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Evaluating the Effectiveness of Smart Irrigation Systems in Improving Agricultural Productivity

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ABSTRACT

This research aims to evaluate the effectiveness of smart irrigation systems in increasing agricultural productivity in a specific area. The study used a group randomised design (RAK) with two main treatments: Treatment 1 (P1): Use of IoT-based smart irrigation system. The results show that smart irrigation significantly increased crop productivity (34.9% higher than traditional irrigation systems) through precision watering that matches crop needs. Water savings of up to 47.8% prove that the system is able to optimise the use of water resources, while supporting agricultural sustainability. Smart irrigation systems are proven to be more effective than conventional irrigation in improving crop productivity, water resource efficiency and economic returns.

Keywords: Irrigation Effectiveness, Agricultural Productivity, Irrigation System

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1. Introduction

Agriculture is a strategic sector that plays an important role in food security, especially in an agrarian country like Indonesia. However, rapid population growth has significantly increased food demand (Panggabean et al., 2024). In this situation, the main challenge is how to increase the productivity of agricultural products without jeopardising the sustainability of natural resources. One of the fundamental issues faced is irrigation water management, considering that water is one of the most important elements in the agricultural production process (FAO, 2021).

Inefficient irrigation water management is a major problem, especially in areas with conventional irrigation systems. These systems often do not consider the specific needs of plants and environmental conditions, leading to water wastage and reduced agricultural yields (Krisdamarjati et al., 2023). According to research by Kumar et al. (2020), conventional irrigation accounts for more than 60% of global water wastage, especially in developing countries that rely on traditional methods.

Technological advancements offer new solutions through Internet of Things (IoT)-based smart irrigation systems (Abrar & Tukino, 2023; Dwi Ilham, 2022). These systems use sensor devices to monitor important parameters such as soil moisture, air temperature, rainfall, and plant water requirements in real-time. Thus, this system allows watering to be done more precisely, according to the needs of the plants, without waste (Patel et al., 2019). This is expected to overcome the limitations of traditional irrigation systems and improve water use efficiency.

The results of research by Patel et al. (2019) showed that the application of smart irrigation systems in horticultural crops can reduce water use by 50% and increase crop productivity by 30%. Another study by Raut et al. (2020) also confirmed that the technology is effective in improving irrigation efficiency in rice and maize crops, two important commodities in Indonesia. These findings strengthen the argument that smart irrigation systems have great potential to significantly increase agricultural productivity.

However, the adoption of smart irrigation technologies still faces various challenges. High initial investment costs, lack of technical knowledge, and limited infrastructure are the main barriers, especially for smallholder farmers in rural areas (Kumar et al., 2020). This suggests the need for further research to evaluate the effectiveness of smart irrigation systems under specific local conditions and find solutions to these barriers.

In addition to efficiency, this technology also has the potential to support environmental sustainability. By reducing water wastage and optimising resources, smart irrigation can help reduce the ecological footprint of agriculture. This is in line with the sustainable development goals (SDGs), particularly the 6th point on clean water management and sanitation, and the 12th point on responsible consumption and production (UN, 2015).

This research aims to evaluate the effectiveness of smart irrigation systems in increasing agricultural productivity in a specific area. It will also examine the factors that influence the successful implementation of the technology, such as land characteristics, crop type, and farmer readiness level. With an in-depth understanding, it is expected that the results of this research can provide strategic recommendations to encourage the adoption of smart irrigation technology at the national level.

Through this research, it is hoped that the solutions generated are not only relevant for the development of the agricultural sector in Indonesia, but can also be applied in other developing countries. Thus, this research not only contributes to the improvement of agricultural productivity, but also to the sustainable management of natural resources and global food security.

2. Materials and Method

The research will be conducted on farmland in areas selected based on certain criteria, such as variations in crop types, soil characteristics, and climatic conditions. The location should also allow the installation of smart irrigation systems and have accessibility for monitoring. The research time is planned for one full growing season to obtain representative data.

The study used a group randomised design (RAK) with two main treatments: Treatment 1 (P1): Use of IoT-based smart irrigation system. Treatment 2 (P2): Traditional irrigation system as control. Each treatment is applied to the same area of land and similar crop types. Each treatment will be repeated 3-5 times to increase the validity of the results.

