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PAPER

Smart Fertigation for Home Gardening: Development of an ESP32-Based Automated Fertilizer Mixing and Monitoring System

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ABSTRACT

Home gardening has become increasingly popular due to growing interest in sustainable food production and urban agriculture. However, maintaining accurate fertilizer concentration remains a challenge for many gardeners because manual mixing often leads to inconsistent nutrient delivery and reduced plant growth performance. This paper presents the development of the Household Fertilizer (HOFER), an Internet of Things (IoT)-based smart fertigation system designed for home gardening applications. The proposed system integrates an ESP32 microcontroller, Total Dissolved Solids (TDS) sensor, water level sensors, peristaltic dosing pumps, water pumps, a web-based dashboard, MySQL database, and Telegram Bot communication. A prototyping methodology was adopted to design, develop, test, and refine the system iteratively. The developed prototype automates fertilizer mixing, nutrient monitoring, and irrigation processes while providing real-time monitoring, historical data logging, and remote notification capabilities. Performance evaluation demonstrated that the system successfully maintained nutrient concentrations within acceptable tolerance ranges and provided reliable monitoring and communication performance. The proposed solution improves nutrient delivery accuracy, reduces human error, enhances user convenience, and demonstrates the potential of IoT technologies in supporting sustainable home gardening and precision agriculture practices.

KEYWORDS

IoT; ESP32; Smart Fertigation; Home Gardening; Automated Fertilizer Mixing; TDS Monitoring; Precision Agriculture

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1. INTRODUCTION

The advancement of Internet of Things (IoT) technology has enabled automation in various sectors, including agriculture and home gardening [5], [11], [12], [17]. Precision nutrient management plays a crucial role in ensuring healthy plant growth, optimal yield, and sustainable resource utilization [10], [15], [18]. Traditional fertilizer preparation methods often rely on manual measurement and mixing processes, which are susceptible to human error and inconsistency [11], [12].

Home gardeners frequently face difficulties in maintaining proper fertilizer-to-water ratios. Incorrect nutrient concentrations may lead to poor plant development, nutrient deficiencies, or fertilizer wastage [10], [15]. Furthermore, the absence of monitoring systems makes it difficult for users to identify nutrient imbalances and respond to changes in water quality [14], [17].

To address these challenges, this study proposes the Household Fertilizer (HOFER), an IoT-enabled smart fertigation system that automates fertilizer mixing, nutrient monitoring, and plant watering operations [6], [11], [14]. The system utilizes an ESP32 microcontroller as the main controller and incorporates sensors, pumps, database integration, and Telegram-based remote control functionality [3], [4]. The objective is to provide a practical, affordable, and user-friendly solution for home gardening environments while supporting precision agriculture practices [12], [17]. The specific objectives of this study are, to develop an automated fertilizer mixing system that ensures accurate fertilizer-to-water ratios. To implement real-time monitoring and historical data logging through IoT technologies. To enable remote control and notification capabilities using Telegram integration.

2. METHOD

This project adopted the Prototyping Methodology due to its flexibility and suitability for Internet of Things (IoT)-based system development. Prototyping is widely used in embedded system and smart agriculture projects because it enables iterative development, continuous testing, and progressive refinement of both hardware and software components [11],

[14], [17]. The methodology allows developers to identify system requirements, evaluate functionality, and improve system performance through repeated feedback cycles before final deployment.

The development process consisted of five major phases: requirements gathering, quick design, prototype development, user evaluation and refinement, and final implementation. Each phase contributed to the gradual enhancement of the HOFER system and ensured that both functional and user requirements were achieved.

2.1 Requirements Gathering

The requirements analysis phase identified the need for automated fertilizer dosing, nutrient concentration monitoring, water level detection, historical data storage, and remote user interaction. Target users include home gardeners, hobbyists, students, and small-scale farmers. The requirement analysis was conducted by examining common challenges associated with manual fertilizer preparation, nutrient inconsistency, and the lack of monitoring capabilities in home gardening environments [10], [15], [18].

In addition, requirements related to real-time communication, wireless connectivity, and automated control were considered to ensure compatibility with modern smart agriculture practices [11], [12]. The analysis also emphasized affordability and ease of use to encourage adoption among non-technical users.

2.2 Quick Design

A preliminary system architecture was developed to define interactions between sensors, pumps, databases, and communication modules. Hardware and software requirements were identified and integrated into a unified design framework. The architecture was designed based on IoT system principles consisting of sensing, processing, communication, and application layers [17], [19], [20].

