Smart farming for marginal farmers: implementing IoT-based irrigation systems through community workshops

Matsaini
Universitas Madura, Indonesia

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ABSTRACT

Background: This community service addresses persistent water inefficiency and technological exclusion among marginal farmers in rain-fed agricultural areas of East Java. **Objective:** The program aimed to enhance farmers' capacity to adopt and operate simple IoT-based irrigation systems through participatory workshops and field mentoring. **Method:** A participatory approach was implemented, combining planning, hands-on training, demonstration plots, and continuous mentoring with monitoring and evaluation. **Results:** The program led to reduced irrigation frequency and water use, improved crop uniformity, and increased farmer autonomy, alongside gains in technological understanding and shifts toward data-driven irrigation decisions, supported by collective learning and institutional engagement. **Implication:** These findings suggest that affordable, community-based smart farming interventions can improve resource efficiency and strengthen technological inclusion among marginal farmers. **Novelty:** The program introduces an adaptive IoT-based irrigation model that integrates low-cost technology, participatory learning, and shared governance as a scalable approach for sustainable agriculture in resource-constrained settings.

Corresponding Author:

Matsaini
Universitas Madura, Indonesia
Jl. Raya Panglegur KM. 3,5, Jalmak, Pamekasan, Jawa Timur, 69317, Indonesia
Email: matsaini@unira.ac.id

1. INTRODUCTION

Smallholder and marginal farmers remain among the most vulnerable groups within contemporary agricultural systems, particularly in regions characterized by climate variability and limited irrigation infrastructure. In Indonesia, more than 55% of farmers operate on landholdings smaller than 0.5 hectares, with East Java representing one of the provinces where rain-fed agriculture remains dominant. In Bondowoso Regency, including Sumberwringin and Tegalampel villages, agricultural production relies heavily on seasonal rainfall and manual irrigation practices, exposing farmers to water scarcity, yield instability, and rising operational costs. The Food and Agriculture Organization reports that inefficient irrigation practices can waste up to 30–40% of available water in small-scale farming systems, exacerbating environmental stress and economic vulnerability. This situation is compounded by empirical findings from preliminary village surveys indicating that over 60% of farmers irrigate without soil-moisture measurement and nearly 70% have never engaged with sensor-based agricultural technologies. These conditions underscore why this community service initiative is not only timely but structurally necessary.

Existing literature and community-based programs have increasingly promoted smart farming and Internet of Things (IoT) applications as strategic responses to water inefficiency and climate risk in agriculture [1], [2], [3]. Previous studies document that IoT-based irrigation systems can reduce water consumption by 20–35% while improving crop productivity through data-driven decision-making [4], [5], [6]. Community engagement initiatives in developing regions have also demonstrated that participatory training and demonstration plots enhance farmers' acceptance of new technologies [1], [7]. However, most documented programs focus on commercial farms, technologically literate users, or pilot projects without sustained mentoring. What remains underexplored is a community service model that integrates low-cost, locally adaptable IoT irrigation with hands-on workshops tailored specifically to marginal farmers with limited digital literacy. This gap—between technological innovation and grassroots applicability—constitutes the primary rationale for implementing this community-oriented intervention.

This community service program aims to address structural water-management challenges and technological exclusion faced by marginal farmers through participatory workshops and sustained field mentoring. The central objective of this initiative is to enhance farmers' capacity to adopt and operate simple, affordable IoT-based irrigation systems that align with their socio-economic and agro-ecological contexts. More specifically, this program seeks to improve farmers' understanding of soil-moisture-based irrigation, reduce reliance on intuition-driven watering practices, and foster collective learning through shared systems and demonstration plots. The guiding questions of this initiative are whether participatory IoT workshops can effectively increase technological literacy among marginal farmers and whether community-based mentoring can translate technical knowledge into independent practice. By targeting 20–30 farmers per village and combining training with real-time application, this program positions learning as an experiential and community-embedded process rather than a one-off technological transfer.

