Decision Support System Based on IoT and Mamdani Fuzzy Logic for Nutrient Management in Hydroponic Plants on Urban Rooftop Farming

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ARTICLEINFO

Keywords: Decision Support System, IoT, Fuzzy Mamdani, Hydroponics, Urban Agriculture

ABSTRAK

Urban agriculture has emerged as a viable solution to address the challenge of limited land availability in urban areas. Hydroponic systems, as a soil-less cultivation method, are gaining popularity due to their efficiency. However, nutrient management in hydroponic farming remains a significant challenge. This study proposes the development of a Decision Support System (DSS) based on the Internet of Things (IoT) and Mamdani fuzzy logic to provide automated nutrient recommendations based on environmental parameters. This approach aims to enhance the efficiency, accuracy, and automation of small-scale hydroponic farming management in urban settings..

INTRODUCTION

The growth of urban populations has led to a reduction in the availability of productive land for cultivation. This has created a demand for agricultural solutions that are efficient, space-saving, and environmentally friendly. One emerging solution is urban agriculture using the hydroponic method, a technique of growing plants without soil by utilizing a mineral nutrient solution. Hydroponic systems allow for optimal crop production in limited spaces such as rooftops or home terraces (Putri et al., 2022).

Despite its many advantages, hydroponic farming requires special attention, particularly in managing nutrient levels. Nutrient imbalances can hinder plant growth and reduce productivity. Therefore, an automated system is needed to detect environmental conditions and provide real-time nutrient recommendations.

The Internet of Things (IoT) technology has been widely utilized across various fields, including agriculture. The integration of sensors, microcontrollers, and network connectivity enables the monitoring of environmental parameters such as temperature, humidity, pH, and electrical conductivity (EC). These data can be analyzed to support

automated decision-making through a Decision Support System (DSS). The Mamdani fuzzy method is a preferred approach for handling uncertainty in data and making rule-based linguistic decisions.

This study aims to design and implement an IoT-based DSS using Mamdani fuzzy logic to provide automated nutrient recommendations in hydroponic systems. The proposed system is expected to improve the efficiency of modern urban agriculture, also known as algoculture.

TINJAUAN PUSTAKA

1. Urban Agriculture and Hydroponics

Urban agriculture is a food production system carried out in urban areas by utilizing limited spaces such as rooftops, yards, and building walls. Hydroponics is the most commonly used method due to its high efficiency in land and water use (Putri et al., 2022).

2. Internet of Things (IoT)

IoT in the context of agriculture involves the use of sensors and connected devices to automatically monitor environmental conditions. The collected data is transmitted to a central system for analysis and used in the decision-making process (Priyanto & Iskandar, 2023).

3. Decision Support System (DSS)

A DSS is a computer-based system that supports decision-making by processing data and models. In the context of hydroponics, a DSS can assist farmers in determining optimal nutrient requirements based on plant and environmental conditions (Widodo & Suryanto, 2021).

4. Mamdani Fuzzy Logic

Mamdani fuzzy logic is used to handle uncertainty and ambiguity in input data. By applying linguistically based if-then rules, the system can provide more flexible decisions that resemble human reasoning (Setiawan et al., 2021).

METODOLOGI

This research adopts a system engineering approach based on Internet of Things (IoT) technology and Mamdani fuzzy logic in developing a Decision Support System (DSS) for nutrient management in urban rooftop hydroponic farming. The research

methodology includes system design, data acquisition, fuzzy logic processing, system implementation, and system performance evaluation. Each stage is detailed as follows:

1. System Design

The system is designed with an architecture consisting of three main components:

a. Sensors

The sensor component functions as a tool to measure key environmental parameters in hydroponic farming. The sensors used include temperature sensors (DHT22 or DS18B20), pH sensors, electrical conductivity (EC) sensors, and air humidity sensors. Data obtained from these sensors serve as the initial input for the decision-making system.

b. Data Processing Unit

This unit uses an ESP32 microcontroller integrated with WiFi and Bluetooth modules. The ESP32 periodically collects data from all sensors and sends it to a cloud-based server (such as ThingsBoard or Firebase) using MQTT or HTTP protocols. The data is then analyzed to produce decisions based on fuzzy logic.

c. Mamdani Fuzzy Decision Support System

The Mamdani fuzzy DSS is designed as the core of the logic processing. This system receives input data from sensors (temperature, pH, EC) and processes it using a predetermined rule base. The system's output is a recommended volume of nutrients to be added to the hydroponic solution, expressed either in numerical values (ml or ppm) or linguistic categories (low, medium, high).

The system design considers modularity and scalability, allowing for future upgrades and development, including the addition of other sensors such as a light sensor (lux meter) or a dissolved oxygen sensor.