The ESP32 microcontroller was selected as the primary processing unit due to its integrated Wi-Fi capability, low cost, and suitability for IoT applications [3], [4], [8]. The design phase also considered future scalability, allowing additional sensors and intelligent automation features to be incorporated in future system enhancements.

2.3 Prototype Development

The initial prototype was developed using ESP32 firmware, TDS sensors, water level sensors, dosing pumps, and a web-based monitoring dashboard. Database connectivity and Telegram Bot functionality were also implemented. The prototype integrated both hardware and software modules to enable automated nutrient preparation, monitoring, and remote control operations [14], [17].

The TDS sensor was utilized to monitor nutrient concentration levels continuously, while water level sensors ensured adequate water availability before the fertilizer mixing process was initiated. Peristaltic dosing pumps were programmed to dispense Fertilizer A and Fertilizer B automatically based on predefined operational parameters. Sensor readings and operational status were transmitted through Wi-Fi communication and stored in a MySQL database for monitoring and analysis purposes [3], [4].

2.4 User Evaluation and Refinement

Testing was conducted to evaluate fertilizer mixing accuracy, sensor reliability, dashboard responsiveness, and notification performance. Feedback obtained from testing activities was used to refine the system and improve operational stability. Multiple testing cycles were performed to identify potential hardware and software issues and to verify the accuracy of nutrient concentration measurements.

The evaluation process focused on ensuring reliable sensor performance, accurate fertilizer dosing, stable communication between system components, and user-friendly interaction through the dashboard and Telegram Bot interface [14], [17]. Any inconsistencies detected during testing were addressed through software modifications and hardware calibration procedures.

2.5 Final Implementation

The final system integrates automated dosing, nutrient monitoring, data logging, and remote control functions into a complete smart fertigation solution suitable for home gardening environments. The implementation successfully combines sensing technologies, automated control mechanisms, wireless communication, and user interaction platforms within a single integrated architecture [11], [14], [17].

The completed HOFER prototype provides users with real-time monitoring capabilities, automated fertilizer management, historical data storage, and remote notification features. The final implementation demonstrates the practical application of IoT technologies in improving nutrient management efficiency, reducing human intervention, and supporting sustainable home gardening practices [15], [18].

2.6 Hardware Architecture

The proposed HOFER system consists of several integrated hardware components designed to automate fertilizer preparation, nutrient monitoring, and plant irrigation processes. The main hardware components include ESP32 Microcontroller, TDS Sensor, Contact Water Level Sensor, Non-Contact Water Level Sensor, Peristaltic Dosing Pumps, DC Water Pump, Oxygen Mixing Pump, LCD Display, Buzzer Alert System, 12V Battery Power Supply.

The ESP32 microcontroller serves as the central controller responsible for collecting sensor readings, processing data, executing control algorithms, and coordinating communication between all hardware and software components [3], [4], [8]. Its integrated Wi-Fi capability enables seamless connectivity with external databases, web dashboards, and Telegram communication platforms without requiring additional networking modules.

The TDS sensor is utilized to measure nutrient concentration within the fertilizer solution. Continuous monitoring of Total Dissolved Solids (TDS) allows the system to determine whether the nutrient concentration falls within the desired range for plant growth [14], [17]. This measurement is essential in preventing nutrient deficiencies and excessive fertilizer application, both of which may negatively affect plant health [10], [15].

Two types of water level sensors were incorporated to improve operational reliability. The contact water level sensor measures water depth directly, while the non-contact water level sensor detects liquid presence without direct exposure to the solution. The combination of both sensors minimizes false readings and enhances water level detection accuracy during fertilizer preparation and irrigation operations.

Peristaltic dosing pumps are responsible for dispensing Fertilizer A and Fertilizer B into the mixing tank. These pumps provide accurate and controlled nutrient dosing, making them suitable for fertigation applications that require precise fertilizer concentration management [11], [18]. The DC water pump subsequently transfers the prepared nutrient solution to plants once the target concentration has been achieved.

An oxygen mixing pump is included to improve nutrient homogenization within the mixing tank. Continuous circulation ensures that dissolved nutrients are distributed uniformly before irrigation occurs. Additional user feedback is provided through an LCD display and buzzer alert system, allowing users to monitor operational status and receive warnings when abnormal conditions are detected.

The entire system is powered by a 12V battery supply, enabling flexible deployment in locations where direct electrical infrastructure may not be readily available.

