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Revitalization of an IoT-Based Greenhouse as a Solution for Precision and Sustainable Agriculture

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ABSTRACT

The community partnership program was designed to revitalize the greenhouse at the Taman Teknologi Pertanian (TTP) Kutai Kartanegara through the integration of Internet of Things (IoT) based automation and frugal innovation. The initiative was implemented collaboratively by Politeknik Negeri Samarinda using a participatory action approach that actively involved local farmers throughout the planning, implementation, and evaluation processes. The program was executed in four structured phases: (1) Preliminary Assessment and Consultation, which identified inefficiencies in the existing sprinkler irrigation system; (2) Design and Prototyping, which developed a low-cost screw-adjusted drip irrigation model allowing precise water control; (3) IoT System Development, which incorporated DHT sensors, relay switches, and smartphone-based control for real-time monitoring; and (4) Installation and Training, which ensured full system implementation and capacity building among participating farmers. The results showed a successful transformation of the greenhouse into an automated and efficient agricultural environment, significantly enhancing crop management and resource optimization. The new system allowed both manual and automatic operation, improving water-use efficiency and reducing maintenance efforts while minimizing environmental impact. Moreover, the participatory training strengthened farmers' digital and technical competencies, enabling them to manage and maintain the IoT-based system independently with increased confidence and adaptability. The program's outcomes highlight how affordable, context-appropriate technology, when supported by community participation and institutional collaboration, can contribute to sustainable and inclusive agricultural innovation. Ultimately, this initiative serves as a scalable and replicable model for integrating low-cost digital technology into smallholder farming systems, promoting productivity, resilience, and the digital transformation of rural agriculture in Indonesia.
***Keywords**: Community Empowerment, Frugal Innovation, IoT-based Greenhouse, Precision Agriculture, Sustainable Farming*

ABSTRAK

Program kemitraan masyarakat ini dirancang untuk merevitalisasi greenhouse di Taman Teknologi Pertanian (TTP) Kutai Kartanegara melalui integrasi otomatisasi berbasis Internet of Things (IoT) dan inovasi frugal (tepat guna). Inisiatif ini dilaksanakan secara kolaboratif oleh Politeknik Negeri Samarinda menggunakan pendekatan tindakan partisipatif (participatory action) yang secara aktif melibatkan petani lokal di sepanjang proses perencanaan, pelaksanaan, dan evaluasi. Program ini dilaksanakan dalam empat tahapan terstruktur: (1) Penilaian Awal dan Konsultasi, yang mengidentifikasi inefisiensi pada sistem irigasi sprinkler yang ada; (2) Perancangan dan Pembuatan Prototipe, yang mengembangkan model irigasi tetes berbiaya rendah dengan penyesuaian sekrup yang memungkinkan kontrol air secara presisi; (3) Pengembangan Sistem IoT, yang menggabungkan sensor DHT, sakelar relai, dan kontrol berbasis ponsel pintar untuk pemantauan secara real-time; dan (4) Instalasi dan Pelatihan, yang memastikan implementasi sistem secara penuh serta peningkatan kapasitas di kalangan petani peserta. Hasil kegiatan menunjukkan keberhasilan transformasi greenhouse menjadi lingkungan pertanian yang otomatis dan efisien, sehingga secara signifikan meningkatkan manajemen tanaman dan optimalisasi sumber daya. Sistem baru ini memungkinkan pengoperasian secara manual maupun otomatis, meningkatkan efisiensi penggunaan air, dan mengurangi upaya perawatan sekaligus meminimalkan dampak lingkungan. Selain itu, pelatihan partisipatif ini memperkuat kompetensi digital dan teknis para

