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Development and Implementation of an Automatic Eco-Enzyme Fertilizer Irrigation System for Smallholder Farmers in a Central Java Regency

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ABSTRACT
Background: Farmers in Pejawaran District, Banjarnegara Regency, Central Java face economic challenges, labor shortages due to aging farmers, and the need for more sustainable agricultural practices. The development and implementation of automatic eco-enzyme fertilization technology is proposed as a solution to support productivity and improve farming efficiency in this community service program.
Purpose of the Study: This community service activity aims to develop and implement automatic eco-enzyme fertilization technology for farmers in Pejawaran District to enhance productivity, address labor constraints, and promote sustainable agriculture.
Methods: The program applies a three-stage community service method consisting of pre-development, development, and post-development stages. The pre-development stage involves a needs analysis study. The development stage includes (1) selection of features, materials, and components, (2) firmware design creation, and (3) tool manufacturing. The post-development stage comprises socialization and implementation in Sarwodadi and Giritirta Villages, followed by evaluation of system usability and impact.
Results: The needs analysis indicates that the technology has potential to overcome economic challenges, increase productivity, and alleviate labor shortages among elderly farmers. Implementation results show that farmers find the system easy to use and time-saving, despite challenges in accessing and understanding technology. Although immediate impacts on crop yields and operational costs are not yet significant, farmers feel more confident using eco-enzyme fertilizer and recommend adding a manual timer button for users without cellphones.

Keywords
Smart farming; organic; fertilizer; eco-enzyme; automatic sprinkle

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Introduction

Pejawaran District is one of the Districts located in the upper Banjarnegara Regency. Located at an altitude of 1,150 m above sea level with land conditions that are mostly hilly plateaus and have andosol soil types, the association is brown and yellowish brown and is neutral to acidic (Kecamatan Pejawaran, 2019). Medium to high soil productivity can be used for dry fields and agricultural land (Derpsch et al., 2024). Pejawaran District, which has an area of 52.3 km² or around 5.9% of the total area of Banjarnegara Regency, consists of 17 villages. In December 2023, the population of this district was recorded at 46,314 people, consisting of 22,324 women (48.20%) and 23,990 men (51.80%) (BPS Kabupaten Banjarnegara, 2024). The agricultural sector is one of the main economic drivers in Pejawaran, with seasonal vegetables such as cayenne pepper, potatoes, and carrots being widely cultivated. The harvested area for these crops increased in 2023 compared to 2022, reflecting the growth of the agricultural sector in this region. For example, potato and cayenne pepper production increased to 81,383 and 249,470 quintals, while carrot harvests increased significantly to 137,800 quintals (BPS Kabupaten Banjarnegara, 2024).

However, the agricultural sector in Banjarnegara faces various challenges. One problem that continues to emerge is the fluctuation of commodity prices, which is caused by uncertain weather conditions, pest attacks, and poor market structures (Agriculture, Fisheries and Food Security Service of Banjarnegara Regency 2022). The presence of pests and diseases allows farmers to provide chemical fertilizers and pesticides to eliminate pests and diseases quickly. However, excessive application of chemical fertilizers and pesticides can result in degradation of agricultural land. This can be in the form of decreased soil fertility, as a result of which the balance of plant nutrients will be disrupted so that there is a decrease in crop yields in terms of quality and quantity.

Long-term dependence on chemical fertilizers carries a major risk to soil health. Plants cannot fully absorb nutrients from artificial fertilizers, so chemical residues accumulate and cause soil compaction and a decrease in the population of soil-decomposing organisms (Duan et al., 2023). This dependence also increases the demand for chemical fertilizers, which worsens soil degradation and reduces agricultural productivity (Lalremsang et al., 2023). Ultimately, farmers' revenue will diminish due to reduced soil productivity, the escalating demand for fertilizers, and the elevated cost. This explanation necessitates the utilization of organic fertilizers as an alternative to diminishing reliance on chemical fertilizers and to enhance compromised soil conditions. Therefore, using organic fertilizer can be an alternative to overcome this. Organic fertilizers offer significant advantages over chemical or artificial fertilizers, particularly regarding environmental impact and sustainability (Avery, 2021). Unlike artificial fertilizers, organic fertilizers reduce the risk of water and soil pollution as they do not contain harmful chemicals. They enhance soil structure, increasing its ability to retain water and nutrients, thereby reducing erosion and runoff. Being made from renewable resources such as composted plant material and animal manure, organic fertilizers contribute to a more sustainable agricultural system and help reduce waste by using organic waste from agriculture and households (Pajura, 2024).