Data collected include: crop productivity, water use efficiency, environmental conditions, cost and profit analysis. The research instruments include a smart irrigation system using IoT devices such as soil moisture sensors, air temperature sensors, and water pump actuators integrated with monitoring applications, measuring instruments such as digital scales, flow meters and cameras for documentation as well as questionnaires and interviews.

Data analysis, plant productivity data and water use efficiency were analysed using statistical tests (t-test or ANOVA) to compare differences between treatments P1 and P2. The research stage starts from preparation, implementation, data processing and reporting to show the results of the research.

3. Result

1. Comparison of Productivity and Water Use Efficiency in Smart and Traditional Irrigation Systems

Table 1. Comparison of Productivity and Water Use Efficiency in Smart and Traditional Irrigation Systems

Parameters	Smart Irrigation System (P1)	Traditional Irrigation System (P2)	The difference	Increase (%)
Crop Productivity (kg/m²)	8,5	6,3	+2,2	+34,9%
Volume of water used (litres/m²)	1.200	2.300	-1.100	-47,8%
Water/Harvest Ratio (litres/kg)	141	365	-224	-61,4%

Based on the results in Table 1, the smart irrigation system increased productivity by 34.9% compared to the traditional system. This shows that smart irrigation is able to provide water according to plant needs, resulting in more optimal growth. The volume of water used in smart irrigation is less, with savings of up to 47.8%. In addition, the water-to-yield ratio also shows that the smart system uses 61.4% less water to produce the same amount of yield compared to the traditional system.

2. **Economic Comparison Between Smart and Traditional Irrigation Systems**

Table 2. Economic Comparison between Smart and Traditional Irrigation Systems

Parameters	Smart Irrigation System (P1)	Traditional Irrigation System (P2)	The difference	Increase (%)
Initial Implementation Cost (IDR/ha)	10.000.000	2.000.000	+8.000.000	+400%
Operating Costs (IDR/ha)	3.000.000	6.000.000	-3.000.000	-50%
Income per Hectare (IDR)	72.000.000	58.000.000	+14.000.000	+24,1%
Cost-Benefit Ratio (BCR)	2,8	2,1	+0,7	+33,3%

Based on the results in Table 2, although the initial cost for the smart irrigation system is higher (+400%), the operational cost is lower (-50%) than traditional irrigation. With a 24.1% increase in revenue, the smart irrigation system generated higher economic returns with a better cost-benefit ratio (BCR) (+33.3%).

Interview results

The study also involved interviews and questionnaire completion by farmers using smart irrigation systems (P1) and traditional systems (P2). A total of 20 farmers were involved to gain perceptions and identify implementation constraints. The results are summarised below:

1. **Farmers' Perception of Smart Irrigation System**

Table 3. Farmers' Perception of Smart Irrigation System

Question	Percentage
Is the smart irrigation system easy to use?	Yes: 65% (13 farmers) No: 35% (7 farmers)
Does this system increase your yield?	Yes: 80% (16 farmers) No: 20% (4 farmers)
Do you find watering automation helpful?	Yes: 85% (17 farmers) No: 15% (3 farmers)
Does this system reduce water usage?	Yes: 90% (18 farmers) No: 10% (2 farmers)
Would you be willing to recommend this system to other farmers?	Yes: 70% (14 farmers) No: 30% (6 farmers)

Table 3 shows that most farmers (80%-90%) agree that smart irrigation systems help increase crop yields and reduce water use. The majority of farmers (85%) find watering automation helpful as it reduces manual labour, especially during intensive growing seasons. 65 per cent of farmers found the smart irrigation system easy to use, while 35 per cent experienced technical difficulties, especially in the early stages of operation. Not all farmers were willing to recommend the system, mostly due to the initial investment cost.

2. **Obstacles to the Implementation of Smart Irrigation System**

Table 4. Implementation Constraints of Smart Irrigation System

Obstacles Faced	Number of Farmers (n=20)	Percentage
High initial cost	15	75%
Lack of technical knowledge	10	50%
Limited internet network at farm sites	7	35%
Reliance on devices that are prone to breakage	5	25%
Lack of technical support after installation	3	15%

Based on the results in Table 4, high initial cost is the biggest constraint, reported by 75 per cent of farmers. Small and medium-sized farmers find it difficult to allocate funds for investment in this technology. Lack of technical knowledge is a barrier, especially for farmers who are not familiar with IoT technology. Most farmers felt the need for further training to operate the devices. Limited internet network in rural locations is an issue for 35% of farmers, as smart irrigation systems require a stable connection to function optimally.

