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Community-Based Development of Adaptive Digital SOPs for Hydroponic Farming at BGD Hydrofarm

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ABSTRACT

Background: Community-based hydroponic farming at BGD Hydrofarm faces challenges including manual monitoring, static Standard Operating Procedures (SOPs), and limited digital literacy, which reduce operational efficiency and accuracy. This community service program addresses these issues through the introduction of adaptive digital technologies.

Purpose of the Study: This study aims to improve hydroponic management practices and strengthen community capacity by co-developing adaptive digital SOPs that support data-driven decision-making at BGD Hydrofarm.

Methods: A participatory approach was applied, including needs assessment, co-design sessions, system development, training workshops, and participatory monitoring and evaluation. The GardenKeeper system integrates IoT-based sensors (monitoring pH, TDS, temperature, humidity, and plant visual condition) with generative artificial intelligence (Google Gemini AI) to provide real-time monitoring and adaptive SOP recommendations via a mobile application.

Results: The program resulted in reduced manual workload, improved monitoring efficiency, and increased partner confidence in using digital technology. Behavioral shifts from experience-based to data-driven decision-making were observed, with SOP consultations becoming a shared reference for collective action. Partners independently operated the application, and external stakeholders (Ministry of Cooperatives and SMEs, IGES) recognized the system's potential scalability. The before-after comparison showed improved digital confidence, reduced operational errors, and strengthened collaborative decision-making.

Keywords
Community Service; Hydroponics; Digital SOP; IoT; Generative Artificial Intelligence

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Introduction

The projected increase in the global population, which is expected to exceed 9.1 billion by 2050 (Bongaarts & United Nations Department of Economic and Social Affairs., 2020), presents a major challenge in meeting worldwide food demands. Conventional soil-based agriculture faces multiple limitations, including restricted land availability, soil degradation, climate change, and a high dependence on chemical fertilizers and pesticides. These conditions have driven the emergence of modern agricultural innovations that are more efficient, sustainable, and environmentally friendly. One rapidly developing method is hydroponics, a soilless cultivation system that utilizes nutrient solutions as the primary growing medium.

The hydroponic method offers several advantages over traditional cultivation techniques. First, hydroponics can reduce land use by up to 90% and can be implemented in densely populated urban areas (Resh., 2022; Agnal et al., 2024). Second, this system enables water savings of approximately 70–80%, as nutrient solutions can circulate and be reused (Monisha et al., 2023; Yerukola & Narendra., 2024). Third, the quality of the harvest tends to be higher and more uniform, making it well-suited to meet modern market standards (Perera et al., 2024). It is therefore unsurprising that hydroponics has become one of the key strategies in advancing urban farming and sustainable agriculture.

The success of hydroponic cultivation is highly dependent on the ability to maintain stable environmental and nutrient parameters, particularly Total Dissolved Solids (TDS), solution pH, temperature, humidity, and light intensity (Patel et al., 2024). Instability in these values may lead to plant stress, delayed growth, or even crop failure (Resh., 2022). Therefore, precise monitoring and rapid adjustment to field conditions are essential.

Hydroponics represents an innovative agricultural approach in which plants are cultivated without the use of soil, relying instead on water-based solutions enriched with essential minerals(Putra & Yuliando., 2015). This technique has been increasingly adopted because of its efficient resource utilization and its capacity to produce high-quality crops (Wildan & Anisa., 2024). By enabling controlled environment agriculture, hydroponics supports higher yields and facilitates plant cultivation in unconventional settings, including arid deserts and polar regions. Furthermore, its adaptability allows the method to be applied across a wide range of plant species, from fruit-bearing to ornamental, through various hydroponic systems and practices (Kumar et al., 2022; Putra et al., 2024).

However, in practice, hydroponic cultivation in the field, including at BGD Hydrofarm, still faces several challenges. Environmental conditions are monitored manually, making the process highly dependent on the operator's accuracy. In addition, the Standard Operating Procedures (SOPs) applied are static, existing as fixed documents that do not adapt to the daily variations in plant conditions. As a result, operational decisions are often inaccurate, slow, and prone to human error.