One of the uses of organic fertilizer is through the eco-enzyme method. This method is done by fermenting food or kitchen waste utilizing three primary components: sugar, kitchen waste, and water (Irmansyah et al., 2024). The treatment enhances water quality in contaminated water, showing a substantial improvement in metrics such as Total Suspended Solids (TSS) in iron-polluted water, achieving a reduction rate of 99.9% (Yong et al., 2022). Eco-enzymes can enhance plant growth by utilizing the nutritious components obtained from the amalgamation of organic materials (Ginting & Mirwandhono, 2021). Laboratory results indicate that the organic fertilizer derived from fruits and vegetables contains NPK levels between 0.09-0.1% and C-organic content ranging from 0.01-2.13%. Nonetheless, the enzymatic activity initiates plant development (Fadlilla et al., 2023). eco-enzymes are organic substances consisting of organic acids, protein chains, and mineral salts. Eco-enzymes that ferment fruits can also be combined with vegetables, tap water,

and molasses. According to the fruit or vegetable used, the enzymes contain protease, amylase lipase, and many other enzymes (Arun & Sivashanmugam, 2015; Selvakumar & Sivashanmugam, 2017).

One step that can be taken to make it easier for farmers to apply liquid eco-enzyme fertilizer is through automatic sprinklers as part of smart farming. Using eco-enzymes can be efficient with smart farming technology that can automatically water eco-enzymes on plants. Smart farming promotes precision agriculture with modern, sophisticated technology, enabling farmers to remotely monitor the plants (Dhanaraju et al., 2022). Smart farming helps agricultural processes, such as harvesting and crop yields, as the automation of sensors and machinery has made the farming workforce more efficient (O'Grady & O'Hare, 2017). The technologies convert traditional farming methods to automatic devices, causing a technological revolution in agriculture. According to Sudarmaji et al. (2019) the greatest advantages of applying automatic sprinkler or drip irrigation systems are the labor and time efficiency and cost savings. Once installed, the system can be set to a timer to water at specific time intervals a day during cultivation. This means the farmer or user does not need to worry about watering the plants. Another advantage is that the sprinklers and drippers can be positioned and pointed so that water is more effectively targeted where it is needed. In general, treatment of plant maintenance, such as the watering process that most plant farmers often do, is still done manually by farmer workers. The use of manual systems has weaknesses; one of them is human error because the assessment of crop farmers is still subjective (Wossen et al., 2022).

Seeing this potential, this innovation aims to develop and implement an automatic eco-enzyme liquid fertilizer irrigation system for organic vegetable cultivation in Pejawaran District. Melalui, the appropriateness of appropriate technology can help community members maintain the ongoing development (sustaining the development) and adjust technology to overcome future conditions in a changing environment (Sianipar et al., 2013). Applying this technology is expected to increase agricultural productivity, improve soil quality, and provide sustainable solutions for farmers in the area. Thus, this research does not only focus on technical aspects but also broader social and economic impacts on the farming community in Pejawaran.

Method

The development of this system was conducted as part of the KKN-PPM community service program of Universitas Gadjah Mada, which focused on technological empowerment for smallholder farmers in Pejawaran District, Banjarnegara Regency. The program employed a three-stage methodological approach consisting of pre-development, development, and post-development stages designed to ensure that the technology is contextually relevant and user-oriented.

The pre-development stage served as a participatory needs analysis to identify the actual technological requirements and challenges faced by local farmers. Using a qualitative approach, observations and interviews were conducted with farmers in Giritirta Hamlet, Giritirta Village, and Tlodas Hamlet, Sarwodadi Village, to map their primary needs. These farmers were identified as the end-users of the technology, making their input essential for informing the design requirements and ensuring the system was tailored to their specific agricultural challenges.

The development stage focused on translating these identified needs into a functional technological solution. This stage integrated the process of selecting features, materials, and components, alongside the design of system architecture, including firmware design, block diagram creation, flowchart preparation, and the coding process. The tool manufacturing process was conducted in a laboratory environment, encompassing soldering, assembly, testing, and iterative refinement to ensure the two produced units met the necessary performance specifications for

field application.

The post-development phase centered on implementation and participatory evaluation to assess the social and technical impact of the technology within the actual agricultural environment. This stage involved the installation of the devices in Tlodas Hamlet, Sarwodadi Village, and Giritirta Hamlet, Giritirta Village, followed by socialization sessions to instruct farmers on the operation and maintenance of the technology. The final activity involved a comprehensive evaluation to determine the extent to which the technology influenced agricultural cultivation and user practices within the community.