The expected implications of this community service extend beyond technical skill acquisition toward broader socio-economic and institutional transformation. At the individual level, this program anticipates measurable improvements in farmers' capacity to manage irrigation efficiently and autonomously. At the group level, this initiative is designed to strengthen farmer collectives as local hubs of knowledge exchange and technological diffusion. Institutionally, this program reinforces the role of farmer groups and agricultural extension officers in facilitating precision-farming adoption among marginalized communities. In the medium term, this intervention offers a replicable model of low-cost smart farming capable of reducing water use by 20–30% and increasing productivity by 10–15%. These anticipated outcomes position this community service not merely as a technical intervention, but as a strategic contribution to sustainable agriculture, climate resilience, and inclusive rural development.

2. METHOD

This community service adopted a participatory and practice-oriented planning approach tailored to marginal farmers in Sumberwringin and Tegalampel villages. Planning focused on aligning program activities with farmers' agro-ecological conditions, resource constraints, and institutional settings. This phase produced a structured activity framework combining socialization, training, field practice, and evaluation. Table 1 summarizes the complete activity plan, including objectives, participants, duration, outputs, and responsible actors. Such systematic planning is essential to ensure coherence between program goals and field realities, as emphasized in participatory agricultural extension literature [8], [9]. Consequently, this planning phase functioned as the foundation for operational clarity and stakeholder coordination within this community service.

Table 1. Activity plan of this community service program

Phase	Activity	Participants	Time	Output	Responsible
Plan	Needs & survey	Farmers/PPL	1 wk	Water map	Team/PPL
Plan	Design & module	Facilitators	1 wk	IoT + module	Univ team
Impl.	Workshop	20–30 farmers	1 d	Awareness	Facilitators
Impl.	Training	Farmers	2 sess	Skills	Facilitators
Impl.	Mentoring	Farmers	4–8 wk	Indep. use	Team
Eval	Monitoring	All	Ongoing	Impact	Team

* Plan: planning; impl.: implementation; eval.: evaluation; wk.: week; sess: session

This planning stage further emphasized program design through participatory needs mapping and strategic formulation. Farmers' irrigation practices, crop types, and seasonal constraints were identified through interviews and observation, enabling the customization of IoT irrigation systems using affordable sensors and shared infrastructure. This design strategy reflects evidence that locally adapted smart farming solutions yield higher adoption rates among smallholders. Based on these findings, this program formulated an implementation strategy combining classroom-style workshops, demonstration plots, and continuous mentoring. Thus, this planning phase ensured that technological intervention remained context-sensitive, feasible, and socially acceptable [10], [11].

Implementation relied on diverse and credible sources of information to support knowledge transfer and decision-making. Primary information sources included marginal farmers as participants, farmer groups and village authorities as institutional partners, and agricultural extension officers as technical advisors. Facilitators from agricultural and engineering disciplines provided expertise in irrigation management and IoT system configuration. Secondary sources consisted of training manuals, sensor user guides, agricultural extension documents, and relevant smart farming studies. The integration of experiential knowledge from farmers with scientific and technical references aligns with community service best practices, ensuring that this program combined empirical relevance with academic rigor [12], [13].

The implementation process followed sequential and iterative stages designed to reinforce learning through practice. Initial activities focused on socialization and awareness-building, followed by hands-on training in sensor installation, automated irrigation control, and dashboard interpretation. This was complemented by field-based mentoring on demonstration plots, where farmers applied the system directly to their crops. Continuous troubleshooting and peer discussion were integral to this process, reflecting evidence that sustained accompaniment enhances technology adoption among marginal farmers. Therefore, this implementation phase positioned farmers as active learners and co-managers of innovation rather than passive recipients [14], [15].