2.7 Software Architecture

The software subsystem consists of several interconnected modules that support monitoring, automation, communication, and data management functions. These modules include:

a. Arduino IDE Firmware
b. MySQL Database
c. Web Dashboard
d. Telegram Bot Interface

The firmware developed using Arduino IDE controls all sensor acquisition and actuator operations. The ESP32 continuously gathers data from the TDS sensor and water level sensors before processing the information based on predefined operational rules [3], [4]. Decision-making algorithms determine whether fertilizer dosing, mixing, or irrigation actions are required.

Sensor data collected by the ESP32 are transmitted through Wi-Fi communication to a MySQL database for storage and analysis. Historical data logging enables long-term monitoring of nutrient concentration trends and system performance [10], [14]. The stored data can be utilized to evaluate fertilizer consumption patterns and optimize future nutrient management strategies.

A web-based dashboard was developed to provide users with real-time system visibility. The dashboard displays nutrient concentration levels, water tank status, pump activity, and overall system health. Through graphical visualization and historical records, users can easily monitor system performance and identify operational anomalies.

The Telegram Bot interface serves as a remote communication platform that enables users to interact with the system using mobile devices. Notifications and alerts are automatically transmitted whenever significant events occur, such as low water levels, completion of fertilizer mixing, or abnormal operating conditions [14], [17]. This functionality enhances user convenience and supports remote monitoring without requiring direct access to the physical system.

The integration of database storage, dashboard visualization, and messaging services establishes a complete IoT ecosystem capable of supporting intelligent and automated nutrient management for home gardening applications [11], [12], [17].

2.8 Operational Workflow

The operational workflow begins with water availability verification using both contact and non-contact water level sensors. Before any fertilizer preparation process is initiated, the ESP32 confirms that sufficient water is available within the mixing tank. This preliminary validation step prevents dry-run conditions and protects system components from potential damage.

Once adequate water levels are detected, the ESP32 activates the peristaltic dosing pumps to dispense predetermined quantities of Fertilizer A and Fertilizer B into the mixing tank. The nutrient solution is subsequently mixed using the oxygen pump to ensure homogeneous distribution of dissolved nutrients throughout the tank.

During the mixing process, the TDS sensor continuously monitors nutrient concentration levels. Real-time feedback allows the system to compare measured values against predefined target thresholds. If the measured concentration falls below the target range, additional fertilizer is automatically dispensed until the desired concentration is achieved [14], [17].

After reaching the target nutrient concentration, the DC water pump transfers the prepared solution to the plants. This automated process minimizes human intervention while ensuring consistent nutrient delivery and reducing fertilizer wastage.

Throughout system operation, all sensor readings, pump activities, nutrient concentration values, and alert notifications are recorded in the MySQL database. The information is subsequently displayed through the web dashboard and transmitted via Telegram notifications, enabling continuous monitoring and remote accessibility [11], [14], [17].

The integration of sensing, control, communication, and monitoring components enables HOFER to function as a complete smart fertigation platform capable of supporting efficient nutrient management in home gardening environments.

2.9 Proposed System Architecture

The proposed HOFER architecture is designed based on a layered Internet of Things (IoT) framework to facilitate efficient sensing, data processing, communication, monitoring, and automated control functions. The architecture consists of four primary layers: the sensing layer, control layer, communication layer, and application layer. This layered approach improves modularity, scalability, and maintainability while enabling seamless interaction between hardware and software components [17], [19], [20].

The architecture supports real-time nutrient monitoring, automated fertilizer dosing, irrigation management, historical data storage, and remote user interaction. Figure X illustrates the overall system architecture of the proposed HOFER platform.

a. Sensing Layer

The sensing layer is responsible for collecting environmental and nutrient-related information required for system operation. Accurate sensing is essential in precision agriculture because control decisions are highly dependent on real-time data obtained from field conditions [11], [18]. The sensing layer consists of:

1. TDS Sensor for nutrient concentration monitoring.
2. Contact Water Level Sensor for measuring water depth.
3. Non-Contact Water Level Sensor for liquid presence detection.

The TDS sensor continuously measures the concentration of dissolved nutrients within the fertilizer solution. The measured values are transmitted to the ESP32 controller, where they are compared against predefined nutrient concentration thresholds. This monitoring process ensures that fertilizer levels remain within acceptable ranges for healthy plant development [10], [15].

The water level sensors provide additional operational safety by detecting the availability of water before fertilizer preparation and irrigation activities begin. The implementation of both contact and non-contact sensing technologies improves measurement reliability and minimizes potential sensor inaccuracies caused by environmental conditions.