Specifically, a qualitative study was conducted through interviews and observations at the pre-development and evaluation stages. Using the technology developed, this study uses a phenomenological approach to deeply understand experiences (Van Manen, 2014). Qualitative methods add value to implementation science by helping to describe what is happening and why (Hamilton & Finley, 2019). The incorporation of social aspects in developing this innovation is important to implement the social innovation principle, which mainly emphasizes the importance of implementing technology that is oriented towards problems that exist in society (Kohlgrüber et al., 2019). With this approach, it is hoped that a richer picture can be obtained of the needs, perceptions, and challenges farmers face in adopting an automatic irrigation system with eco-enzyme fertilizer in their agricultural environment. The results of this study will be the basis for evaluating the effectiveness and sustainability of the technology applied.

The following are the stages carried out in this program activity:

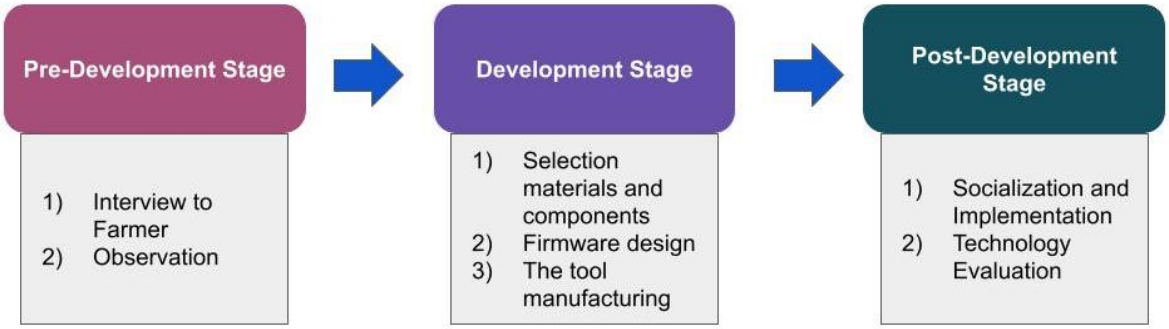


Figure 1. Stages Employed in the Program

Result

Pre Development Findings

At this stage, an analysis of technology adoption needs is carried out by conducting qualitative interviews and field observations. In general, several issues are found in this stage: economic problems related to using chemical fertilizers and organic fertilizers and the problem of limited productive human resources in agriculture, which requires technological innovation to make their work easier.



Figure 2. Interview with Local Farmer



Figure 3. Preliminary Observation at Local Farm

The pre-development stage was conducted through qualitative interviews and field observations in Giritirta Hamlet (Giritirta Village) and Tlodas Hamlet (Sarwodadi Village). This stage aimed to identify the needs, challenges, and readiness of farmers regarding the development of an automatic eco-enzyme fertilizer irrigation system. The findings indicate several major issues faced by farmers in Pejawaran District.

First, farmers experience economic constraints related to fertilizer and agricultural input costs. Chemical fertilizers and pesticides are considered expensive, especially when commodity prices fluctuate. One farmer stated:

"Yes, plus the medicine, the fertilizer is expensive, one treatment is also expensive."

Although organic fertilizers are already known and occasionally used by farmers, they have not yet provided significant economic advantages. Some farmers have used alternatives such as goat urine when chemical fertilizers were unavailable. One farmer explained:

"That was when there were no chemical fertilizers. The beans turned out great, the green was long-lasting."

However, farmers reported that the selling price of organic vegetables in the local market does not differ significantly from conventionally grown vegetables. As a result, the economic incentive to fully transition to organic farming remains limited. One farmer stated:

> *"Here, using organic and chemical fertilizers costs the same… even if the yield is lower with organic, if the price were higher, we would choose organic."*

In addition to economic concerns, limited human resources were identified as a significant issue. Most active farmers in the area are elderly, while younger generations show declining interest in agricultural work. Manual irrigation and fertilizer spraying are physically demanding. One farmer mentioned:

> *"Everything here is manual… I used to pump the sprayer. Now I use an electric one, but my wife said she cannot carry it anymore."*

Farmers expressed optimism about technological innovation, particularly automatic irrigation systems integrated with eco-enzyme fertilizer. They believe such technology could enable planting during the dry season without excessive concern about watering. One informant stated:

> *"I'm happy if there is a tool like this. If the plants survive during the dry season and start flowering, then when the rainy season comes, the harvest can be better."*

Overall, the pre-development findings reveal three primary needs: (1) reducing dependency on costly agricultural inputs, (2) improving efficiency in irrigation and fertilization, and (3) addressing labor limitations among aging farmers. These findings became the basis for designing and developing the automatic eco-enzyme irrigation system.

