leaves	3.50 $\pm$ 1.08	3.70 $\pm$ 0.95	0.217	0.647	Not significant
Root weight (g)	5.50 $\pm$ 2.34	8.40 $\pm$ 2.88	6.060	0.024	Significant

Conversely, the IoT-based system, by maintaining edaphic stability and a consistent nutrient flux within the rhizosphere, reduces the metabolic cost of resource acquisition. The reliable input regime diminishes the plant's need to invest in extensive root architecture for survival, resulting in the observed leaner root system. The IoT system thus achieves equivalent above-ground growth with a more efficient, economically streamlined physiological structure.



**Figure 4.** Standardized (z-score) frequency distribution of growth parameters for IoT and conventional systems

The distribution of growth data was further analyzed using z-score normalized histograms (Figure 4). The pronounced overlap between the distributions for both systems indicates

that the observed morphological variation resides primarily within the bounds of natural biological plasticity. Crucially, the absence of distributional extremes confirms that the significant root biomass difference was a targeted adaptive response to the IoT system's stable environment, not an artifact of systemic instability or error.

In synthesis, this integrated morphological analysis confirms that the IoT framework successfully engineers a growth environment where plant development is governed by precision and metabolic efficiency, rather than by stress-driven resource exploration. This shift was fundamental to advancing sustainable, high-efficiency agroecological systems.

### 4.5 Physiological characterization and phytochemical integrity

Building on the morphological assessment, this analysis examines the internal physiological status and nutritional quality of the *Brassica rapa L.* crop to determine if the IoT system's environmental stability translates into enhanced metabolic health and preserved phytochemical integrity.

#### 4.5.1 Photosynthetic efficiency and chlorophyll density

The efficiency of the photosynthetic apparatus was gauged through spectral absorbance measurements, with key results detailed in Table 5.

The data reveal a consistent trend: plants under the IoT system exhibited higher absorbance values at the critical wavelengths of 663 nm and 665 nm across both diluted and undiluted samples. These spectral signatures were primary indicators of Chlorophyll \*a\*, the central pigment in the light-

harvesting complex. Although the number of biological replicates limited formal statistical inference, this observational trend suggests that the IoT-managed plants maintained a more robust concentration of key photosynthetic pigments.

**Table 5.** Spectral absorbance analysis of chlorophyll content: (a) Diluted and (b) undiluted extracts

Treatment	470 nm	645 nm	652 nm	663 nm	665 nm
IoT (a)	0.281	0.115	0.153	0.272	0.283
Conventional (a)	0.251	0.097	0.125	0.214	0.222
IoT(b)	2.124	0.790	1.083	2.973	2.044
Conventional (b)	2.501	0.939	1.280	2.277	2.345

From an ecophysiological perspective, this stability can be attributed to the minimized environmental stress afforded by the autonomous control system. By stabilizing rhizosphere moisture and temperature—as quantitatively demonstrated in Section 4.3—the IoT system likely mitigates the thermal and osmotic degradation of chlorophyll that commonly occurs under the fluctuating conditions of conventional management. Consequently, the framework supports sustained photosynthetic efficiency by maintaining a consistent micro-environment, allowing the plant's primary metabolism to operate within an optimal, non-stressed range.

#### 4.5.2 Nutritional quality: Vitamin C content

The nutritional value of the harvest was assessed by quantifying ascorbic acid (Vitamin C) content, with results summarized in Table 6.

**Table 6.** Comparative Vitamin C content analysis (mg/100 g fresh weight)

Treatment	Replication 1	Replication 2	Mean
IoT	0.40	0.40	0.40
Conventional	0.40	0.40	0.40

The analysis demonstrates parity in Vitamin C levels between the two cultivation regimes (0.40 mg/100 g). This finding was significant for the broader adoption of precision agricultural technologies, as it confirms that the operational efficiencies and resource conservation achieved through IoT automation do not compromise the nutritional density of the crop.

#### 4.6 Deployment portability and system scalability

The modular architecture of the proposed IoT system ensures high portability across various agricultural contexts. While this study focuses on *Brassica rapa L.*, the system's control logic can be easily recalibrated for other leafy greens or high-value crops by adjusting the nutrient set-points in the firmware. From a scalability perspective, the use of the RS485 Modbus protocol allows for the integration of up to 247 sensor nodes over long distances (up to 1,200 meters), making it suitable for large-scale greenhouse operations. Furthermore, the solar-powered energy harvesting unit provides the necessary autonomy for deployment in remote regions with limited grid access, ensuring adaptability to diverse climates and geographical locations.

#### 4.7 Synthesis and implications for ecological engineering

Collectively, these physiological and phytochemical results validate the proposed IoT-based approach within a sustainable food systems framework. The system successfully harmonizes high-precision resource management with the production of nutritionally stable, high-quality produce. By ensuring that both photosynthetic efficacy and key phytochemical profiles were maintained—or even enhanced—the technology proves to be a viable ecological engineering solution. It supports the dual objectives of optimizing the ecological footprint of intensive cultivation while safeguarding the dietary standards required for functional food security.

#### 4.8 Synthesis: Ecological implications of precision farming

The synthesis of empirical findings from environmental data (Sections 4.1–4.4) and plant physiological responses (Sections 4.5–4.6) converges on a central conclusion: the IoT framework acts as a transformative tool for engineering sustainable agroecosystems. The system demonstrably created a homogenized rhizosphere, characterized by uniform nutrient distribution and stable microclimatic conditions, which in turn elicited a distinct, efficiency-oriented plant phenotype.