2. Data Acquisition and Processing

Data is collected from each sensor installed in the hydroponic system. The microcontroller reads the data at specified intervals (e.g., every 5 minutes) and sends it to the IoT server. The next stage is data processing, which includes:

a. Fuzzification

Numerical sensor values are converted into linguistic values, for example, temperature = "high", pH = "normal", EC = "low". Each parameter has a membership function in the form of a triangle or trapezoid, tailored to the characteristics of hydroponic parameter values.

b. Mamdani Fuzzy Inference

The inference process uses if-then rules based on expert knowledge. The system evaluates input combinations to determine how strongly a rule applies. The minimum value of the input membership is used to determine the fuzzy implication.

c. Defuzzification

Fuzzy output values are converted into crisp values using the centroid method. The final result is a recommended volume of nutrients, expressed in milliliters or ppm, to be added to the hydroponic system.

All processes are automated and run in real-time, enabling farmers to receive immediate recommendations for nutrient management.

3. Rule Base Design

The rule base is designed based on input from hydroponic experts, previous research, and experimental analysis. The fuzzy rules follow linguistic if-then statements, such as:

a. IF EC is low AND pH is optimal THEN Nutrient = high
b. IF EC is high AND Temperature is high THEN Nutrient = low
c. IF pH is too low AND Temperature is low THEN Nutrient = medium

A total of 12 main fuzzy rules were developed, covering combinations of three input variables. Linguistic variables are classified into three to five categories per variable (e.g., temperature → low, normal, high).

The advantage of this approach lies in its flexibility in rule formulation and its ability to represent uncertainty, which often arises in environmentally driven agricultural management.

4. System Implementation and Testing

The system was implemented in a small-scale hydroponic installation on a rooftop, using lettuce (Lactuca sativa) as the test plant. Lettuce was chosen due to its popularity as a leafy vegetable in hydroponic studies and its requirement for precise nutrient management.

The system was tested using two management methods:
a. Manual method: nutrient management based on the farmer's experience without system assistance.

b. Automated method: nutrient management based on DSS fuzzy recommendations.
During the cultivation period, data were recorded on nutrient volume applied, plant growth, leaf health, and final harvest yields. These data were used to compare the effectiveness and efficiency between the two methods.

5. System Evaluation
System performance was evaluated by considering the following aspects:
a. Recommendation Accuracy
Accuracy was measured by comparing the system's recommendations to the actual needs of the plants (based on growth and harvest results). The accuracy value reached more than 85% for lettuce under optimal conditions.

b. Plant Productivity
Productivity was measured based on the fresh weight of the harvest. An increase of 12–18% in productivity was observed with the automated method compared to the manual method.

c. Time and Cost Efficiency
The system enabled a reduction in monitoring time and decision-making by 30–40%, as well as operational cost savings of 15–20% over a single growing season.

Overall, this methodology demonstrates that the integration of IoT and fuzzy logic offers an effective and measurable solution for improving the efficiency of nutrient management in urban rooftop hydroponic farming.

RESEARCH RESULT

This study underwent several stages to obtain representative results regarding the implementation of a Decision Support System (DSS) based on the Internet of Things (IoT) with Mamdani Fuzzy Logic for nutrient management in hydroponic crops within an urban rooftop farming environment. The results were compiled through system functionality testing, sensor data collection, data processing using Mamdani Fuzzy Logic, and system effectiveness evaluation.

1. Sensor and IoT Device Functionality Testing

The IoT devices used consist of pH sensors, TDS (Total Dissolved Solids) sensors, temperature sensors, and humidity sensors. All sensors were tested by comparing real-time data from the sensors with conventional measuring instruments. The results showed that the average deviation was only around ±0.2, indicating a high level of accuracy in the IoT devices.

2. Nutrient Data Collection and Adjustment

During a 14-day period, nutrient levels in the hydroponic solution were monitored regularly. The data obtained were processed into fuzzy ranges based on three main categories: low, medium, and high.

Example:
a. pH < 5.5 = Acidic (Low)
b. 5.5 ≤ pH ≤ 6.5 = Neutral (Medium)
c. pH > 6.5 = Alkaline (High).

3. Fuzzification Process and Mamdani Fuzzy Inference

The system performs fuzzification based on sensor input data. One of the applied rules is as follows:
If (pH = Neutral) and (TDS = Low) and (Temperature = Normal), then (Nutrient = Add Nutrient).
The inference process is executed using the MIN-MAX method, followed by defuzzification using the centroid method:
Z=∫μ(z)·z dz∫μ(z) dzZ = \frac{\int \mu(z) \cdot z \; dz}{\int \mu(z) \; dz}Z=∫μ(z)dz∫μ(z)·zdz
(Kusumadewi, 2010)

The centroid formula is used to determine the crisp output recommended by the system, such as the volume of nutrient solution that should be added.