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petani, sehingga memungkinkan mereka untuk mengelola dan merawat sistem berbasis IoT tersebut secara mandiri dengan tingkat kepercayaan diri dan kemampuan adaptasi yang lebih tinggi. Capaian program ini menyoroti bagaimana teknologi yang terjangkau dan sesuai konteks, apabila didukung oleh partisipasi masyarakat dan kolaborasi institusional, dapat berkontribusi pada inovasi pertanian yang berkelanjutan dan inklusif. Pada akhirnya, inisiatif ini berfungsi sebagai model yang dapat diskalakan dan direplikasi untuk mengintegrasikan teknologi digital berbiaya rendah ke dalam sistem pertanian berskala kecil, guna mendorong produktivitas, ketahanan, dan transformasi digital pada sektor pertanian perdesaan di Indonesia.
Kata Kunci: *Greenhouse* Berbasis IoT, Inovasi Frugal, Pemberdayaan Masyarakat, Pertanian Berkelanjutan, Pertanian Presisi

BACKGROUND

The rapid advancement of Internet of Things (IoT)–based smart farming presents significant opportunities to enhance agricultural efficiency, productivity, and environmental sustainability in Indonesia. However, adoption remains limited due to high implementation costs, technical complexity, and low digital literacy among smallholder farmers who dominate the sector (Hugeng et al., 2023; SUSANTI et al., 2021; Tubagus & Mahyuni, 2024; Wanda et al., 2024). These challenges are compounded by inadequate digital infrastructure and uneven internet access in rural areas, constraining farmers' ability to fully integrate IoT systems into their practices (Johan et al., 2024; Lokot Muda Harahap et al., 2024).

To accelerate adoption, stronger collaboration between the government, private sector, and non-profit organizations is essential. Policy instruments such as financial incentives, rural connectivity programs, and farmer training initiatives can reduce entry barriers and enhance digital readiness (Larasati et al., 2024; Lokot Muda Harahap et al., 2024; Muhida, 2025). Pilot projects and demonstrations can further build trust by showcasing tangible benefits of IoT systems in improving efficiency and sustainability (Konita Lutfiyah et al., 2025). In a broader context, integrating IoT with artificial intelligence, big data analytics, and blockchain offers transformative potential for Indonesian agriculture, though this requires clear regulatory frameworks to address data privacy and ethical use (Barki & Rachmah, 2024).

Precision agriculture, or smart farming, represents a transformative model that integrates advanced technologies such as sensors, drones, GPS, and Internet of Things (IoT) systems with automation and data analytics to optimize agricultural operations. This approach enables real-time monitoring and data-driven decision-making, improving efficiency, productivity, and environmental sustainability (Dong & Ren, 2025; Tyagi et al., 2024). Supported by artificial intelligence and predictive analytics, precision agriculture enhances yield forecasting, soil monitoring, and irrigation management while minimizing resource waste and emissions (Branzova, 2024; Pandey, 2025; Roy, 2025). Despite its potential to increase profitability and support global food security, widespread adoption remains limited by high costs, low technical capacity, and weak infrastructure. Overcoming these barriers through policy support, capacity-building, and digital inclusion is essential for achieving sustainable and equitable agricultural transformation (Dong & Ren, 2025; Sharma, 2023; Shigueoka & Cavichioli, 2025).

Kutai Kartanegara Regency in East Kalimantan is predominantly an area of smallholder agriculture that confronts ongoing difficulties due to inadequate irrigation infrastructure and limited uptake of contemporary agricultural equipment. Local studies indicate that poor irrigation infrastructure limit planting intensity and decreased production, emphasizing persisting water management constraints in the region (Niaga Asia, 2025). Moreover, local authorities observe that numerous farmers continue to depend on traditional, labor-intensive methods due to their restricted ability to embrace and utilize current technology, leading to inconsistent technological adoption (Niaga Asia, 2025). These characteristics indicate that traditional farming practices are inadequate for fostering efficient and sustainable agriculture. Thus, the implementation of Smart Farming IoT is essential for facilitating accurate irrigation, real-time environmental surveillance, and automated management, which directly mitigate water inefficiency, labor reliance, and climate-associated hazards. The deployment of Smart Farming IoT at Taman Teknologi Pertanian (TTP) Kutai

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Kartanegara constitutes a pertinent and contextually suitable solution to local agricultural issues.