A review of the literature indicates that research on IoT-based hydroponic systems has advanced significantly in the domains of monitoring and automated control. For instance, Tatas et al. (2022) designed a low-cost IoT-based system called iPONICS, which integrates water and environmental quality sensors with fuzzy logic as the basis for irrigation control. Another study by Khadijah et al. (2024) expanded the scope of monitoring by employing multiple sensors—including pH, TDS, temperature, humidity, and light intensity—while optimizing communication through WiFi and LoRaWAN for real-time monitoring. Furthermore, Ching et al. (2025) developed a prototype for automatic nutrient control using pH and EC/TDS sensors in an NFT system, whereas Thakur et al. (2023) presented a comprehensive study integrating sensors, cloud platforms, and threshold-based control mechanisms. Nevertheless, these systems remain limited to static rule implementations, such as threshold values or fuzzy logic, resulting in standard operating procedures (SOPs) that are rigid and insufficiently adaptive to contextual variations.

Meanwhile, research on the application of Artificial Intelligence (AI) in agriculture has begun to demonstrate its potential to provide more adaptive solutions. Singh et al. (2024) introduced Farmer.Chat, a generative AI-based chatbot capable of delivering contextual recommendations for smallholder farmers. Although relevant, this study remains limited to linguistic consultation and has not yet been directed toward developing SOPs derived from sensor data. On the other hand, Agustian et al. (2022) employed a fuzzy inference system within an NFT hydroponic setup to automatically regulate pH and TDS; however, this approach is characterized more by dynamic rule-based control than by generative, conversation-driven interaction (Vishram et al., 2024).

BGD Hydrofarm is a community-based hydroponic enterprise operating at the micro–small business level and managed collaboratively by a small team of practitioners. The organization consists of several active members who are directly involved in daily cultivation activities, including nutrient management, plant monitoring, and harvesting. Although the members possess practical experience in hydroponic farming, their activities largely rely on manual observation and conventional record-keeping. Digital tools and automated decision-support systems have not yet been systematically adopted, resulting in high dependence on individual experience and increasing operational workload.

The selection of BGD Hydrofarm as a community partner was based on a preliminary needs assessment conducted through direct discussions and field observations. The assessment revealed three main challenges: manual monitoring of hydroponic parameters, the use of static and non-adaptive Standard Operating Procedures (SOPs), and limited digital literacy in utilizing emerging agricultural technologies. At the same time, BGD Hydrofarm demonstrated strong motivation to improve productivity and openness to technological innovation, making it a suitable partner with high potential for sustainable impact. These conditions justified the implementation of a technology-assisted community service program tailored to the partner's real operational needs (Gourshettiwar & Reddy, 2024).

Based on the identified research gap and field conditions, this community service program focuses on BGD Hydrofarm, a community-based hydroponic enterprise managed collaboratively at the micro–small business level. The organization consists of several active members involved in daily cultivation activities, including nutrient management, plant monitoring, and harvesting. Although the members possess practical experience in hydroponic farming, operations are still dominated by manual observation and static Standard Operating Procedures (SOPs), with limited adoption of digital technologies. Preliminary needs assessment conducted through discussions and field observations revealed key challenges, namely manual parameter monitoring, non-adaptive SOP implementation, and limited digital literacy. At the same time, BGD Hydrofarm demonstrated strong motivation and readiness to adopt technological innovations, making it a suitable partner with high potential for sustainable impact.

Therefore, this community service initiative was designed not only as a technological intervention but also as a social empowerment program aimed at fostering measurable behavioral and organizational change. Expected social outcomes include a shift from experience-based to data-driven hydroponic management, improved confidence in utilizing IoT- and AI-based systems, and strengthened institutional practices through adaptive digital SOPs. By integrating co-developed IoT infrastructure with generative AI and continuous partner assistance, this program seeks to transform static operational procedures into interactive, context-aware tools, thereby enhancing efficiency, reducing manual workload, and supporting the long-term sustainability of hydroponic practices at BGD Hydrofarm.

Method

Figure 1 illustrates the participatory process flow adopted in this community service program, emphasizing continuous collaboration between the service team and BGD Hydrofarm.

