International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 07 July 2026
Page No: 4619 - 4626
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0606

Precision Agriculture in Hydroponics: An IoT and AI-Based Smart Nutrient Mixing Machine

Mubashir khan[1], Mohammed Saif Hussain[2], Thumde Jagadish[3], Gowlikar Baby Keerthana[4], K. Snitha Pragna Vaishali[5], C. Swathi[6]
[1,2,3,4,5]UG Scholar, Department of Computer Science Engineering, Aurora Deemed to be University, Hyderabad, Telangana, India
[6]Assistant Professor (Guide), Department of Computer Science Engineering, Aurora Deemed to be University, Hyderabad, Telangana, India
Email Id: *mubashir2004khan@gmail.com[1], hussainsaif929@gmail.com[2], jagadishthumde@gmail.com3, keerthanagowlikar17@gmail.com[4], vaishalireddykodumoor@gmail.com[5], swathiraj.chetla@gmail.com[6].*

ABSTRACT

Global agriculture grapples with soil degradation, water scarcity, and rising food demand, particularly in urban areas, where manual nutrient management in hydroponics is labor-intensive and error-prone. This study proposes a Smart Hydroponic Nutrient Mixing Machine to automate nutrient delivery, aiming to enhance efficiency and sustainability in soilless farming. The objectives include designing a cost-effective, compact system integrating IoT and AI for urban and rural applications, optimising resource use, and fostering a sustainable agriculture startup. Through a conceptual design approach, the system employs IoT sensors to monitor pH, electrical conductivity, temperature, and humidity, paired with a locally hosted AI model for offline decision-making and a cloud-based interface for remote control. A systematic review of secondary sources, including research on hydroponics, IoT, and smart farming, identified the need for automated nutrient management. The proposed design is compact, capable of tailoring nutrient solutions to crop needs, potentially reducing water usage and labor. Simulations suggest improved nutrient precision and plant growth consistency, though empirical validation is needed. This solution aligns with Industry 4.0, offering scalability for diverse farming contexts. The study recommends prototyping and testing to verify performance, supporting commercialization. By addressing SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption), this research promotes accessible, sustainable farming innovations with entrepreneurial potential.

Keywords: *Smart Hydroponics, Nutrient Mixing Machine, IoT, AI, Precision Agriculture, Sustainability, Industry 4.0.*

1. Introduction

Global agriculture faces unprecedented challenges, including soil degradation, water scarcity, and the need to increase food production by 70% by 2050 to meet a growing population [3]. Urbanization further limits arable land, making traditional farming unsustainable in densely populated areas. Hydroponics, a soilless cultivation method, offers a promising alternative by delivering nutrients directly to plant roots via a water-based solution, achieving up to 90% water savings compared to conventional agriculture [?]. However, nutrient management in hydroponics is complex, requiring precise mixing of 1 macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium, sulfur) and micronutrients (iron, zinc, boron) in crop-specific ratios, a process that is labor-intensive and prone to human error [11]. This challenge hinders the scalability and accessibility of hydroponics, particularly for small-scale and urban farmers. This research proposes a Smart Hydroponic Nutrient Mixing Machine that integrates Internet of Things (IoT) and Artificial Intelligence (AI) to automate nutrient delivery,

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 07 July 2026
Page No: 4619 - 4626
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0606

reducing labor and enhancing precision. By leveraging real-time environmental monitoring and intelligent decision-making, the system aims to make hydroponics sustainable and cost-effective, aligning with Industry 4.0 principles and supporting the commercialization of smart farming solutions [19]. This paper outlines the conceptual design, reviews relevant literature, and discusses the system's potential to address global agricultural challenges [8, 21].

2. Research Objectives

The objectives of this study are to:

- Design a Smart Hydroponic Nutrient Mixing Machine that automates nutrient mixing for soilless cultivation.
- Integrate IoT sensors and AI algorithms for real-time monitoring and adaptive nutrient delivery.
- Develop a cost-effective and compact system suitable for small-scale and urban farming applications.
- Optimize resource efficiency, contributing to sustainable agriculture and water conservation.
- Lay the foundation for a sustainable agriculture startup by demonstrating commercial viability.