Furthermore, preliminary assessments indicated that the existing greenhouse infrastructure required significant modernization, particularly in irrigation control, temperature regulation, and energy efficiency. Building upon the successful first-year collaboration in 2024, during which Politeknik Negeri Samarinda introduced a misting sprayer and automatic watering system. The second-year program in 2025 aimed to revitalize the physical and operational components of the greenhouse, develop an IoT-enabled irrigation and environmental monitoring system, and empower local farmers through participatory training and technology transfer. These initiatives are closely aligned with both national and global agendas promoting sustainable agricultural transformation through affordable digital innovation. The integration of frugal innovation principles was particularly significant, ensuring that the technological interventions remained cost-effective, locally adaptable, and easily maintainable, thereby enhancing the long-term viability and inclusiveness of smart farming initiatives (Vasavi et al., 2025).

METHOD

Papers Participatory Action Research (PAR) is a research methodology that emphasizes community involvement, action-oriented solutions, and collaborative knowledge creation. In PAR, community members are actively engaged as co-researchers, ensuring that the research is rooted in their lived experiences, thus empowering participants by giving them control over the knowledge produced about their lives and social issues (Brown, 2024a). The approach is action-oriented, focusing not only on understanding social problems but also on taking concrete steps to address them through iterative cycles of planning, action, and reflection, which are integral to the PAR process (Mapfumo et al., 2013a). Furthermore, PAR promotes collaborative knowledge creation, where both researchers and community members co-construct solutions to identified problems. This collaborative approach enhances the relevance and sustainability of the outcomes, ensuring that solutions are both practical and enduring (Dagneau et al., 2025; Day, 2009). The program proceeded through four structured phases:

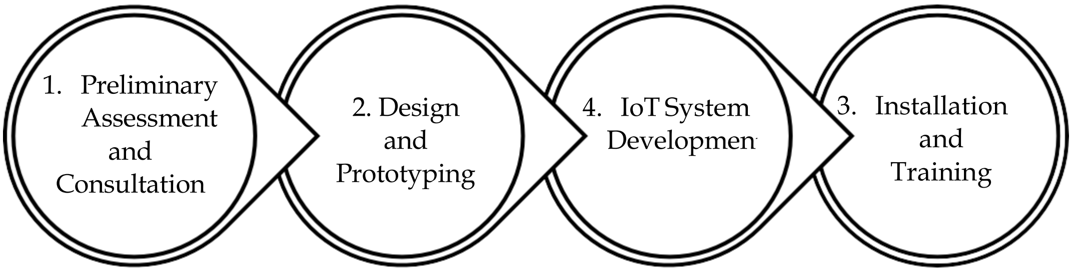

Figure 1. Phases of the IoT-Based Greenhouse Revitalization Program
Processed by the authors, 2026

The project proceeded through a structured series of phases aimed at enhancing the functionality and sustainability of the greenhouse system. In the Preliminary Assessment and Consultation phase, field surveys and collaborative discussions were conducted with TTP greenhouse operators to identify the technical and operational limitations of the existing system. During the Design and Prototyping phase, several low-cost irrigation prototypes were developed and tested. The final model, an innovative screw-adjusted drip irrigation system, was designed to deliver water precisely to the plant roots without wetting the surrounding soil. The screw mechanism facilitated the easy detection and correction of blockages, thereby improving durability and usability. In the IoT System Development phase, various IoT modules, including ESP32 controllers, DHT sensors, and water relays, were installed to automate both irrigation and environmental monitoring. The system was integrated into a smartphone interface, allowing for realtime data access and remote-control capabilities. Finally, during the Installation and Training phase, hardware components such as water tanks, dual pumps, lightweight steel frames, pipes, and electrical parts were installed. Farmers were

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subsequently trained to operate the IoT system, interpret sensor data, and perform necessary maintenance tasks to ensure long-term system efficiency.