Figure 1. Participatory Process Flow of the Community Service Program at BGD Hydrofarm

Participatory Needs Assessment

An initial discussion was conducted with the management team of BGD Hydrofarm to identify the main challenges in hydroponic management. The discussion revealed that nutrient monitoring is still performed manually, the existing SOPs are static, and there is limited understanding of digital technology utilization. The results of this needs analysis served as the foundation for designing a system tailored to the partner's conditions.

Co-Design and Feedback Sessions

The co-design and feedback sessions were conducted collaboratively to ensure alignment with the daily operational needs of BGD Hydrofarm, with community members actively involved in defining system requirements and designing digital SOPs based on existing workflows and cultivation practices. Iterative feedback obtained through discussions and real-world trials enabled continuous refinement of the SOP structure, content, and usability, ensuring that the final system was practical, contextually relevant, and seamlessly integrated into routine hydroponic management. As a result, the team developed an IoT-based hydroponic monitoring system named GardenKeeper, which allows real-time observation of plant conditions via a mobile application installed on users' smartphones, as illustrated in Figure 2, presenting the successfully developed application interface.

Figure 2. UI/UX GardenKeeper Mobile App

System Development and Field Implementation

The co-developed solution was deployed directly within the hydroponic facilities of BGD Hydrofarm to support daily operational activities. Initial testing was conducted in real cultivation conditions to evaluate system functionality, usability, and compatibility with existing workflows. During this phase, partners actively used the system while providing feedback based on practical experience. Observations and partner input were used to make necessary adjustments, ensuring that the system operated reliably and aligned with routine hydroponic management practices before full-scale utilization.

The GardenKeeper IoT device was installed on the hydroponic system to monitor pH, TDS, temperature, humidity, and the visual condition of the plants. Subsequently, the GardenKeeper application was installed and configured on the partner's mobile device, including device registration and synchronization with the backend server. An initial trial was conducted to ensure proper connectivity among the IoT device, backend server, application, and Google Gemini AI. The results demonstrated that sensor data could be displayed in real time and that automated SOP recommendations were accessible through the Chat menu in the application.

Partner Training and Assistance

The training was delivered in the form of a workshop covering the operation of IoT devices, interpretation of sensor data, utilization of the GardenKeeper application, and understanding of automated SOPs. Real-world case simulations were provided, for example, when the pH level dropped below the threshold, the AI generated corrective instructions that were then directly practiced by the partner.

Monitoring & Participatory Evaluation

Monitoring and participatory evaluation were used to assess system use and social effects of the intervention. Observations were performed to investigate how the partners worked with the system as part of their daily hydroponic work and any changes in ordinary working practises. Furthermore, behavioral changes and technology adoption rates were evaluated from interviews regarding partners' perceived benefits and challenges. Findings were discussed with and validated by partners in order to inform accurate interpretation that reflects on productive learning for improvement.

Result

This community service program produced outcomes at both operational and social levels as a result of the participatory approach described in the Method section. Through participatory needs assessment, co-design, capacity building, and continuous mentoring, the co-developed system was integrated into daily hydroponic operations at BGD Hydrofarm. The results demonstrate not only improved efficiency in cultivation activities but also positive behavioral and organizational changes among community members.

System Adoption and Independent Use

Following the deployment of the GardenKeeper system, adaptive digital SOPs were integrated into daily hydroponic management, with partners accessing chat-based recommendations to support decisions on nutrient adjustment and plant care. Observations showed that SOP consultations increasingly guided operational decisions, replacing static documents and individual judgment, indicating that the co-developed SOPs were practical, contextually relevant, and aligned with established workflows. Independent system use during routine monitoring further demonstrated successful adoption, as illustrated in Figure 3, which presents the GardenKeeper mobile application interface implemented and utilized by BGD Hydrofarm for hydroponic SOPs.