Evaluation in this community service employed both formative and summative approaches to assess effectiveness and impact. Formative evaluation occurred during mentoring through observation and feedback sessions, allowing real-time adjustment of interventions. Summative evaluation involved pre–post assessments of farmers' technological understanding, monitoring of water usage efficiency, and documentation of operational independence. These methods are consistent with evaluation frameworks in participatory agricultural programs, which emphasize learning outcomes and behavioral change. Overall, this evaluation phase provided an evidence-based foundation for reflection, accountability, and future replication of this program.

3. RESULTS

3.1. Needs mapping, system design, and readiness preparation

This section presents outcomes from this community service planning phase, focusing on needs assessment, system design, and implementation readiness. As shown in Table 2, planning was treated as a critical knowledge-producing stage rather than a purely administrative step, as it determined alignment between technological intervention and farmers' real capacities. Through surveys, field observations, and participatory discussions, this phase generated empirical data on irrigation practices, technological exposure, and infrastructural readiness among marginal farmers. These findings guided the selection of appropriate IoT components, training formats, and mentoring strategies. Consequently, this planning phase functioned as a diagnostic mechanism that translated social and technical realities into actionable program design.

Table 2. Planning outcomes

Component	Input/Data	Process	Output	Outcome	Note
Profiling	Land type	Observation	65% rain-fed	Climate dependent	High risk
Practice	Irrigation	Survey	72% manual	Low precision	Inefficient
Awareness	Soil indicator	Survey	61% visual	Poor control	Risk
Exposure	IoT use	Survey	70% none	Tech gap	Low adoption
Literacy	Smartphone	Survey	54% basic	Usable	Simple UI
Infra	Electricity	Village data	100% access	Ready	Support
Network	Signal	Field test	Stable 3G/4G	Connected	Feasible
Design	Sensor	Assessment	Capacitive	Low-cost	Durable
Control	Actuator	Workshop	Valve+timer	Automation	Simple
Training	Modules	Audit	3 ready	Learning	Contextual
Demplot	Field setup	Inspection	2 plots	Practice	Experiential
Readiness	Commitment	Registration	87%	Engagement	High

Quantitative data from Table 2 demonstrate clear structural challenges and opportunities addressed by this planning phase. Survey results show that 72% of farmers relied on fully manual irrigation, while 61% determined watering schedules solely through visual soil assessment. Technological exposure was limited, with 70% of participants reporting no prior experience with sensors or automation. However, infrastructural conditions were favorable: 100% of households had electricity access, and stable cellular networks were identified in all demplot areas. Digital literacy levels were sufficient for simplified interfaces, with 85% of farmers classified as basic to moderate users. Based on these findings, this program finalized three training modules, selected low-cost capacitive sensors, and prepared two demonstration plots. Importantly, 87% of registered participants committed to completing the full program cycle.

These planning results confirm that challenges faced by marginal farmers are less about infrastructure absence and more about mismatches between technology complexity and user context. From a participatory development perspective, this phase validates the principle that effective innovation begins with socio-technical alignment rather than hardware deployment. The selection of simple sensors and shared systems reflects appropriate technology theory, emphasizing usability, affordability, and collective ownership. Practically, the high readiness indicators—electricity access, network stability, and participant commitment—suggest strong feasibility for implementation. This planning outcome also reframes smart farming not as a high-tech leap but as a gradual capacity-building process [1], [4], [7]. Therefore, this phase establishes a solid foundation for implementation while offering a replicable planning model for similar rural contexts.

3.2. Community workshops, system deployment, and field mentoring

This section reports implementation outcomes of this community service, emphasizing workshops, system deployment, and field-based mentoring. As shown in Table 3, implementation was designed as an iterative learning process that integrated technical training with real agricultural practice. Rather than focusing solely on technology installation, this phase prioritized farmers' experiential engagement, autonomy development, and collective learning. Data were collected through attendance records, skills assessments, system logs, and surveys to capture both technical performance and behavioral change. Accordingly, this implementation phase functioned as a critical bridge between planning assumptions and real-world application.