System Development Results

Selecting Materials and Components

This stage aims to ensure that the technology developed is not only by the needs of farmers, but also efficient and can be implemented in the field. This process is crucial considering the design and manufacturing of its components, carried out by design and materials engineers (Jayakrishna et al., 2018). The following are the materials and components used in the preparation of the tool:

Table 1. Hardware Components and Technical Specifications

No	Name and Function	Picture	Specification
1	**Solar Panel** Captures sunlight and converts it into electricity to operate irrigation systems and charge batteries.		• Max. Power: 50W • Max. Power Voltage: 18V • Dimension: ±645 × 540 × 35 mm
2	**ACCU 20Ah** Stores energy from solar panels to supply power to the system when there is no sunlight.		• Cycle use: 14.50–14.90V (25°C) • Dimensions: 18 × 7.5 × 16.5 cm

Table 1. Hardware Components and Technical Specifications

3	**Solar Charging Controller** Regulates the flow of electricity from the solar panel to the battery and prevents overcharging.		• PV Input: 130W (12V system) / 260W (24V system) • Maximum Charging Current: 10A
4	**ESP32** The main microcontroller that controls the system, receives data from sensors, and allows connectivity to a smartphone for configuration.		• Wi-Fi 802.11b/g/n + Bluetooth v4.2 • Dual-core up to 240 MHz, 520 KB RAM • 34 GPIOs, supports SPI/I2C/UART
5	**Relay Max 10 Ampere** Controls the flow of electricity to the water pump based on commands from the microcontroller.		• Coil Voltage: DC 5V • Contact Capacity: 10A/250VAC
6	**LCD 16x2** Displays important information such as system status, current time, and irrigation timer configuration.		• 16×2 character LCD with cursor • +5V power supply
7	**RTC DS3231** Provides accurate time to maintain irrigation schedule according to user configuration.		• Time accuracy: ±2 ppm • I2C communication (default address 0x68) • CR2032 backup battery

Table 1. Hardware Components and Technical Specifications

8	**Water Pump** Pumping water to agricultural land according to the specified irrigation schedule.		• Power: 100 Watts • Current: 10 Amps • Flow rate: 8.0 liters/minute

Firmware Design Stage

At this stage, development focuses on firmware design, which includes several important aspects: feature design, block diagram creation, flowchart preparation, and coding process. First, feature design describes the functional elements that will be supported by the system (W. Zhang & Zhou, 2021). For the automatic eco-enzyme fertilizer irrigation system, the main features include power management via solar panels and batteries, pump control using relays, accurate time management via Real-Time Clock (RTC), user configuration capabilities to set timers via smartphones, and data storage capabilities so that timer settings are saved even if the system is turned off. The next stage is creating a block diagram, which visually represents how each component in the system interacts (Sinclair, 2011). This system has two main components: the power supply and the controller. The power supply provides electricity to the controller from solar panels. The energy captured from the solar panels is stored in the battery, which the charger controller regulates. The charger controller plays an important role in regulating energy flow into and out of the battery so that energy use can be carried out efficiently. In the controller section, there is a microcontroller tasked with controlling the relay, which functions to turn the water pump on and off based on the configuration set in the microcontroller. In addition, this microcontroller is connected to the Real-Time Clock (RTC) to maintain time accuracy, which is very important in managing irrigation schedules. The status and configuration details of the system are displayed on the LCD screen, providing real-time information to the user. This system also has a push button allowing users to enter configuration mode. In this mode, the system can be connected to a smartphone to facilitate configuration updates, thus providing flexibility and easier control for the user. The following is a block diagram design that was created:

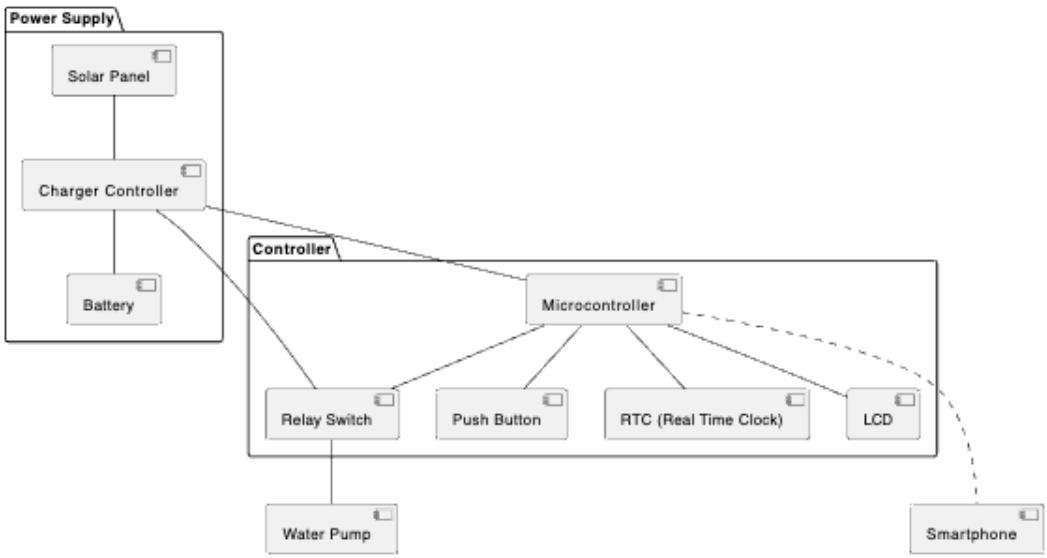


Figure 4. Block Diagram

Next is creating a flowchart that explains the workflow of the eco-enzyme fertilizer irrigation automation system. The flowchart is the central design document around which systems analysts, computer programmers, and end users communicate, negotiate, and represent complexity (Ensmenger, 2016). Creating a flowchart in the eco-enzyme fertilizer irrigation automation system illustrates the main workflow, from retrieving timer configuration data in the microcontroller to saving a new configuration from a smartphone. Configuration data such as ID, start time, duration, and active status are stored using the SPIFFS feature, which ensures that data persists even when the system is turned off. In normal mode, the microcontroller retrieves time from the RTC, checks the timer status, and turns the relay on or off according to the set time. If the system is configurable, the user can connect a smartphone to set a new timer, synchronize with the RTC, and save again. The following is the flowchart that has been created:

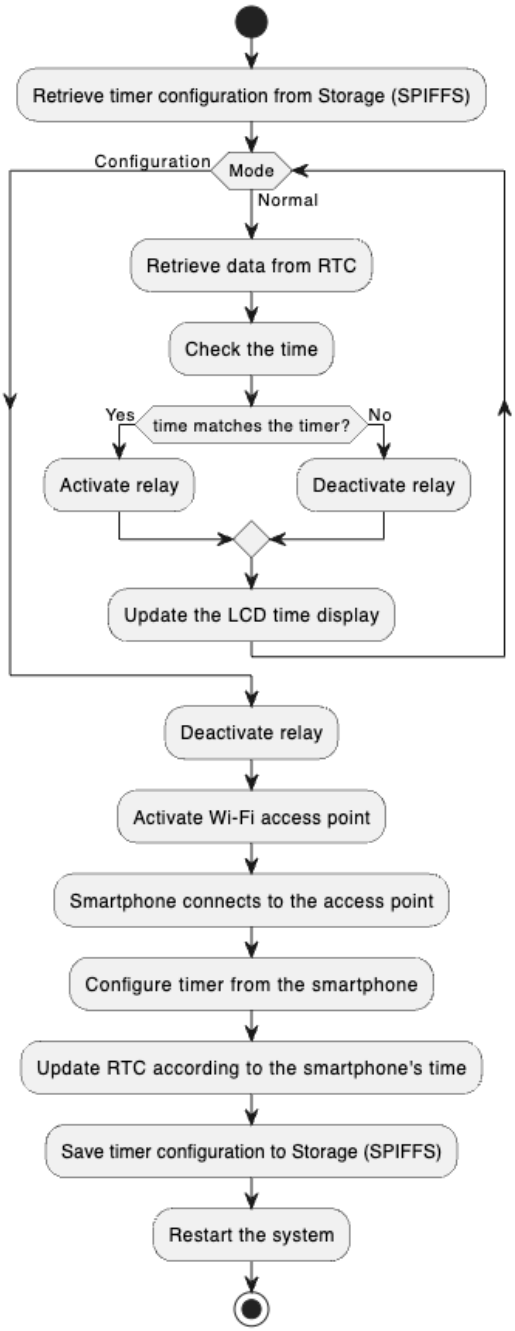


Figure 5. Flowchart of System

Finally, the coding process. The process of developing this firmware is responsible for controlling the entire system, including communication with the RTC for time management, relay settings based on the timer, and displaying information on the LCD. In addition, a push button is used to switch between configuration mode and normal mode, and a Wi-Fi connection is enabled to allow configuration via a smartphone. SPIFFS data storage will save all timer settings even during a power outage. The timer configuration image on a smartphone illustrates an interface that makes it easy for users to set the timer's time, duration, and active status. This user-friendly interface allows users to easily interact with the digital solution to perform the necessary tasks naturally (Diehl et al., 2022). Below is the user interface for timer configuration:

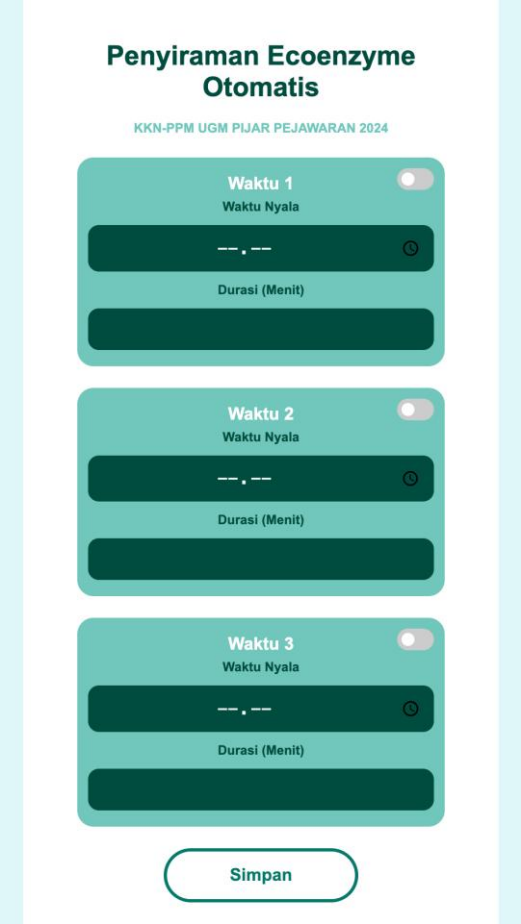


Figure 6. User Interface of Timer Configuration

The Tool Manufacturing Process

At this stage, the previously designed system design begins to be realized in a more realistic and testable prototype form. This process includes several important steps, such as soldering to connect electronic components, coding to fill the microcontroller with a program that regulates system operations, and assembling all components into one complete unit. After the prototype is formed, testing is carried out to ensure the system functions according to the desired specifications. This stage ends with laboratory refinement, correcting deficiencies to produce a tool ready for use in the field.



Figure 7. Tool Manufacturing Process

Implementation and Technology Evaluation

Socialization and Implementation

There are two main activities in the implementation stage: the socialization of tools and the use of eco-enzymes, as well as the implementation process and installation of tools on agricultural land. In the socialization section, there are two focuses in this activity: the tool's operation and the use of eco-enzymes. Before the tool is operated, a socialization session is held for farmers using this technology. Education focuses on how to use the tool, such as how to set the irrigation timer, monitor the status via the LCD display, and reconfigure if necessary. In addition, farmers are also given training on how to care for the tool, including maintaining sensor cleanliness, monitoring battery power, and ensuring that the tool remains in optimal condition for long-term use. The socialization aims to increase farmers' understanding of the benefits of this technology in increasing irrigation efficiency and using organic fertilizers. One aspect that needs further explanation is using eco-enzyme fertilizer in irrigation. Eco-enzyme is an organic fertilizer made from organic waste and is integrated with an automatic irrigation system to increase the efficiency of nutrient distribution to plants. In the socialization, farmers are also given an understanding of the benefits of eco-enzymes for soil and plant health and how this irrigation technology can maximize fertilizer utilization automatically. Figure 8 shows the socialization activities for using tools and methods for making eco-enzymes.



Figure 8. Socialization the Usage of Tools and the Making of Eco-enzyme

The next stage is the device's implementation and installation. Implementation is carried out in two stages according to the selected location. On August 5, 2024, the system was installed in Tlodas Hamlet, Sarwodadi Village. Two days later, on August 7, 2024, the device was implemented in Giritirta Hamlet, Giritirta Village, Pejawaran District, Banjarnegara Regency. The

device installation process involves installing the device on the selected land, ensuring that the system is connected to a power source generated from solar panels and backup batteries. This stage requires careful setup to ensure that all components, including the microcontroller, sensors, and water pumps, work properly according to the specified configuration. Figure 9 shows the implementation activities of the tools on community agricultural land:



Figure 9. Tools Implementation at Tlodas Hamlet, Sarwodadi Village and Giritirta Hamlet, Giritirta Village, Pejawaran District

Technology Evaluation

Evaluating technology is essential for decision-makers to carefully analyze its value and select suitable technologies (Herceg, 2007). The evaluation of the automatic irrigation system integrated with eco-enzyme fertilizer revealed several important findings across ten evaluation aspects, including ease of use, time efficiency, harvest outcomes, resource efficiency, technical challenges, maintenance, user guidance, operational costs, fertilizer preference, and suggested improvements.