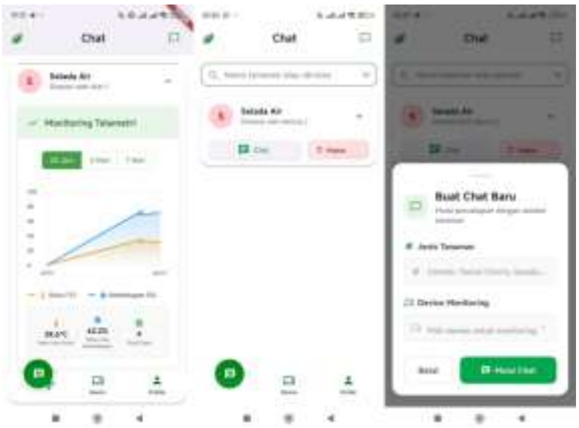

Figure 3. Home screen display of GardenKeeper

Results of Partner Assistance

This stage represents the core of the community engagement program, during which technology was introduced to the partner, namely BGD Hydrofarm. The activities were conducted through a combination of workshops and hands-on field practice as ilustrated in Figure 4 and 5. The workshop sessions covered the following topics:

- Introduction to the fundamentals of IoT-based hydroponic systems.
- Utilization of the GardenKeeper application.
- Simulation of monitoring scenarios and corrective adjustments to nutrient parameters.
- Troubleshooting of IoT devices and the application.

Figure 4. One of the Training Workshop Activities with the Partner and Hands-on Practice in Using the Equipment

Community-Level Outcomes and Social Changes

1. Behavioral Shifts toward Data-Driven Decision Making

A key outcome of the program was a behavioral transition from experience-based practices to data-driven hydroponic management. Prior to the intervention, decisions were made individually based on manual observations. After implementation, system-generated SOP recommendations became a shared reference for collective decision-making among community members. One partner stated: "We no longer rely only on experience. The SOP recommendations help us decide what to do and when to act." This finding reflects the effectiveness of adaptive digital SOPs as tools for guiding consistent and timely actions.

2. Improvement in Digital Literacy and Confidence

Consistent with the capacity-building activities described in the Method section, partners demonstrated improved confidence in using digital and AI-based tools. Initial hesitation during early training sessions gradually decreased as members became familiar with interpreting system recommendations and applying them in real cultivation scenarios. By the end of the program, partners independently operated the application and discussed system outputs collectively.

Monitoring and Evaluation

Based on direct observations, the IoT–AI system operated stably and was readily adopted by the partner after the mentoring sessions without significant obstacles. The partner reported that the system reduced manual workload and accelerated decision-making processes. Interviews further indicated an improvement in the partner's understanding and confidence in utilizing digital technologies.

External evaluations provided broader recognition:

- The Ministry of Cooperatives and SMEs, represented by Reza Fabianus, highlighted that this system has the potential to serve as a national model for cooperatives and SMEs in the field of modern agriculture.
- The Institute for Global Environmental Strategies (IGES), represented by Dr. Sudarmanto Budi Nugroho, emphasized the importance of sustainable environmental practices, particularly the management of hydroponic waste to support zero-waste principles.

Figure 6. Direct Review by External Stakeholders

Both parties expressed full support for this program and acknowledged that cross-sector collaboration among universities, cooperatives, SMEs, and international institutions represents a strategic step toward strengthening modern, technology-driven agriculture and promoting environmentally sustainable innovation.

Figure 7. Group Photo of the Team, Partner, and Representatives from the Ministry of Cooperatives and SMEs and IGES

Before–After Comparison of Hydroponic Management Practices

Table 1 summarizes changes observed between baseline conditions and post-intervention practices at BGD Hydrofarm.

Table 1: Before–After Comparison of Hydroponic Management Practices

Aspect	**Before Program**	**After Program**
SOP Format	Static, document-based	Adaptive, digital
Decision-making	Individual, experience-based	Collective, SOP-guided
Monitoring activities	Manual and repetitive	Condition-driven
Operational errors	Frequent	Reduced
Digital confidence	Low	Increased

An additional outcome of the program was the emergence of informal coordination roles related to the use of the digital SOP system. One member informally assumed responsibility for supporting SOP consultation and system usage during daily operations. Decision-making also became more collaborative, with system recommendations discussed jointly before execution, indicating strengthened institutional practices within the community.

