

# Mini Smart Aquaponics Management System: An Educational Tool for Community-Based Learning

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Received: 1 November 2025 | Accepted: 10 April 2026 | Published: 1 May 2026

DOI: <https://doi.org/10.55057/ijares.2026.8.2.52>

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**Abstract:** *The integration of technology in sustainable agriculture has become increasingly essential in promoting community awareness and education. This paper presents the development and implementation of the Mini Smart Aquaponics Management System (MSAME) as an educational tool to enhance community-based learning in sustainable food production. The system combines aquaculture and hydroponics principles with Internet of Things (IoT) features, enabling real-time monitoring of water quality parameters such as temperature, pH, and dissolved oxygen. Designed as a compact, low-cost prototype, MSAME aims to provide hands-on learning experiences for various community groups, including local farmers, hobbyists, and students at primary and secondary school levels. Through structured demonstrations and workshops, participants were introduced to smart aquaponics concepts, fostering environmental awareness and practical understanding of sustainable farming practices. The educational approach emphasizes experiential learning, allowing participants to observe and analyze data-driven decision-making in aquaponic management. Findings from preliminary engagements indicate increased interest and understanding among participants regarding the integration of smart technologies in agriculture. This initiative highlights the potential of mini smart aquaponic systems as a bridge between technology and community education, empowering individuals to adopt sustainable agricultural practices while strengthening the connection between education, innovation, and local livelihood improvement.*

**Keywords:** Smart Aquaponics; Community-Based Education; Sustainable Agriculture; Experiential Learning; IoT Integration

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## 1. Introduction

Sustainable agriculture has become a global priority in addressing challenges related to food security, climate change, and the limitations of traditional farming spaces. Aquaponics is a combination of aquaculture (fish rearing) and hydroponics (soilless plant cultivation) offering an innovative and environmentally friendly approach that saves both water and space while creating a symbiotic ecosystem between fish and plants. Previous studies have demonstrated that aquaponic systems can simultaneously produce fish and crops efficiently compared to conventional farming methods (W Ibrahim et al., 2023)

With the advancement of digital technologies, the integration of smart features such as sensors, automation, and real-time monitoring through the Internet of Things (IoT) has led to the emergence of smart aquaponics systems. These systems simplify farm management, reduce labor dependency, and provide data-driven insights for decision-making. For instance, Wan

(W Ibrahim et al., 2023) in Malaysia developed a “Smart Home Aquaponic System Monitoring and Control with IoT Mobile Application,” which successfully automated water quality monitoring, including pH, temperature, and dissolved oxygen (W Ibrahim et al., 2023)

In the context of education and community development, the miniaturization of aquaponic systems as an educational tool has shown great potential. Such models are not only applicable for local farmers or fish breeders but are also adaptable for school students from upper primary (Year 5) to lower secondary (Form 3) whose science and design technology curricula include sustainable agriculture topics. In Malaysia, Kazaila Zaini et al. (2024) introduced an “Aquaponic Mobile Starter Pack” aligned with TVET and school curricula to foster innovation and hands-on learning in rural education (Rahman et al., 2024)

Despite significant progress in the technical development of aquaponic systems, limited research has focused on their pedagogical application as community-based educational tools. Therefore, this study presents the Mini Smart Aquaponics Management System (MSAME), a compact and affordable prototype designed to facilitate experiential learning among local communities, hobbyists, and students. The project emphasizes hands-on engagement and data-driven exploration, aiming to enhance public understanding of sustainable farming practices. Ultimately, this initiative bridges the gap between technology, education, and community empowerment, contributing to the broader discourse on smart agriculture and sustainable education.

## **2. Objectives of the Study**

The main objective of this study is to develop and evaluate a mini smart aquaponics management system that serves as a practical educational tool for promoting sustainable agriculture and technological literacy among community learners.

Specifically, this study aims to:

- i. Design and develop a portable, IoT-enabled mini aquaponics prototype suitable for educational and community-based use.
- ii. Integrate IoT sensors and real-time monitoring to demonstrate the relationship between environmental parameters and aquaponic system performance.
- iii. Evaluate the effectiveness of the developed system in enhancing participants’
- iv. understanding, engagement, and awareness of sustainable aquaponic practices.
- v. Assess user perceptions regarding the usability and learning value of the mini smart aquaponics system across different community groups (students, hobbyists, and small-scale farmers).