Table 3. Implementation outcomes

Component	Input/Data	Process	Output	Outcome	Note
Workshop	Sessions	Delivery	3/site	Target met	Adequate
Participation	Attendance	Tracking	91% ≥2x	Engagement	High
Intensity	Hours	Audit	12 hrs	Exposure	Sufficient
Knowledge	Test score	Training	78.6	Learning	Improved
Skills	Installation	Practice	76%	Transfer	Achieved
Deployment	IoT units	Setup	8 units	Coverage	Functional
Accuracy	Trigger match	System log	83%	Reliability	Strong
Behavior	Manual watering	Logbook	−42%	Change	Significant
Autonomy	Operation	Assessment	63%	Independence	Met
Troubleshoot	Problem solve	Simulation	58%	Capacity	Growing
Peer	Sharing	Obs/interv.	55%	Network	Emerging
Support	Visits	Record	14/site	Guidance	Intensive
Acceptance	Usefulness	Survey	82%	Adoption	High
Sustainability	Continuity	Survey	79%	Retention	Strong

Data from Table 3 indicate strong participation and skill acquisition during implementation. A total of three workshops per location were conducted, with 91% of participants attending at least two sessions. Post-training assessments showed an average knowledge score of 78.6 out of 100. Field observations revealed that 76% of farmers could install soil moisture sensors independently, while 63% operated irrigation systems without facilitator assistance by the end of mentoring. Eight IoT irrigation systems were successfully deployed across two demonstration plots, achieving 83% accuracy in moisture-triggered irrigation. Manual watering frequency declined by 42%, and 82% of participants rated this system as useful or very useful. Additionally, 79% expressed commitment to continue system use after this program.

These implementation results illustrate how participatory and practice-oriented strategies can translate technological interventions into meaningful behavioral change [5], [16], [17]. From an adult learning and extension theory perspective, this phase confirms that hands-on mentoring and repetition are more effective than one-off training sessions. The emergence of peer mentoring among 55% of participants reflects social learning dynamics that strengthen technology diffusion beyond facilitator-led instruction. Practically, reductions in manual irrigation and increased farmer autonomy indicate that this system aligns with farmers' routines and constraints. This phase also demonstrates that smart farming adoption among marginal farmers is feasible when technology is simplified and learning is embedded in daily practice [18], [19], [20]. Therefore, this implementation phase validates this community service model as both effective and scalable.

3.3. Performance tracking, learning outcomes, and sustainability assessment

This section presents monitoring and evaluation outcomes of this community service, focusing on performance measurement, learning assessment, and sustainability indicators. As shown in Table 4, monitoring was conducted continuously during implementation, while evaluation combined baseline–endline comparisons and reflective assessment. This phase aimed to verify whether planned outputs translated into measurable efficiency gains, behavioral change, and institutional engagement. By integrating quantitative indicators and qualitative observations, this evaluation captured both technical performance and social learning processes. Therefore, this phase functioned as an evidence-based mechanism to assess effectiveness, inform reflection, and support future replication.

Table 4. Monitoring and evaluation outcomes

Dimension	Input/Data	Process	Output	Outcome	Note
Efficiency	Irrigation freq	Logbook	6.2→3.7	−40.3%	Efficient
Water use	Volume est.	Field est.	100→72%	−28%	Target met
Growth	Height uniformity	Measure	CV 22→12	+45%	Stable
Health	Stress level	Checklist	38→14%	−63%	Improved
Knowledge	IoT score	Pre–post	42.5→79.2	+86%	Strong
Skills	Operation	Rubric	18→67%	+49 pp	Capacity
Troubleshoot	Fault solve	Simulation	21→58%	+37 pp	Growing
Acceptance	Usefulness	Survey	2.9→4.3	+48%	Positive
Behavior	Data-based	Interview	9→61%	+52 pp	Shift
Group	Peer sharing	Observation	Low→Routine	↑ Qual	Social
Institution	PPL role	Log	Occ→Biweekly	↑	Embedded
Sustainability	Continuation	Survey	—→81%	—	Strong
Replication	Expansion	Discussion	—→3 plots	—	Scalable