Discussion

The results of this community service program demonstrate that the co-development of adaptive digital SOPs successfully addressed the main challenges identified at BGD Hydrofarm, namely manual monitoring practices, static operational guidelines, and limited digital literacy. These findings directly answer the program's objective of transforming hydroponic management from experience-based practices toward data-driven and collaborative decision-making.

From an operational perspective, the integration of IoT-based monitoring with generative AI enabled real-time environmental assessment and context-aware SOP recommendations. This finding is consistent with previous studies indicating that IoT systems significantly improve accuracy and efficiency in hydroponic management by reducing dependence on manual observations (Tatas et al., 2022; Khadijah et al., 2024). However, unlike earlier implementations that relied on static threshold rules or fuzzy logic, the adaptive SOPs generated in this program provided interactive and situational guidance, allowing partners to respond more appropriately to dynamic cultivation conditions. This supports recent arguments that generative AI can enhance decision-support systems by translating sensor data into actionable knowledge rather than fixed control commands (Singh et al., 2024; Vishram et al., 2024).

Beyond technical improvements, the most significant outcomes of this program were social and behavioral changes within the partner community. The observed shift from individual, experience-based decision-making to collective, SOP-guided practices reflects increased organizational learning and shared responsibility. This aligns with participatory community service theory, which emphasizes that sustainable technology adoption occurs when communities are actively involved as co-creators rather than passive recipients (Gourshettiwar & Reddy, 2024). The co-design process used in this program strengthened local ownership and ensured that digital SOPs were perceived as practical and contextually relevant, facilitating long-term adoption.

The improvement in digital literacy and confidence among community members further highlights the importance of continuous mentoring and hands-on training. Consistent with capacity-building literature, skills transfer and behavioral change were not achieved through system deployment alone but through iterative learning supported by real operational scenarios (Putra & Yuliando, 2015; Monisha et al., 2023). This explains why partners were able to independently operate the system and trust AI-generated recommendations over time.

In comparison with previous IoT-based hydroponic initiatives that primarily focused on automation and control efficiency (Ching et al., 2025; Patel et al., 2024), this program extends existing knowledge by demonstrating how adaptive digital SOPs can function as social learning tools. The emergence of informal coordination roles and collective discussion prior to operational decisions indicates institutional strengthening within the community, an outcome that is rarely discussed in technically oriented hydroponic system studies.

At a broader level, the findings suggest that integrating participatory approaches with adaptive digital technologies can amplify the social impact of community service programs in agriculture. External recognition from governmental and international stakeholders further supports the potential scalability of this model for other small-scale hydroponic communities seeking sustainable and technology-driven transformation.

Nevertheless, this program was implemented in a single community context, which may limit the generalizability of the findings. Future community service initiatives could involve multiple partner sites and longer-term evaluations to assess sustained behavioral change and institutional resilience. Further development of predictive features and expanded AI explainability may also enhance trust and effectiveness in adaptive digital SOP systems.

Conclusion

This community service program demonstrates that the co-development of adaptive digital Standard Operating Procedures (SOPs) can serve as an effective community engagement strategy rather than merely a technological intervention. Throughout the program, members of BGD Hydrofarm actively participated in all stages, including needs identification, co-design of operational workflows, system testing, and participatory evaluation. This collaborative approach positioned the community as co-creators, ensuring that the solution reflected local practices and real operational challenges.

Beyond technical implementation, the program resulted in meaningful social changes within the partner community. Observable outcomes included a shift from experience-based to data-driven hydroponic management, increased confidence in utilizing digital and AI-based tools, and the emergence of more collaborative decision-making practices. The adoption of adaptive digital SOPs reduced dependency on individual expertise and strengthened shared responsibility among members, indicating improved organizational learning and institutional capacity.

From a broader community service perspective, this case study highlights several key lessons. First, technology-driven community programs are more sustainable when developed through participatory and co-design approaches. Second, capacity building and continuous mentoring are critical for fostering behavioral change and long-term adoption. Finally, adaptive digital SOPs can function as social learning tools that support collective decision-making, not merely as technical guidelines. These insights offer valuable guidance for future community service initiatives seeking to integrate digital innovation with meaningful social empowerment in agricultural and other community-based contexts.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article. All activities were conducted in accordance with institutional ethical standards and partner agreements.

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