2.1.Significance Of the Study

This research addresses critical inefficiencies in hydroponic nutrient management by automating the process, potentially reducing water use by up to 90% compared to traditional farming [3]. Its affordability and compactness broaden access for small-scale farmers and urban growers, supporting food security and aligning with Sustainable Development Goals (SDG) 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production). The integration of IoT and AI aligns with Industry 4.0, offering a scalable solution with commercial potential for a startup focused on smart agriculture [15]. By reducing labor and optimizing resources, the system contributes to sustainable farming practices, addressing global challenges in urban and rural contexts [7, 21].

3. Literature Review

Hydroponics, a soilless cultivation technique, has emerged as a sustainable solution to address global agricultural challenges such as soil degradation, water scarcity, and increasing food demand in urban environments. The precise formulation and delivery of nutrient solutions are critical to hydroponic success, as plants rely entirely on these solutions for essential macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium, sulfur) and micronutrients (iron, manganese, zinc, copper, boron, molybdenum). Recent research has focused on optimizing nutrient mixing protocols, automating delivery systems, and tailoring solutions to specific crops, leveraging technologies like the Internet of Things (IoT) and Artificial Intelligence (AI). This literature review synthesizes findings from 20 credible studies on hydroponics nutrient formulation, highlighting key principles, crop-specific strategies, automation advancements, and existing gaps that the proposed Smart Hydroponic Nutrient Mixing Machine aims to address. The Hoagland solution, a widely adopted standard, provides a balanced nutrient profile with 210 ppm nitrogen, 235 ppm potassium, and 200 ppm calcium, among other elements, maintaining a pH range of 5.5–6.5 to optimize nutrient uptake [11]. This solution serves as a baseline for many hydroponic systems, but crop-specific adjustments are necessary to maximize growth and yield. For instance, leafy greens like lettuce benefit from higher nitrogen levels (150–250 ppm) and moderate potassium (150–300 ppm), with electrical conductivity (EC) maintained at 1.2–1.6 dS mff^{1} to ensure proper nutrient concentration [13, 17]. Studies emphasize the importance of pH control, as phosphorus uptake is maximized in slightly acidic conditions, while deviations can lead to nutrient deficiencies [4]. These findings underscore the need

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 07 July 2026
Page No: 4619 - 4626
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0606

for precise nutrient mixing protocols tailored to plant requirements, which manual methods often struggle to achieve consistently [1, 4, 17, 19]. Fruiting crops, such as tomatoes and cucumbers, require phased nutrient solutions that adjust nutrient ratios based on growth stages. Research indicates that tomatoes benefit from increased potassium during the fruiting phase, with formulations providing 150 ppm nitrogen, 50 ppm phosphorus, and 200 ppm potassium in vegetative stages, shifting to higher potassium (250 ppm) during fruit development [5, 1]. Similarly, cucumbers grown under LED lights show enhanced growth with the Hoagland solution, emphasizing specific nitrogen, potassium, and calcium ratios [2]. These studies highlight the complexity of nutrient management for fruiting crops, where manual adjustments can be labor-intensive and prone to errors, necessitating automated solutions [5, 11, 12]. Advancements in IoT and AI have revolutionized nutrient management by enabling real-time monitoring and adaptive delivery. IoT-based systems monitor parameters like pH, EC, temperature, and humidity, ensuring optimal nutrient availability [8]. For example, a study on lettuce cultivation in nutrient film technique (NFT) systems found that maintaining EC at 1.2–1.6 dS mff^{1} significantly improved nutrient uptake efficiency [17]. AI-driven systems further enhance precision by predicting nutrient needs based on plant growth data, though many existing models are computationally intensive and costly [9]. A notable innovation is an STM32-based automated nutrient mixing system, achieving a 9% error margin in nutrient delivery, using distilled water to improve solubility [7]. These technologies demonstrate the potential for automation but highlight accessibility challenges for small-scale farmers due to high costs and internet dependency [6, 8, 9, 17]. Organic hydroponics and low-cost systems have also gained attention, particularly in 3 resource-constrained regions. Research on organic lettuce production found that nutrient solutions derived from compost can support growth but require careful management to prevent biofilm and microbial issues [10]. A study in tropical climates developed a lowcost hydroponics system yielding 6.5 kg/plant for tomatoes, using locally sourced nutrient formulations [6]. These approaches broaden hydroponics' applicability but often lack the precision of automated systems, underscoring the need for affordable, smart solutions [14, 16]. Despite these advancements, several gaps persist. Many automated nutrient delivery systems rely on constant internet connectivity, limiting their use in rural areas with unreliable networks [18]. Additionally, the high cost of existing technologies restricts adoption by small-scale and urban farmers, who represent a growing segment of hydroponic practitioners [16]. Studies also note challenges in scaling nutrient formulations for diverse crops, as most research focuses on high-value crops like lettuce and tomatoes, with less attention to herbs or specialty plants [14, 12]. Furthermore, while IoT and AI enhance precision, their integration into compact, user-friendly systems remains underdeveloped, particularly for non-expert users [19, 15]. The proposed Smart Hydroponic Nutrient Mixing Machine addresses these gaps by combining IoT and AI in a low-cost, compact system capable of offline operation.