The continuous acquisition of sensor data enables real-time monitoring and supports adaptive nutrient management within the HOFER system [14], [17].

b. Control Layer

The control layer represents the core decision-making component of the system. The ESP32 microcontroller serves as the central processing unit responsible for coordinating sensing, automation, communication, and user notification functions [3], [4], [8]. The ESP32 performs several critical operations, including:

1. Sensor data acquisition.
2. Nutrient concentration analysis
3. Fertilizer dosing control.
4. Irrigation pump activation.
5. Alert generation.
6. Communication management.

Upon receiving sensor readings, the controller executes predefined control algorithms to determine the required operational actions. If nutrient concentration values fall below the target threshold, the ESP32 activates the peristaltic dosing pumps to dispense additional fertilizer solution. Conversely, when the desired concentration level is achieved, fertilizer dosing is terminated and irrigation processes may proceed.

The controller also supervises safety-related operations such as water level verification and overflow prevention. Through continuous monitoring and automated decision-making, the control layer minimizes human intervention while maintaining system efficiency and reliability [11], [14].

c. Communication Layer

The communication layer facilitates data exchange between the hardware subsystem and external monitoring platforms. Reliable communication is a critical requirement in IoT-based agricultural systems because it enables real-time monitoring, remote management, data synchronization, and energy-efficient sensor networking [13], [17], [19].

The communication layer utilizes the built-in Wi-Fi capability of the ESP32 module to establish connectivity with:

1. MySQL Database.
2. Web Dashboard.
3. Telegram Bot Platform.

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Sensor readings, operational status information, and alert messages are transmitted through wireless communication channels and stored in the database. The communication layer supports bidirectional data flow, enabling users to receive information from the system while also interacting with the platform remotely.

The use of Wi-Fi communication reduces infrastructure costs and simplifies deployment for home gardening environments. Furthermore, wireless communication enables seamless integration with existing Internet-based services and future cloud computing platforms [14], [20].

d. Application Layer

The application layer serves as the user interaction interface and provides monitoring, visualization, and notification functionalities. This layer transforms raw sensor data into meaningful information that can be easily interpreted by users [10], [17]. The application layer consists of two primary components:

1. Web Dashboard

   The web dashboard provides a centralized platform for real-time system monitoring and historical data analysis. Key dashboard functions include:

   a) Displaying real-time PPM readings.
   b) Displaying water tank status.
   c) Monitoring pump activities.
   d) Recording historical operational data.
   e) Presenting system health information.

   The dashboard enables users to evaluate nutrient concentration trends, monitor irrigation activities, and identify potential operational issues. Historical data records also support performance analysis and long-term nutrient management optimization [10], [14].

2. Telegram Bot

   The Telegram Bot functions as a remote communication and notification platform. The bot automatically sends alerts and status updates to users whenever significant events occur within the system. The Telegram Bot provides the following capabilities:

   a) Low water level notifications.
   b) Mixing completion alerts.
   c) Overflow warnings.
   d) Remote monitoring support.
   e) User interaction through mobile devices.

This communication mechanism improves user convenience by allowing remote supervision without requiring direct access to the physical gardening environment. The implementation of Telegram messaging also provides a low-cost and widely accessible solution for IoT-based notification services [14], [17].

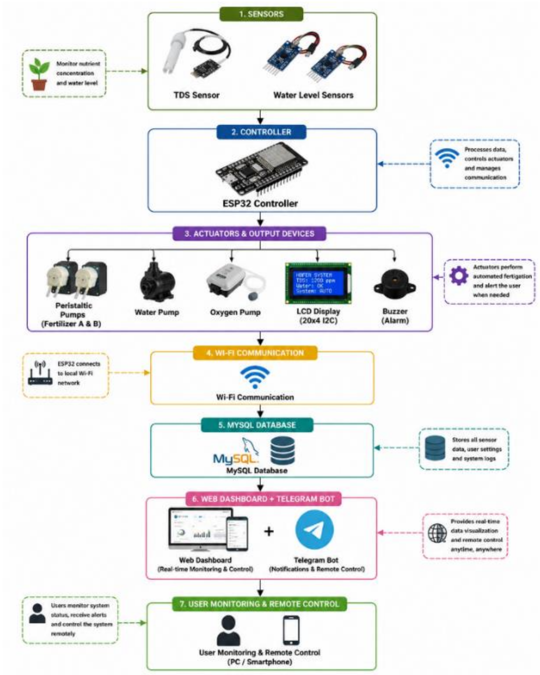

Figure 1. System Architechture

e. Architecture Summary

The proposed HOFER architecture successfully integrates sensing technologies, automated control mechanisms, wireless communication infrastructure, and user-oriented monitoring platforms within a unified IoT ecosystem. The layered architecture enhances system modularity and simplifies future expansion, allowing additional sensors, cloud services, artificial intelligence modules, and advanced automation functions to be incorporated without significant architectural modifications [6], [9], [20].