The effectiveness of the activities was assessed utilizing a multi-faceted approach often employed in Participatory Action Research (PAR) and Internet of Things (IoT)-based precision agricultural investigations. The assessment included technical performance, operational efficiency, and capacity-building results. The technical performance was evaluated via direct system testing and observation, concentrating on the reliability of IoT components, sensor responsiveness, irrigation control precision, and system functionality, as suggested in smart farming assessment studies (Kim & Jung, 2022; Torky & Hassanein, 2020). Operational effectiveness was assessed by contrasting conditions prior to and after implementation, utilizing metrics such as water-use efficiency, irrigation uniformity, labor reduction, and system usability, which are commonly employed in evaluations of automated irrigation and precision agriculture (Psaltis et al., 2018; Xue et al., 2017). Capacity-building outcomes were evaluated via practical demonstrations, supervised practice, and reflective discussions to gauge farmers' proficiency in independently operating, maintaining, and troubleshooting the system, in alignment with PAR-based evaluation methodologies that prioritize empowerment and skill development (Brown, 2024b; Mapfumo et al., 2013b). This comprehensive evaluation method guaranteed that program success was assessed not solely by technological performance but also by enhancements in operational efficiency and community capability.

RESEARCH LOCATION

This community partnership program was conducted at the greenhouse located in the Taman Teknologi Pertanian (TTP) Kutai Kartanegara Regency, East Kalimantan Province. The selection of this location was based on preliminary assessments indicating that the existing greenhouse infrastructure required significant modernization, particularly in irrigation control, temperature regulation, and energy efficiency. Furthermore, Kutai Kartanegara is predominantly an area of smallholder agriculture that confronts ongoing difficulties due to inadequate irrigation infrastructure and the limited adoption of modern agricultural technology by local farmers. Thus, the deployment of IoT-based smart farming at TTP Kutai Kartanegara constitutes a pertinent and contextually suitable solution to address the local agricultural challenges.

RESULT AND DISCUSSION

The community service program was implemented in four sequential phases, each contributing to the successful revitalization and automation of the greenhouse system at Taman Teknologi Pertanian (TTP) in Kutai Kartanegara.

Phase 1: Preliminary Assessment and Consultation

In the Preliminary Assessment and Consultation phase, an on-site evaluation was conducted at the Agricultural Technology Park (TTP) in Kutai Kartanegara to assess the condition of the greenhouse and its existing irrigation system. As shown in the image, the greenhouse relied on a sprinkler-based irrigation system positioned at the centre of the planting beds. This system dispersed water across the entire area, wetting not only the planting surfaces but also the surrounding walkways and structural components. Such a configuration resulted in inefficient water management, as a large portion of water was lost through evaporation and surface runoff rather than reaching the plant roots. Moreover, the water distribution pattern was uneven certain areas of the planting beds became overly saturated, while other sections received little or no water, leading to inconsistent soil moisture and uneven crop growth potential. The greenhouse's overall condition prior to intervention also showed signs of neglect, including overgrown weeds, uneven planting beds, and deteriorated infrastructure. These observations highlighted the urgent need for a more precise, efficient, and sustainable irrigation system, which subsequently guided the design and development of an IoT-based drip irrigation model in the following project phases.

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Figure 2. Initial condition of the TTP greenhouse showing the sprinkler system causing uneven water distribution and inefficient irrigation.
Source: Author's personal collection, 2026

Phase 2: Design and Prototyping

Based on the initial assessment, several low-cost irrigation prototypes were designed and tested collaboratively with local stakeholders. In the Design and Prototyping phase, several irrigation technologies were tested to identify a system that was both affordable and practical for smallholder use. As shown in the image, initial trials involved commercial sprinkler and drip irrigation components. However, to reduce procurement costs and improve local adaptability, a frugal innovation approach was introduced by modifying standard PVC pipes with screw (bolt) mechanisms. This design innovation enabled both manual and automatic water control, allowing users to regulate flow at specific points without complex tools or expensive equipment. The system also made it easy to identify and repair damaged or non-functioning sections, significantly reducing maintenance time and effort. Overall, this low-cost, screw-adjusted pipe system offered a more efficient, sustainable, and labour-saving alternative to commercial sprinkler or drip systems.