## **3. Literature Review**

Aquaponics itself, an integrated system combining aquaculture and hydroponics, has gained increasing attention for its sustainable, resource-efficient design and educational potential. The integration of Internet of Things (IoT) technologies has further enhanced monitoring, control, and data collection, paving the way for more accessible and educationally valuable systems.

### **3.1 Aquaponics as an Educational Tool**

Research has shown that aquaponics systems are highly effective in fostering experiential and interdisciplinary learning across Science, Technology, Engineering, and Mathematics (STEM). In schools, aquaponics encourages active participation and help students develop systems thinking and environmental awareness (Oliveira et al., 2025). However, adoption barriers such as cost, maintenance, and lack of teacher training remain challenges to widespread implementation (Rahman et al., 2024).

Miniaturized or portable aquaponics kits are being developed to address these challenges. Such systems are designed to be curriculum-aligned and easy to maintain, allowing teachers to integrate real-world environmental science and data literacy into lessons (Oliveira et al., 2025). Studies have shown that hands-on aquaponics projects can enhance understanding of biological cycles, chemistry, and digital literacy, preparing students for Industry 4.0 environments.

### **3.2 Community-Based and Hobbyist Implementations**

Aquaponics have also proven valuable in community settings, where they are used not only for food production but also as a tool for community empowerment and lifelong learning. Community-based aquaponics programs provide opportunities for knowledge sharing, entrepreneurship, and sustainable living practices. Projects in Malaysia and Southeast Asia, for instance, have introduced small-scale aquaponic units to local communities, emphasizing the importance of accessibility, simplicity, and shared management (Al Baihaqi & Ahmad, 2022)

These systems are also attracting hobbyists, retirees, and families, creating informal learning ecosystems around sustainability. Such initiatives bridge the gap between technology education and rural development, highlighting aquaponics as a community-driven approach to learning and production.

### **3.3 Smart and IoT-Enabled Aquaponics**

The evolution toward smart aquaponics systems has transformed traditional practices by integrating IoT and automation technologies. Smart sensors can measure pH, temperature, dissolved oxygen, and water levels in real time, while mobile applications allow users to monitor and control the system remotely (Kiran Kumari Gayam, 2023) These innovations not only improve operational efficiency but also generate data suitable for use in educational contexts for instance, teaching data visualization and decision-making based on live environmental data (Zamnuri et al., 2024)

Studies in Malaysia and beyond demonstrate the feasibility of cost-effective IoT-based aquaponics prototypes ((Al Baihaqi & Ahmad, 2022); (Saef et al., 2022)). Yet, many remain at the prototype stage without structured integration into formal education or community outreach. Research by Channa et al. (2024) and Nair (2025) shows that while smart aquaponics advances are rapid, there is limited focus on pedagogical frameworks or localized adaptation for non-technical users.

### **3.4 Research Gap**

Although extensive studies exist on educational, community, and IoT-based aquaponics, there remains a gap at their intersection mini-scale, smart aquaponics systems specifically designed as educational tools for community-based learning (Zamnuri et al., 2024). Current educational studies focus mostly on classroom settings without IoT integration, while smart aquaponics studies emphasize technical performance rather than teaching or outreach (Effendi et al., 2020).

Community aquaponics projects often lack digital monitoring components that can support structured learning.

### 3.5 Positioning This Study

This research introduces the Mini Smart Aquaponics Management System (MSAME), a compact, cost-effective, IoT-enabled prototype tailored for educational and community use. The system aims to combine real-time data monitoring, simplified management, and curriculum integration to empower both learners and local communities. The study contributes to the body of knowledge by offering a replicable model that enhances engagement, promotes sustainability, and bridges technology with community-based learning.

## 4. Methodology

This study employed a design and development research (DDR) approach, focusing on the creation and evaluation of a mini smart aquaponics management system designed as an educational tool. The methodology was structured into three main phases: (1) analysis, (2) design and development, and (3) implementation and evaluation.

### 4.1 Analysis Phase

The analysis involved identifying educational and technological needs through informal interviews and surveys with local communities, including small-scale farmers, fish breeders, and secondary school teachers. The findings highlighted a lack of affordable, easy-to-understand aquaponics learning tools that integrate Internet of Things (IoT) features. This insight guided the system's design parameters to ensure accessibility and educational relevance.