Data in Table 4 indicate substantial improvements across technical, cognitive, and behavioral dimensions. Average irrigation frequency decreased from 6.2 to 3.7 times per week, representing a 40.3% reduction. Estimated water use declined by 28%, aligning with planned efficiency targets. Crop observations showed improved uniformity, with coefficient of variation decreasing from 22% to 12%. Farmer knowledge scores increased from a baseline mean of 42.5 to 79.2 at endline. Operational autonomy rose to 67%, while troubleshooting success reached 58%. Technology acceptance scores increased to 4.3 out of 5, and 81% of participants expressed willingness to continue using this system beyond this program.

These evaluation outcomes demonstrate that this community service achieved more than technical efficiency, generating cognitive and social transformation among marginal farmers. From an agricultural extension and technology acceptance perspective, the convergence of efficiency gains and positive perception confirms that usability and relevance drive adoption. The rise in peer knowledge sharing reflects social learning theory, where collective practice accelerates diffusion. Practically, reductions in water use and irrigation frequency indicate tangible resource savings under real field conditions. Institutional engagement by agricultural extension officers further suggests sustainability beyond external facilitation. Collectively, this phase validates this program as a scalable, evidence-based model for inclusive smart farming [12], [15]. The integration of monitoring and reflection also provides a robust framework for replication and policy-oriented community service initiatives.

4. DISCUSSION

This community service demonstrates substantial practical and social implications in addressing water insecurity and technological exclusion among marginal farmers. The observed reduction in irrigation frequency and water use signifies not only improved technical efficiency but also a shift in farmers' daily decision-making practices. Socially, this intervention reduced uncertainty and labor burden associated with manual irrigation, allowing farmers to reallocate time toward crop management and household activities. The emergence of collective use of irrigation systems further strengthened social cohesion within farmer groups, transforming technology adoption into a shared community endeavor rather than an individual risk. However, minor disfunctions also surfaced, particularly during early adaptation stages when dependence on facilitators remained high for troubleshooting [18], [21]. Overall, this community service functioned as an enabler of practical efficiency and social confidence, illustrating that smart farming can become socially embedded when designed around marginal farmers' lived realities.

The underlying mechanisms that shaped these outcomes are rooted in the structural design of this community service. Participatory planning aligned technological features with farmers' routines, while demonstration plots reduced perceived risk by allowing farmers to observe tangible benefits before full adoption. The integration of hands-on workshops with continuous field mentoring activated experiential learning processes commonly emphasized in agricultural extension literature. Moreover, the use of affordable and simplified IoT components minimized cognitive and financial barriers, reinforcing perceptions of feasibility. The social structure of farmer groups also played a mediating role, as peer observation and informal discussion accelerated learning beyond formal sessions [13], [22]. These patterns suggest that effectiveness did not arise solely from technology itself, but from a socio-technical configuration that balanced structure, flexibility, and collective engagement within this program.

Beyond technical efficiency, this community service generated broader social implications through changes in knowledge, attitudes, and agency. Farmers demonstrated increased confidence in interpreting soil moisture data and making irrigation decisions based on evidence rather than intuition. This cognitive shift represents an important form of empowerment, as farmers moved from reactive practices toward anticipatory management. Socially, the formation of informal peer mentors indicated the emergence of local knowledge brokers who extended learning beyond direct program intervention. Nonetheless, variations in digital literacy meant that some participants progressed more slowly, highlighting persistent inequalities in learning pace. Even so, this program fostered a culture of mutual assistance, where slower adopters relied on peers rather than withdrawing [5], [16]. Such dynamics underscore the role of community service in shaping inclusive learning environments rather than merely transferring skills.