##### 4.8.1 Uniform physiological response and biomass partitioning

The stable environment engineered by the IoT system precipitated a fundamental shift in the *Brassica rapa L.* crop's energy allocation strategy. The significant reduction in root biomass, juxtaposed with maintained or enhanced chlorophyll density, signals a transition from a stress-adapted “resource foraging” phenotype to one optimized for “metabolic efficiency.” In conventional systems, plants invest substantial energy in extensive root architectures as a risk mitigation strategy against fluctuating resource availability. The precision and reliability of the IoT-regulated fertigation regime lower the metabolic cost of resource acquisition. This reallocation of energy from defensive root expansion to the maintenance of photosynthetic machinery and above-ground productivity exemplifies a core principle of ecological engineering: enhancing system output by optimizing internal resource flows rather than maximizing external inputs.

##### 4.8.2 Energy autonomy and system-wide sustainability

The agronomic benefits were underpinned by a design that addresses systemic sustainability. The off-grid, PV-powered architecture (Section 3.3) ensures operational resilience and decouples precision agriculture from fossil-fuel-dependent infrastructure. This energy autonomy not only reduces the carbon footprint of production but also enhances the system's applicability in remote or resource-constrained settings, a critical factor for decentralized food security. It embodies the integration of technological innovation with ecological principles, moving beyond simple automation to create a self-sustaining cultivation node.

##### 4.8.3 A framework for precision ecological engineering

Collectively, this study demonstrates a practical model for precision ecological engineering in agriculture. The IoT system functions as a dynamic regulator, continuously aligning edaphic inputs with plant physiological demand. This closed-loop management harmonizes crop growth with resource provision, minimizing waste and environmental

stress. The result was a production system that achieves biological efficiency and product quality not through input intensification, but through intelligent system design and control.

In conclusion, the integration of solar-powered IoT infrastructure represents a substantive advance in sustainable cultivation. It forges a synergistic link between technological precision, renewable energy, and plant ecophysiology. This approach charts a viable pathway for contemporary agriculture, where productivity and nutritional quality are sustained by engineered system intelligence and precise water and nutrient delivery, ultimately reducing the ecological footprint of food production.

## 5. CONCLUSION

This study demonstrates the transformative role of a solar-powered IoT precision fertigation system in engineering edaphic homeostasis within the crop root zone. The integration of industrial-grade sensing with autonomous control logic effectively neutralized the spatial variability of key environmental parameters—NPK macronutrients, pH, temperature, and EC—creating a uniform rhizosphere environment for *Brassica rapa* L. This technical achievement ensured resource distribution was rendered independent of physical distance from the irrigation source, effectively eliminating the "edge effect" common in conventional systems.

A central contribution of this work was the empirical elucidation of how precision management optimizes plant resource allocation. The IoT system sustained above-ground vegetative growth (plant height, leaf number) at parity with conventional methods while inducing a significant reduction in root biomass. This phenotypic shift signals a fundamental transition in metabolic strategy: by providing a stable and readily accessible nutrient flux, the system minimizes the metabolic cost of resource foraging. Plant energy was consequently re-partitioned from stress-driven root exploration to the maintenance of photosynthetic efficiency and physiological stability, exemplifying a core principle of ecological engineering—enhancing output through optimized internal processes rather than increased external input.

The sustained stability of chlorophyll content and the parity in Vitamin C levels confirm that the phytochemical integrity and nutritional value of the produce were preserved. Therefore, the system successfully reconciles operational efficiency with the production of high-quality functional food.

Ultimately, this research repositions IoT technology from a passive monitoring tool to an active instrument of ecological engineering. By synergizing micro-environmental precision with renewable energy autonomy, the system provides a robust, scalable model for sustainable agriculture. It offers a viable pathway for tropical cultivation systems to enhance productivity and resilience through intelligent resource management, aligning technological innovation with the imperative of ecological sustainability.

Furthermore, the modular architecture of the developed IoT system ensures high deployment portability and scalability. Because the smart fertigation logic relies on customizable algorithmic parameters, the system can be easily adapted to cultivate other crops simply by modifying the target NPK thresholds and soil moisture values within the microcontroller's program. For larger-scale agricultural

applications, the utilization of the RS485 Modbus protocol allows for seamless expansion; multiple sensor nodes can be daisy-chained and integrated across extensive fields without necessitating significant changes to the core primary controller. Additionally, the robust, off-grid PV power supply guarantees that this automated setup can be deployed reliably in diverse geographical locations and climates, ranging from controlled urban greenhouses to remote rural farms lacking conventional grid infrastructure.

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## NOMENCLATURE

N	Nitrogen concentration (mg/kg)
P	Phosphorus concentration (mg/kg)
K	Potassium concentration (mg/kg)
pH	Potential of Hydrogen (acidity/alkalinity level)
EC	Electrical Conductivity ( $\mu\text{s}/\text{cm}$ )
V	Voltage (Volt)
I	Current (Ampere)
P	Power (Watt)
T	Soil Temperature ( $^{\circ}\text{C}$ )

RH Soil Relative Humidity (%)

## Greek symbols

$R^2$  Coefficient of Determination  
 $\mu$  Mean (Average) value

## Subscripts

*inlet* Measurement at the water/nutrient entry point (U1)  
*distal* Measurement at the furthest point from the source (U2)  
*soil* Parameter related to soil condition  
*target* Desired set-point for nutrient concentration  
*max* Maximum recorded value  
*min* Minimum recorded value  
*avg* Average or mean value