3. RESULTS AND DISCUSSION

The developed HOFER prototype was successfully implemented and evaluated to assess its ability to automate fertilizer mixing, nutrient monitoring, irrigation control, and remote communication. The evaluation focused on fertilizer dosing accuracy, sensor performance, data transmission reliability, dashboard functionality, and user notification effectiveness. The results demonstrated that the system was capable of performing automated fertilizer preparation while maintaining nutrient concentrations within predefined target ranges. The integration of sensing technologies, automated dosing mechanisms, and wireless communication provided a reliable platform for smart home gardening applications. Similar findings have been reported in previous IoT-based agriculture studies, where automation significantly improved operational efficiency and reduced manual intervention requirements [11], [14], [17].

3.1 Automated Fertilizer Mixing Performance

One of the primary objectives of HOFER was to ensure accurate fertilizer-to-water ratios through automated nutrient dosing. The implemented peristaltic pump system successfully dispensed Fertilizer A and Fertilizer B according to predefined control parameters. Continuous monitoring by the TDS sensor allowed the system to dynamically adjust fertilizer addition whenever nutrient concentration levels deviated from target values.

Testing results indicated that the automated dosing mechanism maintained nutrient concentrations within acceptable tolerance levels for home gardening applications. The ability to automatically correct nutrient concentration levels minimizes the risk of under-fertilization and over-fertilization, both of which can negatively affect plant growth and nutrient uptake efficiency [10], [15].

Compared with conventional manual fertilizer preparation methods, the automated approach significantly reduced dependency on user experience and manual measurements. This finding supports previous research highlighting the benefits of precision agriculture technologies in improving nutrient management consistency and reducing resource wastage [11], [12], [18].

3.2 Sensor Monitoring Performance

The TDS sensor and water level sensors operated effectively throughout the testing period. Continuous sensor measurements enabled real-time monitoring of nutrient concentration and water availability within the system. The TDS sensor consistently detected changes in nutrient concentration during fertilizer mixing operations. This capability allowed the ESP32 controller to make real-time dosing decisions based on actual nutrient conditions rather than predetermined dosing schedules. Such adaptive control mechanisms are commonly recognized as important features in modern smart agriculture systems [14], [17].

Similarly, both contact and non-contact water level sensors successfully detected water availability before fertilizer mixing and irrigation processes were initiated. The implementation of dual sensing mechanisms improved operational reliability by reducing the likelihood of inaccurate water level readings and preventing system operation under insufficient water conditions.

The successful integration of multiple sensors demonstrates the effectiveness of combining real-time sensing technologies with automated control systems for home gardening applications [11], [18].

3.3 Communication and Data Management Performance

The ESP32 Wi-Fi module successfully established communication between hardware components, the database server, and remote monitoring interfaces. Sensor readings were transmitted and stored in the MySQL database without significant communication failures throughout the testing process.

Historical data logging provided users with the ability to review previous nutrient concentration records and system activities. Data collection and storage capabilities are important components of smart agriculture systems because they support long-term performance evaluation and data-driven decision making [10], [17].

The web dashboard successfully displayed real-time nutrient concentration readings, water level status, pump activities, and overall system conditions. Dashboard responsiveness remained stable throughout testing, allowing users to monitor system operations effectively.

The results confirm that the implemented communication architecture was capable of supporting reliable data acquisition, storage, visualization, and retrieval functions necessary for IoT-based agricultural monitoring systems [14], [19], [20].

3.4 Telegram Notification Performance

Telegram integration proved effective as a remote communication mechanism between users and the HOFER system. Notifications were successfully delivered for important operational events, including low water level warnings, fertilizer mixing completion alerts, and overflow notifications.

Testing demonstrated that notification delivery times remained consistently low under stable Wi-Fi conditions. Fast notification delivery enhances user awareness and enables prompt responses to system events. Similar communication approaches have been widely adopted in IoT monitoring systems due to their simplicity, accessibility, and low implementation cost [14], [17].

The ability to receive system updates remotely improves overall usability, particularly for users who are unable to physically monitor their gardens throughout the day. This feature contributes significantly to the practicality of the proposed system for home gardening applications.