5. System Implementation and Effectiveness Evaluation

The system was tested on five rooftop hydroponic units with various types of plants. The parameters observed included changes in plant growth (height, number of leaves), nutrient solution conditions, and manual interventions.

Table 1. Average System Effectiveness Based on Plant Growth Categories

Parameter	Sebelum SPK	Setelah SPK	Keterangan
Rata-rata tinggi (cm)	12.5	18.9	Peningkatan signifikan
Jumlah daun	5.3	9.1	Bertambah 71%
Intervensi manual/minggu	7	2	Penurunan drastis

5. System Performance Validation

To measure the system's accuracy, a Confusion Matrix was used based on 50 system test cases

Table 2. Confusion Matrix of Decision-Making by the DSS System

	Prediksi Tambah	Prediksi Tidak	Total
Real Tambah	22	2	24
Real Tidak Tambah	3	23	26

System Accuracy:

Accuracy =TP+TNTP+TN+FP+FN=22+2350=90%\text{Akurasi} = \frac{TP + TN}{TP + TN + FP + FN} = \frac{22 + 23}{50} = 90\%

These results indicate that the system is fairly reliable in providing nutrient recommendation decisions

DISCUSSION

Based on the results of this study, the IoT-based decision support system utilizing Mamdani fuzzy logic has proven to provide a significant contribution to nutrient management in hydroponic crops within urban rooftop farming environments. The strength of this system lies in its ability to acquire real-time data from EC, pH, and temperature sensors, which are then processed to automatically generate nutrient addition recommendations. Through a strong integration between hardware and software components, the system is not only capable of identifying plant conditions but also responding swiftly to environmental changes.

These findings are consistent with the study by Purnomo and Nugroho (2020), which reported that the use of Mamdani fuzzy logic in nutrient management can improve fertilization efficiency by up to 30%. Fuzzy logic has proven to be highly suitable in uncertain contexts such as nutrient regulation, where environmental parameters are not always in ideal conditions and often change dynamically. The system developed in this study applies a linguistic approach to define rules based on expert experience, making it more adaptive to real-world field conditions.

Furthermore, the integration of IoT in this system reinforces the findings of Aziz et al. (2021), who stated that IoT device utilization can reduce human error in monitoring growing environments. Timely data acquisition and the system's accuracy in responding to plant needs make it superior to conventional methods. The IoT also allows remote access and monitoring via internet connectivity, making it highly suitable for urban farming practices that rely heavily on technology and automation.

In terms of time efficiency, the system shows a significant improvement, as farmers no longer need to manually monitor nutrient conditions. This is particularly beneficial for urban farmers with limited time and space. This innovation simplifies decision-making related to nutrient application, which was previously done manually and often based on intuition or subjective experience. By reducing reliance on intuition, consistency in nutrient delivery can be better maintained, ultimately improving crop productivity and quality.

Moreover, the system's accuracy rate of 90%, as obtained from testing with the confusion matrix, demonstrates high reliability in providing recommendations. This accuracy level can still be improved by collecting more training data and fine-tuning the membership functions. In the future, the adoption of machine learning algorithms to adapt and optimize fuzzy rules could be a next step in enhancing the system's adaptability to various climate conditions and plant types.

The implementation of this system is expected to make rooftop urban farming more sustainable and appealing to urban communities, especially amidst land scarcity and the growing need for food self-sufficiency. Beyond technical benefits, such technology also has the potential to educate the public on the importance of resource efficiency and local food security. AI and IoT-based technologies serve as key enablers in addressing future challenges in modern agriculture. It can be concluded that this technological integration not only impacts crop yield but also shapes a new paradigm in smarter, automated, and data-driven farming practices.

CONCLUSIONS AND RECOMMENDATIONS

This study concludes that the Decision Support System (DSS) based on the Internet of Things (IoT) and the Mamdani Fuzzy Logic method has proven to be effective and applicable in assisting urban farmers in managing hydroponic plant nutrition more efficiently and accurately. The system integrates sensors to measure environmental parameters such as pH, Electrical Conductivity (EC), and temperature in real-time, which are then processed by a fuzzy algorithm to generate optimal nutrient addition recommendations based on plant conditions. This approach bridges the gap between automated data measurement and expert knowledge-based decision-making, which was previously done manually and tended to be subjective.

Time efficiency and reduced human error are two major advantages of implementing this system. In practice, farmers no longer need to perform periodic measurements and record-keeping, as the entire process is automated and accessible via digital devices. This not only saves time and labor but also minimizes the risk of human error, especially in urban environments that often face limitations in human resources and time. The technology has a tangible impact on improving the effectiveness of farming activities in limited spaces such as rooftops, balconies, or home gardens.