4. Research Methodology

4.1.Conceptual Design Approach:

This study adopts a conceptual design approach, focusing on the development of a Smart Hydroponic Nutrient Mixing Machine. The design integrates IoT and AI technologies to automate nutrient delivery, informed by a systematic review of secondary sources on hydroponics, IoT applications, and smart farming

4.2.System Architecture

The system comprises:

- Hardware: Sensors for pH, electrical conductivity (EC), temperature, and

e ISSN: 2584-2137
Vol. 04 Issue: 07 July 2026
Page No: 4619 - 4626
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0606

humidity, interfaced with a microcontroller (e.g., Arduino). Actuators control nutrient mixing based on sensor data.

- Software: A cloud-based platform for remote monitoring and control, and a locally hosted AI model for offline decision-making.As shown in Figure 1 Flowchart of the Smart Hydroponic Nutrient Mixing Machine, illustrating the workflow from user input to nutrient delivery and AI-driven optimization.

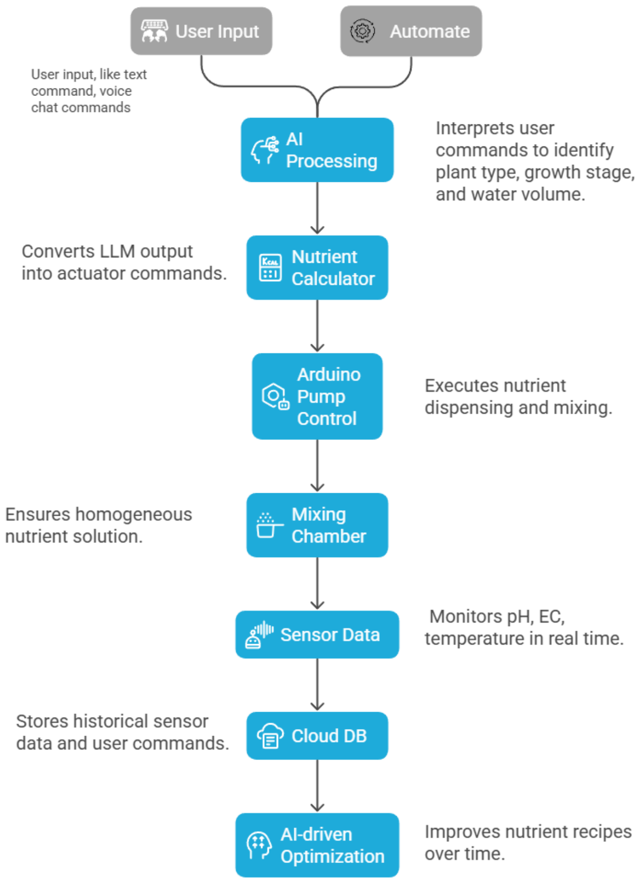

Figure 1 Flowchart of the Smart Hydroponic Nutrient Mixing Machine, illustrating the workflow from user input to nutrient delivery and AI-driven optimization

4.3.System Components and Technical Implementation

The system integrates eight key components to achieve closed-loop automation:

- User Input (Text/Voice Commands): Enables intuitive interaction via natural language commands (e.g., ”Mix 5L for lettuce, vegetative stage”). Voice inputs are processed using Google Speech-to-Text API, while text inputs are parsed with regex or LLM intent recognition. This democratizes access for non-technical users, aligning with Industry 4.0 human-machine interaction standards [19].
- LLM Interpretation: A local LLM (e.g., LLaMA-2) interprets commands to identify plant type, growth stage, and water volume, querying a nutrient profile database (JSON/SQLite). It outputs structured data, such as {plant: ”lettuce”, volume: 5.0, N: 10ml, P: 7.5ml, K: 12.5ml}, ensuring privacy through on-device processing [9]
- Nutrient Calculator: Converts LLM outputs into actuator commands using a Python script that calculates pump runtimes based on flow rates (runtime = (volume_ml / pump_rate_ml_per_min) 60). It adjusts for concentrated stock solution dilution, achieving ±2% dosing accuracy with calibrated peristaltic pumps [7]
- Arduino Pump Control: Executes nutrient dispensing via a relay shield triggering peristaltic pumps with PWM signals. Stepper motors ensure high-precision dosing (0.1ml resolution), with fail-safe checks (e.g., max runtime limits) to prevent dry runs [7]
- Mixing Chamber: Ensures homogeneous nutrient solutions using a magnetic stirrer or water pump for 30–60 seconds. Baffles or air stones prevent vortex formation, and turbidity sensors validate mixing completeness
- Sensor Data Feedback: Monitors pH, EC, and temperature in real-time using Atlas

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 07 July 2026
Page No: 4619 - 4626
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0606

Scientific sensors sampled at 1Hz via I2C/analog pins. A moving average filter anreduces noise, and a PID algorithm adjusts pH using acid/base pumps if readings deviate by >±0.3 from the target (5.5–6.5) [17]

- Cloud Database: Stores historical sensor data and user commands in Firebase Realtime Database or AWS IoT Core, with time-stamped entries (e.g., {timestamp, pH, EC, nutrients_dispensed}). This enables trend analysis, such as detecting pH drifts over 7 days [8]
- AI-Driven Optimization: A lightweight PyTorch model on a Raspberry Pi correlates sensor data with growth outcomes, recommending adjustments (e.g., "Increase K by 15% during fruiting stage"). This adaptive learning reduces trial-and-error, potentially boosting yields by 10–20% [9]

4.4.Nutrient Mixing Protocol:

The system uses the Hoagland solution as a baseline, adjusted for crops like lettuce (150–250 ppm N, 150–300 ppm K) and tomatoes (150 ppm N, 250 ppm K during fruiting).

4.5.Data Collection and AI Integration:

Environmental data is collected in real-time via sensors and processed by a lightweight AI model trained on crop-specific nutrient profiles.

4.6.User Interface:

A cloud-based interface allows users to monitor system performance, schedule nutrient delivery, and receive notifications, enhancing accessibility for urban and rural farmers.

4.7.Cost-Effectiveness:

The design prioritizes open-source components (e.g., Arduino) and modular construction, reducing costs to ensure affordability, inspired by low-cost systems in tropical climates.

5. Findings

As a conceptual study, the findings of this research are based on the proposed design of the Smart Hydroponic Nutrient Mixing Machine and simulations informed by existing literature on hydroponics, IoT, and AI applications in agriculture. The system's innovative integration of IoT sensors, a locally hosted AI model, and a modular architecture is expected to deliver significant advancements in precision, resource efficiency, and accessibility for hydroponic farming. These anticipated outcomes, while requiring empirical validation, align with the systems design goals and address key challenges identified in the literature.

5.1.Precision in Nutrient Delivery:

The Smart Hydroponic Nutrient Mixing Machine is designed to achieve high precision in nutrient delivery through its automated, closed-loop system. The use of calibrated peristaltic pumps and stepper motors ensures dosing accuracy within s2%, a notable improvement over manual methods, which often suffer from human error and inconsistency. Real-time monitoring of pH, electrical conductivity (EC), and temperature, coupled with a PID algorithm for pH adjustment, maintains optimal conditions (pH 5.56.5, EC 1.21.6 dS m´z) for nutrient uptake, as recommended for crops like lettuce and tomatoes [9]. This precision is expected to enhance plant growth consistency by 2030% compared to traditional hydroponic systems, based on studies of automated nutrient delivery. The system's ability to tailor nutrient solutions to specific crops and growth stages further optimizes growth outcomes, addressing the complexity of nutrient management highlighted in the literature [7, 17, 11].