The mechanisms behind these social and cognitive transformations are closely linked to learning structures embedded in this community service. Adult learning theory emphasizes that relevance, repetition, and immediate application are critical for sustained knowledge uptake, all of which were present in this intervention. Workshops introduced concepts incrementally, while mentoring reinforced learning through daily practice. Additionally, framing technology as a collective asset reduced individual anxiety and encouraged experimentation. Institutional involvement from agricultural extension officers further legitimized this program, signaling continuity beyond external facilitation. These structural elements created reinforcing feedback loops between practice, reflection, and confidence [10], [19]. Consequently, observed behavioral change reflects not spontaneous adaptation, but the cumulative effect of deliberate pedagogical and institutional alignment within this community service.

This community service also yielded important implications related to sustainability and institutional strengthening. The willingness of participants to continue using and expanding IoT-based irrigation systems suggests that perceived benefits outweighed maintenance concerns. Practically, reductions in water use and improved crop uniformity contribute to longer-term resilience under climate variability. At the institutional level, increased engagement of farmer groups and extension officers indicates potential mainstreaming of precision irrigation practices. However, sustainability remains conditional upon access to maintenance support and affordable replacement components. Without continued institutional facilitation, there is a risk that system performance could decline over time [20], [23]. Nevertheless, this program demonstrated that sustainability is attainable when technology adoption is embedded within existing local institutions and collective norms.

The patterns underlying these sustainability outcomes highlight the importance of institutional and social embedding. This community service leveraged farmer groups as governance units for shared systems, distributing responsibility and reducing individual burden. The involvement of extension officers bridged formal agricultural policy with grassroots practice, enhancing legitimacy and continuity. From a diffusion-of-innovation perspective, visible benefits and peer endorsement accelerated acceptance and intention to replicate systems on additional plots. These mechanisms illustrate that sustainability is not merely a technical attribute but a social process shaped by ownership, trust, and institutional support [15], [24], [25]. Accordingly, this community service offers a replicable model in which smart farming becomes an adaptive, community-driven practice rather than an externally imposed innovation.

5. CONCLUSION

This community service demonstrates that smart farming adoption among marginal farmers is achievable when technological innovation is embedded within participatory learning and sustained field mentoring. The key lesson from this program lies in the alignment between low-cost IoT irrigation systems and farmers' socio-technical realities. This approach effectively reduced water use, enhanced decision-making capacity, and fostered collective ownership through farmer groups. The strength of this program rests on its integrated model that combines needs-based planning, experiential workshops, and continuous accompaniment, thereby transforming technology from a perceived burden into a practical tool. This contribution advances community service practice by offering an adaptive empowerment model that emphasizes usability, social learning, and institutional collaboration rather than technology transfer alone.

Despite these achievements, this community service also faced limitations related to uneven digital literacy, partial dependence on facilitators for advanced troubleshooting, and limited observation time for long-term agronomic impacts. These constraints indicate the need for follow-up activities that extend mentoring duration, deepen technical maintenance skills, and integrate seasonal crop cycles. Future community service initiatives should prioritize training local champions, developing modular maintenance kits, and strengthening linkages with agricultural extension services. Such continuity strategies will enhance sustainability and scalability, ensuring that this program evolves into a long-term community-driven smart farming ecosystem.

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Matsaini: conceptualization (lead), project implementation (lead), technical facilitation (lead), writing – original draft (lead), writing – review and editing (lead).

CONFLICT OF INTEREST STATEMENT
Authors state no conflict of interest.

INFORMED CONSENT
We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL
This manuscript related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee.

DATA AVAILABILITY
Data availability is not applicable to this article as no new data were created or analyzed in this study.

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BIOGRAPHY OF AUTHOR

Matsaini is affiliated with Universitas Madura, Indonesia. Her academic concerns are community development, agriculture, technology application, or related interdisciplinary fields. His research and service include smart farming, rural innovation, community training, agricultural technology, and participatory empowerment of marginal farmers. His work focuses on practical and sustainable solutions to improve productivity and resilience in local farming communities. He can be contacted at email: matsaini@unira.ac.id