Overall, farmers perceived the system as relatively easy to use after repeated trials and guidance. Although some farmers initially experienced difficulties due to limited familiarity with digital technology, they gradually became accustomed to operating the system. In terms of time efficiency, farmers reported that the system reduced the manual effort required for irrigation and fertilization. Previously, irrigation and fertilization had to be conducted manually by walking around the farm and carrying equipment, whereas the automatic system allowed farmers to activate the process through a mobile phone. However, because no direct time measurement was conducted, the extent of time savings could not yet be expressed quantitatively as a percentage.

The system was also perceived to improve the efficiency of water and fertilizer use because distribution became more targeted to the plants, reducing unnecessary waste. However, improvements in harvest quality or quantity were not yet clearly observed because the system had only been applied to a limited section of the farmland. Farmers also reported several technical challenges, especially among older farmers or those who did not own or regularly use mobile phones. Some users still had difficulty setting the irrigation schedule accurately, indicating the need for a more accessible control mechanism.

Regarding maintenance, farmers considered the system relatively simple to care for, requiring only periodic cleaning, especially when exposed to mud. The usage guide was generally understandable and supported by visual instructions, although some technical terms remained difficult for farmers to understand. Therefore, simplifying the language of the guide is recommended. In terms of operational costs, no significant short-term reduction was reported. Nevertheless, farmers expected potential long-term savings because eco-enzyme fertilizer can be produced independently rather than purchased commercially. Farmers also expressed greater confidence in using eco-enzyme fertilizer because it was perceived as safer for plants and soil than chemical fertilizer.

Based on these findings, the main suggested improvement is the addition of a manual button for setting irrigation time. This feature would provide an alternative for farmers who do not own or are not familiar with mobile phones, especially older farmers. Thus, while quantitative performance data such as percentage time savings or cost reduction were not yet available, the qualitative evaluation indicates that the technology has positive perceived value in terms of usability, labor reduction, resource efficiency, and environmental safety.

Table 2. Technology Evaluation Questions and Results

No	Evaluation Theme	Synthesized Findings	Implications/ Recommendations
1	**Usability & Technical Accessibility**	The system initially confused elderly farmers due to a lack of smartphone ownership and unfamiliar digital terminology in the visual guide. However, repeated assistance improved operability.	**Recommendation**: Hardware modification is required to include manual timer controls. The instruction manual must be simplified, avoiding complex technical terms.
2	**Resource & Time Efficiency**	Farmers reported faster irrigation processes compared to manual methods and highly targeted distribution of both water and eco-enzyme fertilizer to the plants.	**Implication:** The automated mechanism effectively reduces physical labor for elderly farmers while optimizing resource utilization.
3	**Agronomic & Economic Impacts**	Immediate improvements in crop yields or direct cost reductions are not yet visible due to the limited application area. Nevertheless, confidence in eco-enzyme safety (vs. pesticides) is high, indicating potential long-term economic viability.	**Implication:** Longitudinal studies on larger plots are necessary to validate agronomic benefits and calculate exact ROI (Return on Investment) for the farmers.
4	**Maintenance & Durability**	The physical maintenance of the equipment is perceived as straightforward, requiring only periodic cleaning from environmental debris.	**Implication:** The hardware design is appropriate for the demanding conditions of local agricultural environments.

Discussion

Socio-Economic Vulnerability and Barriers to Technology Adoption

The findings reveal a complex intersection between economic constraints, demographic shifts, and digital literacy barriers that dictate the adoption of agricultural technology in Pejawaran District. Economically, the decision to utilize eco-enzyme fertilizers is heavily constrained by market realities. Smallholder farmers operate under thin profit margins and high input volatility. Although farmers recognize the ecological benefits of organic inputs, the local market does not offer a differentiated, premium price for organic yields. Consequently, when the financial return of organic and chemical fertilizers remains identical, immediate yield stability takes precedence over long-term ecological sustainability (Y. Zhang et al., 2023). The data indicates that the use of

organic alternatives, such as goat urine, was historically reactive, driven by periodic chemical fertilizer scarcity rather than a strategic paradigm shift towards sustainable agriculture (Gosal et al., 2018; Widiarta et al., 2011).