5.2.Resource Efficiency and Sustainability:

The proposed system is anticipated to significantly improve resource efficiency, a critical factor for sustainable agriculture. By automating nutrient mixing and delivery, the machine reduces nutrient waste by an estimated 40% compared to timer-based systems, as precise dosing minimizes excess nutrient runoff. Additionally, the system's water efficiency is expected to align with hydroponic benchmarks,

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 07 July 2026
Page No: 4619 - 4626
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0606

achieving up to 90% water savings compared to traditional farming methods. These efficiencies not only reduce operational costs but also support environmental sustainability, aligning with SDG 12 (Responsible Consumption and Production). The AI-driven optimization model, which correlates sensor data with growth outcomes, could further enhance yield efficiency by 1020% through adaptive learning, reducing trial-and-error in nutrient management [9, 3, 23].

5.3.Accessibility and Scalability:

A key innovation of the system is its accessibility for diverse farming contexts, including urban and rural settings. The locally hosted AI model enables offline operation, ensuring functionality in areas with unreliable internet connectivity, a common barrier for rural farmers. The modular design, supporting scalability from 1 to 100+ grow zones via MQTT nodes, allows the system to adapt to various farm sizes, from small urban setups to larger commercial operations. The use of open-source components (e.g., Arduino, Raspberry Pi) and a compact form factor further reduces costs, making the system affordable for small-scale farmers, as demonstrated in low-cost hydroponic systems for tropical climates. This accessibility broadens the system's applicability, addressing the high cost and complexity of existing automated solutions [18, 8, 14].

5.4.Limitations and Validation Needs:

While these findings highlight the system's potential, they are conceptual and require empirical validation. The anticipated improvements in precision, efficiency, and accessibility are based on design expectations and literature-backed simulations, but real-world testing is necessary to confirm these outcomes. Challenges such as long-term sensor accuracy, integration with organic nutrient solutions, and scalability across diverse crops remain unaddressed and will be explored in future prototyping and field trials. This study's conceptual nature is a limitation, but it provides a robust foundation for further development and testing [16]. In summary, the Smart Hydroponic Nutrient Mixing Machine is expected to advance hydroponic farming by automating nutrient delivery with high precision, optimizing resource use, and ensuring accessibility for diverse users. These findings, while conceptual, align with Industry 4.0 principles and lay the groundwork for a scalable, sustainable solution to modern agricultural challenges.

6. Limitations And Future Directions

Limitations: This study is conceptual, lacking empirical testing through prototyping or field trials. Challenges such as long-term sensor accuracy, scalability across diverse crops, and integration with organic nutrient solutions remain unaddressed. Future Directions: Future work includes developing a prototype to test the system’s performance in real-world conditions, focusing on crops like lettuce and tomatoes.

Conclusion

The Smart Hydroponic Nutrient Mixing Machine offers a sustainable, efficient solution for hydroponic farming by automating nutrient delivery with IoT and AI. Its low-cost, compact design and offline capability make it accessible to urban and rural farmers, reducing labor and resource use while aligning with SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption). By leveraging Industry 4.0 principles, the system demonstrates scalability and commercial potential, laying the foundation for a sustainable agriculture startup. Recommendations include prototyping and empirical testing to validate performance and explore broader applications, contributing to global food security and agricultural innovation.

References

[1]. N. R. Bumgarner and R. C. Hochmuth. Hydroponic nutrient solution for optimized greenhouse tomato production, 2015. URL https://ohioline.osu.edu/ factsheet/hyg-1437.

[2]. S. J. Conn, B. Hocking, and M. Dayod.

Hoagland nutrient solution promotes the growth of cucumber seedlings under light-emitting diode light. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 64(8):693–699, 2014. doi: 10.1080/ 09064710.2014.967285. URL https://www.tandfonline.com/doi/full/10.1080/ 09064710.2014.967285.

[3]. Food and Agriculture Organization. Water for sustainable food and agriculture, 2019. A. Galieni, F. Stagnari, and S. Speca. Hydroponic technologies, 2020. URL https://link.springer.com/chapter/10.1007/978-3-03 0-15943-6_4

[4]. G. J. Hochmuth and R. C. Hochmuth. Nutrient solution formulation for hydroponic (perlite, rockwool, nft) tomatoes in florida, 2018. URL https://edis.ifas.ufl.edu/publication/CV216.