3.5 Discussion of System Benefits

The implementation of HOFER demonstrates several advantages compared with traditional manual fertilizer preparation methods. First, the automated dosing mechanism improves nutrient concentration consistency by reducing human error during fertilizer mixing. Second, real-time monitoring provides immediate feedback regarding system conditions and nutrient status. Third, remote accessibility allows users to supervise operations without being physically present near the gardening area.

Furthermore, the integration of data logging capabilities supports historical trend analysis and enables users to make more informed decisions regarding nutrient management practices. The combination of sensing, automation, communication, and monitoring technologies aligns with the objectives of modern precision agriculture and smart farming initiatives [11], [12], [15], [18].

Despite these advantages, several limitations were identified during system evaluation. The system remains dependent on stable Wi-Fi connectivity and wireless communication infrastructure for real-time communication and remote monitoring functions. Similar challenges have been reported in IoT-based agricultural deployments, particularly in sensor networking and communication reliability [13], [16], [19]. Network interruptions may temporarily affect dashboard updates and Telegram notification delivery. Additionally, the current implementation is primarily designed for home gardening and small-scale deployment environments.

Future enhancements may incorporate cloud computing platforms, artificial intelligence algorithms, and advanced environmental sensors to further improve system intelligence, scalability, and decision-making capabilities [6], [9], [20].

Overall, the results indicate that HOFER successfully achieved its intended objectives by automating fertilizer preparation, monitoring nutrient concentration, enabling remote communication, and improving operational convenience for home gardeners. The findings demonstrate the potential of IoT technologies to support sustainable and efficient nutrient management practices in modern gardening environments.

3.6 Performance Evaluation

To evaluate the effectiveness and reliability of the proposed HOFER system, several performance indicators were assessed. The evaluation focused on fertilizer mixing accuracy, sensor monitoring performance, communication effectiveness, notification delivery, and overall system reliability. These performance metrics were selected because they directly influence the efficiency of nutrient management and user experience in smart gardening applications [11], [14], [17].

The testing process was conducted under normal operating conditions using the completed prototype. Multiple testing cycles were performed to verify system consistency and ensure that the integrated hardware and software components functioned as intended.

3.6.1 Fertilizer Mixing Accuracy

One of the most critical performance indicators for HOFER is its ability to achieve the desired nutrient concentration through automated fertilizer dosing. To evaluate this capability, several target nutrient concentration values were predefined and compared against the actual concentrations measured by the TDS sensor after the mixing process was completed.

Table 1. Fertilizer Mixing Accuracy

Target PPM	Measured PPM	Difference
500	495	-5
700	708	+8
1000	992	-8
1200	1210	+10

The results demonstrate that the system was capable of maintaining nutrient concentration values within a relatively small deviation from the predefined targets. The maximum observed deviation was ±10 PPM, which represents a minor variation relative to the overall nutrient concentration range.

The observed differences may be attributed to factors such as pump dispensing tolerances, nutrient solution mixing dynamics, and sensor measurement variations. Nevertheless, the deviations remain within acceptable limits for home gardening applications and do not significantly affect fertilizer effectiveness [10], [15].

These findings indicate that the automated dosing mechanism successfully achieved accurate nutrient concentration control while reducing dependency on manual fertilizer preparation procedures. Similar benefits have been reported in precision agriculture systems where automated nutrient management improves consistency and minimizes resource wastage [11], [18].

3.6.2 Sensor Monitoring Performance

The effectiveness of real-time monitoring depends largely on the accuracy and reliability of the sensing subsystem. Therefore, the performance of the TDS sensor and water level sensors was evaluated throughout the testing process.

Table 2. Sensor Monitoring Performance

Parameter	Result
TDS Detection	Successful
Water Level Detection	Successful
Data Logging	Successful
Dashboard Update	Successful

The TDS sensor consistently detected changes in nutrient concentration during fertilizer preparation and irrigation operations. Sensor readings were successfully processed by the ESP32 controller and transmitted to the monitoring dashboard without significant delays.

Similarly, both contact and non-contact water level sensors successfully identified water availability conditions before fertilizer dosing and irrigation processes were initiated. This capability prevented system operation under insufficient water conditions and improved overall operational safety.

The successful performance of the sensing subsystem demonstrates the effectiveness of integrating multiple sensors within a unified IoT-based monitoring environment [14], [17].

3.6.3 Telegram Notification Performance

Remote communication and user notification capabilities were evaluated using the Telegram Bot platform. Several operational scenarios were tested to verify notification accuracy and delivery reliability.