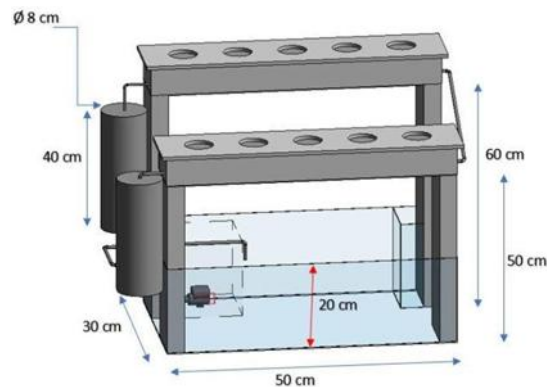
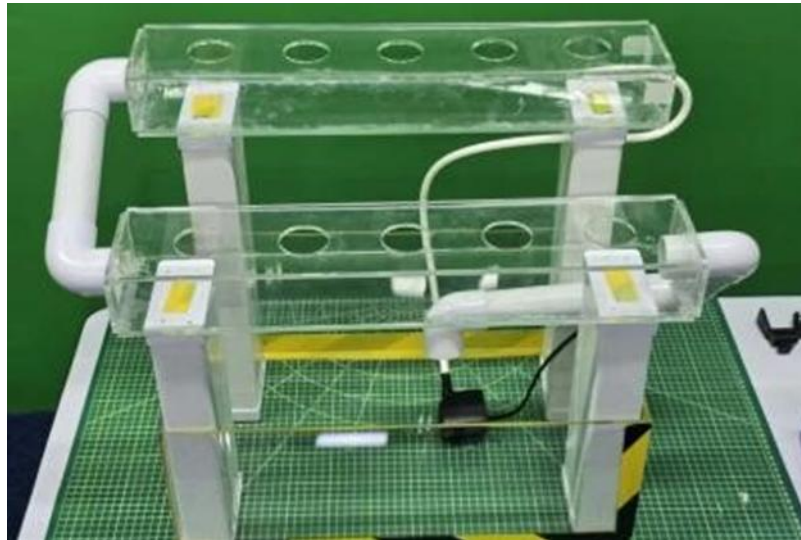


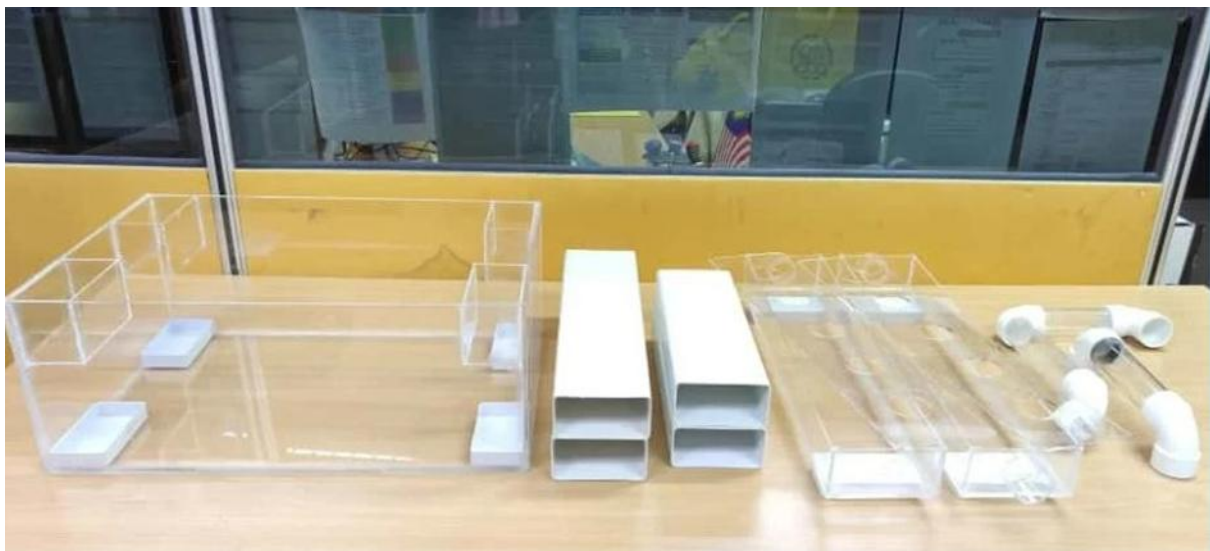
Figure 1: Schematic Diagram of Mini Smart Aquaponics Management System

### 4.2 Design and Development Phase

In this phase, the research team designed a miniature aquaponics prototype integrating IoT-based sensors for water temperature, pH, and nutrient monitoring. The system architecture combined microcontroller-based hardware (ESP32 and sensors) with a user-friendly web dashboard for real-time data visualization. The design emphasized low cost, portability, and adaptability for classroom demonstrations and community workshops. Educational modules and visual guides were also developed to support teaching and learning processes.