Figure 3 Prototype testing of irrigation components and the development of a low-cost screw adjusted pipe system as a frugal innovation for efficient water management.
Source: Author's personal collection, 2026

Phase 3: Iot System Development and Implementation

During the IoT System Development and Implementation phase, automation technology was incorporated into the greenhouse irrigation system to enhance operational efficiency and control accuracy. The system integrated environmental monitoring with IoT-based actuation to enhance irrigation management decisions. Temperature and humidity levels within the greenhouse were assessed using DHT sensors, delivering real-time environmental data pertinent to watering

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choices. These data facilitated more precise scheduling of irrigation activities by representing the microclimatic conditions within the greenhouse.

The irrigation pumps delivering water from storage tanks to the greenhouse planting beds were linked to a WiFi-enabled smart power strip, which served as the primary IoT actuator controller. Farmers can utilize a smartphone application to remotely oversee system status and control specific irrigation units in real time, either manually or based on operational requirements. Figure 4 demonstrates that this configuration integrates sensors, intelligent power management, irrigation pumps, and the greenhouse cultivation zone into a cohesive system. This IoT-based strategy diminished manual labor needs, increased water-use efficiency, and augmented operational flexibility, facilitating the digital revolution of smallholder greenhouse agriculture.

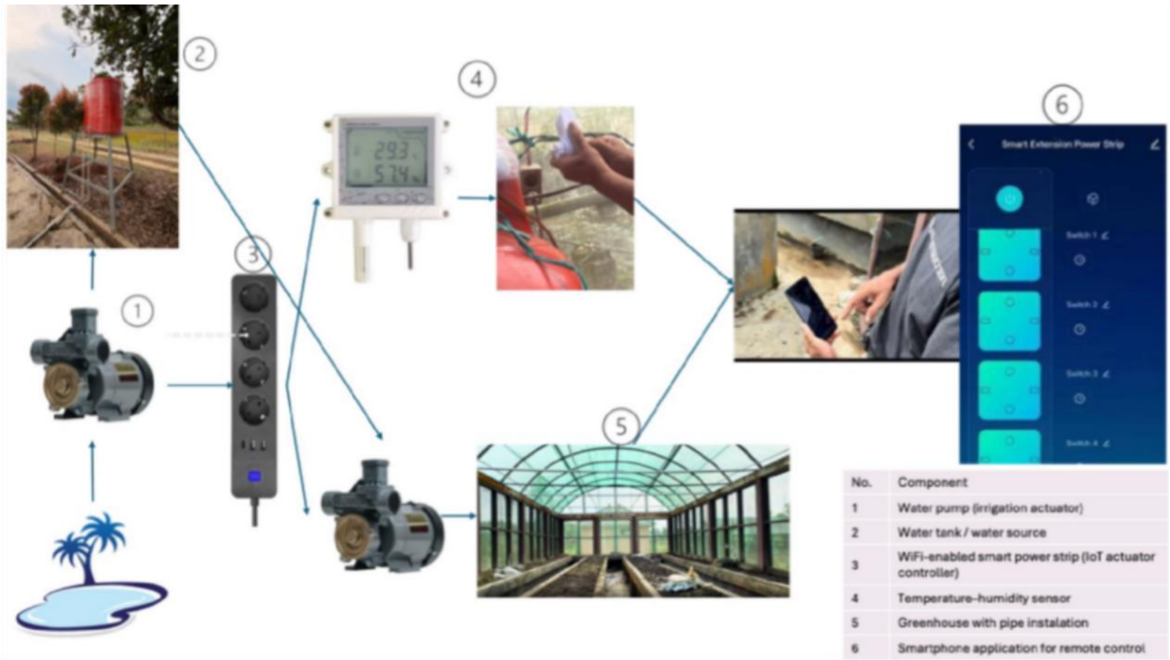

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Figure 4 Implementation of an IoT-Based Greenhouse Irrigation System
Source: Author's personal collection, 2026