Table 4. Telegram Notification Performance

Function	Result
Low Water Alert	Successful
Mixing Completion Alert	Successful
Overflow Alert	Successful
Remote Monitoring	Successful

The Telegram Bot successfully generated and delivered notifications whenever predefined events occurred. Alerts were transmitted immediately after event detection, allowing users to remain informed about system status even when physically distant from the gardening area.

Average notification delivery time was recorded at less than five seconds under stable Wi-Fi conditions. This response time is considered acceptable for home gardening applications where real-time awareness contributes to improved operational management and user convenience [14].

The implementation of Telegram-based communication demonstrates the practicality of low-cost messaging platforms in supporting IoT monitoring and alert systems [17], [20].

3.6.4 System Reliability

Continuous operation testing was conducted to assess the long-term stability and reliability of the proposed system. The evaluation focused on the performance of critical hardware and software components during repeated operational cycles.

Table 5. System Reliability

Test Item	Status
Pump Control	Stable
Sensor Reading	Stable
Database Communication	Stable
Telegram Communication	Stable
Dashboard Monitoring	Stable

The results indicate that all major subsystems operated consistently throughout the testing period. No significant failures were observed in sensor acquisition, pump control operations, database communication, or user notification mechanisms.

Stable communication between hardware and software components contributed significantly to system reliability. The ESP32 controller successfully coordinated sensing, decision-making, and communication activities without noticeable performance degradation [3], [4], [8].

The reliability results suggest that the HOFER prototype is suitable for continuous operation in home gardening environments where frequent monitoring and automated nutrient management are required.

3.6.5 Overall Performance Assessment

The overall evaluation demonstrates that HOFER successfully achieved its intended design objectives. The system effectively automated fertilizer preparation, maintained nutrient concentration accuracy, provided real-time monitoring capabilities, and enabled remote communication through Telegram integration.

The integration of sensing technologies, automated dosing mechanisms, database management, and wireless communication created a complete smart fertigation platform capable of supporting efficient nutrient management practices [11], [12], [17]. Compared with traditional manual fertilizer preparation methods, the proposed system offers significant improvements in operational consistency, monitoring capabilities, and user convenience. The results further validate the suitability of IoT technologies for home gardening applications and support ongoing efforts toward sustainable and data-driven agricultural practices [15], [18].

Overall, the performance evaluation confirms that HOFER is capable of providing reliable, accurate, and user-friendly smart fertigation functionality for small-scale gardening environments.

3.7. Future Work

Although the developed HOFER system successfully achieved its intended objectives, several enhancements can be implemented to further improve its functionality, scalability, intelligence, and long-term usability. Future developments should focus on expanding the system beyond basic automation toward more intelligent and adaptive smart agriculture applications.

3.7.1 Mobile Application Development

Future versions of HOFER may incorporate dedicated Android and iOS mobile applications to provide a more user-friendly monitoring and control environment. A mobile application would allow users to access real-time system information, receive push notifications, configure operational parameters, and review historical data through a centralized interface. Such functionality would improve accessibility and user engagement while enhancing overall system usability [14], [17].

3.7.2 Cloud-Based Monitoring and Data Management

Currently, the system utilizes a local database architecture for data storage and monitoring. Future implementation may integrate cloud-based platforms to enable global accessibility, improved data security, and enhanced scalability. Cloud integration would allow users to monitor gardening activities from any location while supporting large-scale data storage and advanced analytics capabilities [17], [19], [20]. The implementation of cloud services could also facilitate data sharing between multiple devices and support centralized management for users operating several gardening systems simultaneously.

3.7.3 Artificial Intelligence-Based Nutrient Optimization

One of the most promising future enhancements involves the integration of Artificial Intelligence (AI) and Machine Learning (ML) technologies. By analyzing historical nutrient concentration data, environmental conditions, and plant growth patterns, intelligent algorithms could automatically recommend optimal fertilizer concentrations and irrigation schedules [6], [9]. AI-based decision support systems could improve nutrient management efficiency, reduce fertilizer wastage, and adapt system behavior according to changing environmental conditions. This approach aligns with the growing adoption of intelligent agriculture technologies in modern farming practices [9], [18].

3.7.4 Weather-Based Automation

Future versions of HOFER may incorporate weather forecasting services through Application Programming Interfaces (APIs). By integrating weather information such as rainfall probability, temperature, humidity, and solar radiation levels, the system could automatically adjust irrigation and fertilizer scheduling based on anticipated environmental conditions [6], [18]. Such adaptive control strategies would improve water conservation, optimize nutrient utilization, and enhance overall system efficiency.