Therefore, introducing automated eco-enzyme irrigation is insufficient. Furthermore, the demographic reality of an aging agricultural workforce (Susilowati, 2016) introduces a paradox in technology implementation. The automated irrigation system successfully addresses the urgent physical limitations of older farmers by eliminating the physically demanding task of manual spraying. However, the technological interface creates an unintended structural barrier. The dependency on smartphone-based configuration assumes a level of digital literacy that is largely absent among the primary demographic. The farmers' explicit request for a manual timer button highlights a critical disconnect between modern smart-farming assumptions and the users' reality, demonstrating that technological sophistication must not compromise accessibility (Barbieri et al., 2025; Vakkanthula & Nik-Bakht, 2025). Incorporating manual overrides ensures that agricultural innovations do not alienate the population they intend to empower (Pedzisa et al., 2010). Continuous refinement based on user feedback strengthens long-term adoption potential and ensures that the system remains socially embedded rather than externally imposed (Desmal et al., 2023).

Operational Efficacy and Long-Term Agronomic Implications

From an operational standpoint, the automated system demonstrates clear mechanical efficacy. The transition to an automated, targeted distribution mechanism minimizes resource waste and directly addresses the physical toll on elderly farmers. This mechanical success fulfills the primary criteria of appropriate technology by providing contextual, labor-saving solutions (Sianipar et al., 2013). However, the critical limitation of this implementation is the lack of immediate, measurable agronomic impact. The absence of quantifiable improvements in crop yield or operational cost reduction reflects the constraints of a short observation period and a localized implementation scale.

The transition from chemical dependency to organic cultivation is a slow biological process. Decades of continuous chemical fertilizer application have likely led to significant soil compaction and degradation of soil-decomposing organisms (Duan et al., 2023). Rebuilding the soil microbiome using eco-enzymes requires multiple continuous planting cycles. Agricultural productivity changes necessitate longitudinal evaluation to account for seasonal variability and crop growth duration (Nguyen et al., 2025). Therefore, the operational success of the hardware does not automatically equate to immediate agronomic recovery. The most significant short-term outcome is increased farmer confidence in the safety and viability of eco-enzyme fertilizers over chemical alternatives. Confidence plays a crucial role in behavioral transition (Erekalo et al., 2025). To solidify this initiative as a functional social innovation (Phuangprayong & Noonin, 2024), future development must transition from gathering qualitative user feedback to rigorously measuring quantitative metrics, such as soil nutrient recovery and exact economic return on investment (ROI) over extended harvest seasons.

Limitations and Future Development Directions

Several limitations emerged from the current implementation: a) The number of tool units was limited to two locations, b) Evaluation relied primarily on qualitative feedback, and c) The duration of field application was relatively short. Future development should consider expanding the implementation area to generate quantitative data on water savings, fertilizer efficiency, and yield differences. In addition, integrating simplified interface options, including manual control mechanisms, may enhance accessibility for elderly users. Long-term sustainability also depends on continued training, technical assistance, and potential integration with local agricultural institutions. Strengthening the economic ecosystem surrounding organic products would further reinforce technology adoption.

Conclusion

The development and implementation of the automatic eco-enzyme irrigation system successfully provides a mechanical solution to reduce the physical labor and time required for crop maintenance, particularly benefiting the aging farming demographic in Pejawaran District. However, the reliance on smartphone-based configuration poses a significant accessibility barrier for elderly users, underscoring the critical need to integrate manual control interfaces in future iterations. Furthermore, while the technology optimizes resource distribution, immediate improvements in crop yields and cost reductions remain unverified due to the short evaluation period.

Therefore, the long-term sustainability and adoption of this innovation depend on three pivotal actions. First, hardware redesign must prioritize inclusive, user-centered accessibility for farmers with low digital literacy. Second, future research must shift toward longitudinal, quantitative studies across expanded plots to accurately measure soil recovery and economic Return on Investment (ROI). Finally, technological interventions alone are insufficient to drive a paradigm shift toward sustainable agriculture; they must be coupled with structural market incentives that financially reward farmers for transitioning from chemical to organic practices.

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Conflicts of Interest

The authors declare no conflict of interest. The authors confirm that there are no personal, financial, institutional, or other relationships that could be perceived as influencing the representation or interpretation of the research results presented in this study.

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