Phase 4: Installation and Training

In the Installation and Training phase, the project team completed the setup of key infrastructure components and conducted community training to ensure the effective operation of the automated greenhouse system. As shown in the images, the installation included essential components such as a water tank, two water pumps, lightweight steel frames, pipes, electrical wiring and a range of Internet of Things (IoT)-based devices that supported system automation and monitoring. This infrastructure enabled stable water pressure, efficient irrigation, and real-time environmental data collection within the greenhouse. In conjunction with the installation, the team organized hands-on training sessions for local farmers and greenhouse operators, focusing on IoT system operation, data interpretation, troubleshooting, and maintenance procedures. These participatory activities enhanced farmers’ confidence and technical capability in managing both manual and automated irrigation modes. The phase concluded with a collaborative session and documentation involving all participants, reflecting the spirit of shared ownership, sustainability, and community empowerment fostered through the program.

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Figure 5 Installation of key greenhouse infrastructure and community training session with local farmers at TTP
Source: Author's personal collection, 2026

DISCUSSION

The implementation of the IoT-based greenhouse revitalization program at the TTP demonstrates how community-driven technological innovation can enhance agricultural efficiency and sustainability. The introduction of a low-cost screw-adjusted irrigation system improved water use efficiency compared to the previous sprinkler setup, reflecting the success of a frugal innovation approach that balances affordability, durability, and ease of maintenance (Hindocha et al., 2021). The participatory design process also ensured that farmers were directly involved, increasing system acceptance and long-term usability.

The integration of IoT modules, including DHT sensors and smart relay switches, enabled real-time environmental monitoring and remote irrigation control via smartphones. This digital system reduced manual workload and improved precision in water management, aligning with global trends in smart and sustainable farming (Dong & Ren, 2025; Tyagi et al., 2024). Training and mentoring activities further strengthened local technical capacity, empowering farmers to independently manage and maintain the system. Overall, this initiative illustrates how Participatory Action Research (PAR) and frugal innovation can complement each other to achieve inclusive, scalable, and sustainable agricultural transformation at the community level (Brown, 2024a; Dagneau et al., 2025).

The efficacy of the greenhouse revitalization initiative was assessed through a multi-faceted evaluation framework aligned with Participatory Action Research (PAR). Program outcomes were evaluated across three dimensions: technical performance, operational efficiency, and capacity-building impact. The reliable operation of the IoT-based irrigation system, characterized by stable sensor monitoring and responsive pump control through the smart power management device, indicated technical success (Et-Taibi et al., 2024). Operational success was demonstrated through enhanced irrigation uniformity, diminished water loss, and decreased dependence on human labor relative to pre-intervention conditions (Bhagat et al., 2024). The efficacy of capacity-building was evidenced by farmers' proficiency in independently operating the smartphone-based control system and executing basic system maintenance post-training (Rahman et al., 2025). Collectively, these indications validate that the program's effectiveness was assessed by both technological efficacy and tangible community-level results.

CONCLUSION AND RECOMMENDATION

The community service program at the Taman Teknologi Pertanian (TTP) in Kutai Kartanegara successfully revitalized the greenhouse through the integration of IoT-based automation and frugal innovation. The transition from an inefficient sprinkler system to a screw-adjusted drip irrigation model significantly improved water-use efficiency and reduced maintenance complexity. The installation of IoT components such as sensors, relay switches, and smartphone connectivity enabled real-time monitoring and both manual and automatic control of irrigation, enhancing precision and reducing labor intensity.

Moreover, participatory training and mentoring activities empowered local farmers to operate,

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maintain, and troubleshoot the system independently, strengthening their technical and digital capabilities. Overall, this initiative demonstrates that affordable, context-appropriate technologies combined with community participation can produce sustainable and scalable solutions for smallholder farming systems, supporting Indonesia's broader transition toward precision and sustainable agriculture.

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