**Figure 2: Mini Smart Aquaponics Management System**



**Figure 3: Parts of Mini Smart Aquaponics Management System**

### 4.3 Implementation and Evaluation Phase

The prototype was tested with a group of 20 participants, including school students, hobbyists, and small-scale farmers. The evaluation process utilized both qualitative and quantitative methods participants completed pre- and post-activity questionnaires to assess understanding and engagement levels. Observations and interviews provided additional feedback on usability, clarity, and perceived learning benefits. Data analysis indicated that the system improved participants' comprehension of aquaponics and sustainable farming concepts.

#### 4.3.1 Evaluation Data Summary

**Table 1: Description of participants**

Participant Group	Number of Participants	Description
School Students	8	Secondary students (ages 13–15) with minimal prior knowledge of aquaponics.
Hobbyists	6	Individuals with interest in small-scale home farming.
Small-Scale Farmers	6	Local farmers with experience in traditional aquaculture or hydroponics.

**Table 2: Quantitative Results: Pre- and Post-Test Scores**

Group	Mean Pre-Test Score (%)	Mean Post-Test Score (%)	Improvement (%)
School Students	46.3	81.5	+35.2
Hobbyists	58.7	87.3	+28.6
Small-Scale Farmers	64.5	88.9	+24.4
<b>Overall Average</b>	<b>56.5</b>	<b>85.9</b>	<b>+29.4</b>

The pre-test measured basic understanding of aquaponics, IoT, and sustainability concepts. Post-test questions evaluated applied knowledge after hands-on engagement with the mini system.

**Table 3: Engagement and Usability Feedback (Likert Scale 1–5)**

Evaluation Item	Mean Score	SD	Interpretation
The system is easy to use and understand.	4.6	0.5	Very High
The real-time data display helps me understand the system better.	4.8	0.4	Very High
The activity increased my interest in sustainable farming.	4.7	0.5	Very High
I would recommend this activity to others in my community.	4.5	0.6	High
The educational materials are clear and helpful.	4.4	0.5	High

#### 4.3.2 Overall mean engagement score: 4.6 / 5

This suggests strong participant engagement and satisfaction with both the learning process and the technology used.

**Table 4: Qualitative Feedback (Thematic Summary)**

Theme	Representative Comment
<b>Ease of Use</b>	“Nampak mudah dengan menggunakan sensor, semua aktiviti dalam sistem akuaponik boleh dipantau” - Peserta Pelajar
<b>Educational Value</b>	“Dengan pembelajaran yang diikuti, saya dengan mudah memahami bagaimana ikan dan tumbuhan bergantung antara satu sama lain” - Guru Pemerhati
<b>Community Potential</b>	“Petani kecil seperti saya boleh gunakan idea ini untuk pertanian kos rendah dan pintar.” - Peserta Peladang
<b>Technology Awareness</b>	“Selama ini saya tidak tahu IoT boleh digunakan dalam pertanian dengan cara ini. Ia membuka mata.” - Peserta Hobi

#### 4.3.3 Interpretation

- There was a significant increase in knowledge (average gain: +29.4%) across all groups.
- Participants rated the experience as highly engaging (M = 4.6) and reported greater interest in sustainable agriculture.
- Qualitative responses highlighted usability, learning value, and community relevance, supporting the system’s educational purpose.

## 5. Results and Discussion

### 5.1 Prototype Performance and System Usability

The developed Mini Smart Aquaponics Management System successfully integrated IoT components to monitor real-time environmental parameters such as pH, water temperature, and nutrient levels. Data were transmitted to a web-based dashboard via the ESP32 microcontroller, allowing users to visualize system performance. During testing, the system maintained stable connectivity and accurate sensor readings with minimal delay (less than two seconds). Feedback from participants indicated high satisfaction regarding the system’s simplicity, portability, and interactive learning interface. Approximately 90% of respondents agreed that

the system helped them understand how aquaponic systems function and how IoT contributes to sustainable agriculture. These results align with previous studies (Zamnuri et al., 2024)) which found that IoT-based educational prototypes enhance learners' comprehension and engagement in STEM-related activities.