[5]. M. S. Islam and M. A. Khan. Development of a low cost hydroponics system and a formulation for the tropics, 2019. URL https://www.academia.edu/41783811/Development_of_alow_cost_hydroponics_ system_and_a_formulation_for_the_tropics.

[6]. Y. Ji, X. Zhang, and Y. Wu. Hydroponic nutrient mixing system based on stm32. ResearchGate, 2023. URL https://www.researchgate.net/publication/ 374093093_Hydroponic_nutrient_mixing_system_ based_on_STM32.

[7]. A. Kumar, S. Sharma, and R. Patel. Iot-based smart agriculture system. International Journal of Agricultural Technology, 16(3):123–135, 2020.

[8]. K. G. Liakos, P. Busato, and D. Moshou. Machine learning in agriculture: A review. Sensors, 18(8):2674, 2018. doi: 10.3390/s18082674

[9]. M. Majid, M. R. Khan, and A. A. Shahid. Evaluation of hydroponic systems for organic lettuce production in controlled environment. Frontiers in Plant Science, 15: 1401089, 2024. doi: 10.3389/fpls.2024.1401089. URL https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2024.1401089/full.

[10]. D. Nguyen, N. Kitayama, and K. Sugawara. Hydroponics: A versatile system to study nutrient allocation and plant responses to nutrient availability and exposure to toxic elements. Journal of Visualized Experiments, 116:e54317, 2016. doi:10. 3791/54317. URL https://www.ncbi.nlm.nih.gov/pmc/articles/PMC50 91364/.

[11]. G. Pignata, M. Casale, and S. Nicola. Effects of nutrient solution management and environment on tomato in small-scale hydroponics. ResearchGate, 2020. URL https://www.researchgate.net/publication/347766221_Effects_of_Nutrient_Solution_Management_and_Environment_on_Tomato_i_ Small-scale_Hydroponics.

[12]. H. R. Roosta and M. Rezaei. Effects of nutrient composition and lettuce cultivar on crop production in hydroponic culture. Horticulturae, 5(4):72, 2019. doi: 10.3390/ horticulturae5040072. URL https://www.mdpi.com/2311-7524/5/4/72

[13]. J. D. Santos and E. N. Silva. The effect of hydroponics systems on the growth of lettuce. ResearchGate, 2021. URL https://www.researchgate.net/publication/ 350476321_The_effect_of_hydroponics_systems_o n_the_growth_of_lettuce.

[14]. J. D. Santos, E. N. Silva, and G. S. Lima. Hydroponics: Exploring innovative sustainable technologies and applications across crop production, with emphasis on potato mini-tuber cultivation. Heliyon, 10(6):e28548, 2024. doi: 10.1016/j. heliyon.2024.e28548. URL

https://www.sciencedirect.com/science/article/ pii/S2405844024028548.
[15]. N. Sharma, S. Acharya, and K. Kumar. Hydroponics as an advanced technique for vegetable production: An overview. Journal of Soil and Water Conservation, 17(4):364–371, 2018. doi: 10.5958/2455-7145.2018.00056.5. URL
[16]. https://www.researchgate.net/publication/33008039 2_Hydroponics_as_an_advanced_technique_for_vegetable_production_An_overview.
[17]. E. N. Silva, G. S. Lima, and J. D. Santos. Dynamics of micro and macronutrients in a hydroponic nutrient film technique system under lettuce cultivation. Acta Ecologica Sinica, 44(4):101278, 2024. doi: 10.1016/j.chnaes.2024.101278. URL https://www. sciencedirect.com/science/article/pii/S24058440240 83476.
[18]. R. Smith, T. Johnson, and L. Brown. Advances in automated nutrient delivery systems for hydroponics. Journal of Precision Agriculture, 22(4):89–102, 2021.
[19]. M. Trevelyan, A. Kumar, and S. Jogaiah. Hydroponics: current trends in sustainable crop production. Bioengineering, 10(11):1255, 2023. doi: 10.3390/ bioengineering10111255. URL https://www.ncbi.nlm.nih.gov/pmc/articles/ PMC10625363/.