3.7.5 Solar Power Integration

To improve sustainability and reduce energy consumption, future deployments may incorporate solar energy systems as alternative power sources. Solar-powered operation would make the system more suitable for outdoor installations and remote locations where conventional electrical infrastructure is limited [15], [18]. The integration of renewable energy technologies would further support environmentally sustainable gardening practices and reduce operational costs.

3.7.6 Large-Scale Deployment and Greenhouse Applications

Although HOFER was primarily designed for home gardening applications, future research may investigate system scalability for greenhouse environments and commercial agricultural operations. Larger deployments would require support for multiple nutrient tanks, additional sensing nodes, distributed irrigation zones, and centralized monitoring platforms [11], [17]. Scalable architecture designs could significantly broaden the applicability of the proposed system across various agricultural sectors.

3.7.7 Advanced Sensor Integration

Future versions of the system may incorporate additional sensors to improve environmental awareness and decision-making capabilities. Potential sensor additions include: pH Sensor, Electrical Conductivity (EC) Sensor, Temperature Sensor, Humidity Sensor, Soil Moisture Sensor, Light Intensity Sensor. The integration of these sensors would provide a more comprehensive understanding of plant growth conditions and enable more precise nutrient and irrigation management [11], [18].

3.7.8 Predictive Analytics and Smart Recommendations

Another potential enhancement involves the development of predictive analytics capabilities. Historical operational data collected by the system could be analyzed to identify trends, predict nutrient consumption patterns, and forecast maintenance requirements. Predictive models may assist users in optimizing fertilizer usage, reducing operational costs, and preventing potential system failures before they occur. Such capabilities represent an important step toward fully autonomous smart gardening systems and Agriculture 4.0 environments [9], [17], [20].

3.7.9 Future Outlook

The future development of HOFER should focus on combining IoT technologies, cloud computing, artificial intelligence, advanced sensing systems, semantic interoperability frameworks, and renewable energy solutions within a unified smart agriculture ecosystem [7], [20]. These enhancements have the potential to transform HOFER from a home gardening automation platform into an intelligent precision agriculture system capable of supporting sustainable food production, resource optimization, and data-driven decision-making [6], [9], [18], [20].

4. CONCLUSION

This paper presented the design, development, and evaluation of HOFER (Household Fertilizer), an Internet of Things (IoT)-based automated fertilizer mixing and monitoring system developed specifically for home gardening applications. The proposed system integrates ESP32 technology, nutrient concentration sensing, automated fertilizer dosing, water level monitoring, database management, web-based visualization, and Telegram-based communication within a single unified platform [3], [4], [14]. The implementation of HOFER successfully addressed several challenges commonly associated with conventional fertilizer preparation methods, including inconsistent nutrient concentration, human error during fertilizer mixing, and limited monitoring capabilities. By automating fertilizer dosing and continuously monitoring nutrient concentration through TDS measurements, the system was able to maintain nutrient levels within acceptable tolerance ranges while minimizing manual intervention [10], [15]. The developed prototype successfully achieved all research objectives established at the beginning of this study. First, the system was capable of automatically preparing fertilizer solutions with accurate fertilizer-to-water ratios through the use of peristaltic dosing pumps and feedback-based control mechanisms. Second, real-time monitoring and historical data logging were successfully implemented through database integration and dashboard visualization. Third, remote monitoring and notification capabilities were achieved through Telegram Bot integration, allowing users to monitor system status and receive alerts from virtually any location with Internet connectivity [11], [14], [17]. Performance evaluation demonstrated that the system was capable of maintaining nutrient concentration accuracy within a small deviation range from predefined target values. Furthermore, sensor monitoring, database communication, dashboard visualization, and Telegram notification functions operated reliably throughout multiple testing cycles. These results validate the effectiveness of the proposed architecture and demonstrate the feasibility of applying IoT technologies to improve nutrient management in home gardening environments [11], [18]. The integration of sensing technologies, automated control mechanisms, wireless communication infrastructure, and user-oriented monitoring platforms highlights the potential of smart fertigation systems in supporting sustainable gardening practices. The findings of this study are consistent with previous research that emphasizes the role of IoT technologies in enhancing agricultural productivity, resource efficiency, and operational convenience [12], [17], [18]. In conclusion, HOFER provides a practical, affordable, and scalable smart fertigation solution for home gardeners and small-scale agricultural users. The successful implementation of the system demonstrates how IoT-based automation can contribute to improved nutrient management, reduced fertilizer wastage, enhanced monitoring capabilities, and increased user convenience. The proposed system also establishes a foundation for future developments involving cloud computing, artificial intelligence, and advanced precision agriculture technologies [6], [9], [20].

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