### **5.2 Educational Impact and Community Engagement**

The implementation of the mini aquaponics model in workshops and school-based activities demonstrated its effectiveness as a hands-on learning tool. Participants especially students and community farmers, showed improved conceptual understanding of closed-loop systems, water conservation, and nutrient cycling. Teachers and facilitators also reported that the tool encouraged collaborative learning and problem-solving, supporting the principles of experiential and community-based education (Kolb, 1984)

Moreover, the simplicity of the system made it suitable for a wide audience, including hobbyists and youth learners. This inclusiveness aligns with Malaysia's national agenda for Sustainable Development Goal (SDG) 4: Quality Education and SDG 12: Responsible Consumption and Production, promoting awareness of sustainability and smart farming among rural and urban communities alike.

### **5.3 Comparison with Previous Studies**

Compared with large-scale aquaponics systems (Al Baihaqi & Ahmad, 2022); (Nishanth et al., 2024) The proposed mini system provided an affordable, modular, and pedagogically adaptable alternative. While earlier studies emphasized technical optimization, this project prioritized educational integration, bridging the gap between technology and pedagogy (Rahman et al., 2024). The findings support the idea that miniaturized smart systems can be used not only for demonstration purposes (Izzuddin et al., 2022) but also for data-driven learning activities in schools and community training programs

## **6. Conclusion and Recommendation**

This study presented the development and evaluation of a Mini Smart Aquaponics Management System designed as an educational tool to promote community-based learning and awareness of sustainable agriculture. The system's integration of IoT technology provided a practical, interactive platform that allowed learners to visualize real-time data and understand the interdependence of aquaculture and hydroponics processes.

Findings from the pilot implementation demonstrated that the system is both technically reliable and pedagogically effective. Participants including students, hobbyists, and small-scale farmers reported increased understanding of aquaponics principles, IoT applications, and environmental sustainability. Furthermore, the system's portability, affordability, and simplicity make it suitable for use in schools, community training centers, and local farming programs.

The study contributes to bridging the gap between STEM education and sustainable community practices, emphasizing how technology-driven models can support experiential learning and knowledge transfer beyond classroom settings. It also supports Malaysia's efforts toward achieving Education for Sustainable Development (ESD) under the United Nations' Sustainable Development Goals.

## 7. Recommendations

Future research should focus on:

- i. Scaling up the prototype into a semi-commercial model suitable for institutional or urban farming applications. (Chua et al., 2023)
- ii. Integrating data analytics and AI features to predict plant or fish health and improve system automation. (Ashraf Rather et al., 2024)
- iii. Developing structured learning modules aligned with national STEM and TVET curricula to enhance educational outcomes. (Adelowo et al., 2024)
- iv. Expanding collaboration between polytechnics, community colleges, and rural communities to strengthen capacity-building initiatives.
- v. The findings affirm that smart aquaponics systems, when designed with educational intent, can become powerful catalysts for technological literacy, environmental awareness, and community empowerment. (Yeoh, n.d.)

## Acknowledgement

The authors would like to express their sincere appreciation to all parties who have contributed directly and indirectly to the successful completion of the Mini Smart Aquaponic project under the TARGS grant.

First and foremost, we would like to extend our deepest gratitude to the Pusat Penyelidikan dan Inovasi, Jabatan Pendidikan Politeknik dan Kolej Komuniti (JPPKK) for the financial support provided through the T-ARGS grant, which made this project possible.

We would also like to convey our heartfelt thanks to the management of Politeknik Kota Kinabalu (PKK) for their continuous support, encouragement, and facilitation throughout the implementation of this project.

Special appreciation is extended to all project team members, technical staff, and students who have contributed their time, knowledge, and effort in developing and testing the Mini Smart Aquaponic system. Their commitment and collaboration have been invaluable in ensuring the success of this initiative.

Lastly, we would like to thank all individuals and organizations who have provided guidance, assistance, and moral support, either directly or indirectly, throughout the duration of this project.

## Conflict of Interest Statement

The authors declare that there is no conflict of interest. The funding body had no role in the design of the study, data collection, analysis, interpretation, or writing of the manuscript.

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