Moreover, the implementation of this system also indicates a positive direction in supporting the realization of smart farming, which can be applied at small to medium scales in urban areas. Agriculture is no longer confined to rural regions or large tracts of land, but can be adopted by urban communities aiming to practice sustainable and self-sufficient living. This aligns with the global trend toward urban agriculture and precision agriculture, which emphasize efficiency, technological utilization, and environmental sustainability.

In the future, this system has great potential for further development through the addition of various features, such as automated control of nutrient pumps, integration with automatic drip irrigation systems, and the development of a cloud-based mobile application. This application could provide real-time notifications to farmers about environmental conditions, recommended actions, and historical plant growth reports. Such features would enhance user engagement and provide flexible access and control anytime and anywhere.

The recommendations from this study cover two essential aspects. First, there is a need for training and guidance for farmers or end-users on how to use IoT-based systems and basic understanding of fuzzy logic principles. This training is crucial to ensure that the developed technology can be used optimally and does not become a barrier for users with non-technical backgrounds. Active user involvement is also one of the key factors in the successful adoption of technology in the field.

Second, for future development, further research is recommended to explore other artificial intelligence methods such as the Fuzzy Sugeno method, Adaptive Neuro-Fuzzy Inference System (ANFIS), or even the application of machine learning and deep learning models. These approaches would open opportunities to enhance system accuracy and its adaptability to various environmental conditions and plant types. Additionally, the development of multi-sensor systems and the use of edge computing technology can be considered to reduce dependence on internet connectivity and increase system response speed.

Overall, the results of this study provide a valuable contribution to the development of innovative, efficient, and sustainable agricultural technology solutions, especially in the context of urban agriculture. With support from policy, education, and collaboration among academics, industry players, and government, the implementation of such systems is expected to become part of the solution for future food security amid the challenges of urbanization and global climate change.

ADVANCED RESEARCH

This study has several limitations that should be noted as a basis for further development in the future. One of the main limitations is the relatively small amount of test data used during the system validation process. The system testing was conducted using a dataset collected within a specific timeframe and from a relatively limited number of environmental samples. This may affect the system's generalizability in dealing with more diverse hydroponic environmental conditions in the field. Therefore, larger and more varied data collection is needed, covering a range of pH, EC, temperature, plant types, and plant growth stages, so that the developed fuzzy model can achieve greater robustness and reliability.

In addition to data limitations, this study was also constrained by testing conducted at a single location—specifically, one urban rooftop farming site. The rooftop environment had specific characteristics such as light intensity, air humidity, and wind exposure, which may differ from other urban rooftop locations, even within the same city or in different regions. Location variability will affect plant nutrient requirements and the performance of the system's sensors and actuators. Therefore, it is strongly recommended that future research be conducted at multiple locations with varying microclimatic conditions to gain a broader understanding of the resilience and adaptability of the developed system.

Future development may also focus on enhancing system capabilities through the integration of advanced, rapidly evolving technologies. One promising direction is the integration of the IoT and Mamdani Fuzzy-based nutrient management system with blockchain technology. With blockchain implementation, every agricultural activity—from nutrient monitoring and automated fertilization to harvesting—can be recorded

transparently and immutably, creating a more trustworthy and verifiable supply chain system. This would be particularly beneficial for urban agriculture that aims to add value through product traceability, especially for consumer markets that prioritize safety and transparency regarding product origin.

Furthermore, another highly promising development direction is the integration of the system interface with artificial intelligence technologies such as conversational AI or chatbots. This AI-based interface can be developed to allow users to interact naturally with the system through voice or text commands in everyday language. Thus, users without technical backgrounds can still utilize the system effectively without needing to learn the technical aspects of programming or fuzzy logic. The chatbot can also provide guidance, perform basic diagnoses of plant conditions, and recommend direct actions, for example, "Add 100 ml of AB Mix nutrient solution" or "Check the circulation pump—it has been inactive for the past 2 hours."

Additionally, in the context of sustainable development, future research may also consider the use of renewable energy sources such as solar panels to support system operations. This would further enhance the system's efficiency and independence, especially in urban environments aiming to develop eco-friendly farming practices.

Finally, an edge computing-based system architecture approach is also worth exploring in future studies. This approach allows most data processing to occur locally on devices (such as microcontrollers or edge gateways) without relying on continuous internet connectivity. With edge computing, the system can continue to operate optimally even under limited or unstable network conditions, which are common challenges in certain urban areas.

By considering these various development potentials, it is expected that future research will not only improve the system's technical performance but also expand its social, economic, and environmental benefits through the application of smart hydroponic farming technologies in urban areas.

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