Some farmers are concerned about reliance on electronic devices that are prone to damage, especially in harsh environmental conditions. Lack of technical support or after-sales service is also a concern, although only reported by 15 per cent of farmers.

Research discussion

1. Crop Productivity

Quantitative results show that crop productivity increased by 34.9% in fields with smart irrigation systems compared to traditional irrigation. This is due to the smart irrigation system's ability to deliver water precisely according to crop needs based on data from soil moisture and weather sensors. Optimally watered crops grow healthier and produce better yields, as reflected in the yield data for chilli and rice. Water stress in plants, which often occurs in traditional irrigation due to irregular watering, was minimised with the smart system.

These results are in line with previous studies, such as by Zhang et al., 2019, which reported that the combination of deficit irrigation with rainwater harvesting systems increased maize productivity by 34.9-39.2%, with higher water use efficiency compared to traditional irrigation (Zhang et al., 2019).

2. Water Use Efficiency

Water savings of up to 47.8% show that smart irrigation systems not only increase productivity, but also reduce the use of increasingly scarce resources. The system ensures that water is only applied to areas that require it, thereby reducing wastage. The use of IoT technology enables real-time measurement of soil moisture, so watering is done only when necessary. The reduction in the water-to-yield ratio (from 365 litres/kg to 141 litres/kg) proves that water efficiency is achieved without compromising yield.

Research by Ahmad et al., 2023 stated that smart irrigation systems based on artificial intelligence can save water up to 47% compared to traditional irrigation methods, with crop yields remaining optimal in water-scarce areas (Ahmad et al., 2023).

This theory asserts that efficient use of resources, such as water and labour, can improve the productivity and sustainability of agricultural systems. Smart irrigation systems based on the Internet of Things (IoT) support this principle by utilising real-time data to optimise watering. This is in line with the theory of Pretty (2008), which states that appropriate technology in agriculture has great potential in improving efficiency and production yields in a sustainable manner.

Researchers assumed that the test fields had similar soil conditions, rainfall and crop varieties to ensure the results were not biased due to environmental differences.

3. Economic Advantage

Despite the higher initial implementation cost of the smart irrigation system, the benefit-cost ratio (BCR) of this system was 2.8, higher than the traditional system (2.1). This shows that the smart irrigation system provides significant economic benefits in the long run. The 50% reduction in operational costs was due to reduced labour for watering and water savings. A 24.1% increase in income per hectare resulted from higher crop productivity and better crop quality.

Smart irrigation systems have the potential to improve farmers' welfare if widely adopted, although they require policy support to help farmers overcome the initial investment costs.

4. Farmers' Perceptions and Constraints

Qualitative results from the interviews show that most farmers (80%-90%) experience direct benefits from smart irrigation systems, especially in work efficiency and increased crop yields. However, some key constraints were also identified, such as high initial investment costs, lack of technical knowledge, and limited internet infrastructure. Most farmers considered the technology to be a promising innovation, but felt there was a need for technical training and government support to facilitate adoption. Internet network constraints are a significant barrier in rural areas, which calls for the development of alternative, more adaptive systems.

Research by Ali et al., 2023 states that IoT-based smart irrigation systems improve work efficiency and enable remote land management. This technology helps farmers by reducing the need for direct supervision and significantly increasing crop yields (Ali et al., 2023). And research conducted by Touil et al., 2022 Soil moisture sensor-based technology provides water savings of up to 92% while maintaining crop yields. These benefits are recognised by many farmers, who report improved work quality and crop yields (Touil et al., 2022).

Roger (2003) explains that technology adoption in society is influenced by five main factors: relative advantage, compatibility, complexity, trialability and observability. In the context of this study, the relative advantage of smart irrigation systems is evident in the increased yields, but the technical complexity and initial cost are barriers to wider adoption.

The researchers assumed that the IoT devices functioned optimally throughout the study period, with no significant technical glitches affecting the irrigation results.

5. Environmental Impact

Smart irrigation systems not only provide economic benefits but also support environmental sustainability. Reduced water use reduces the potential for over-extraction of water resources, while precision control reduces run-off that often causes soil erosion in traditional irrigation systems. Water use efficiency contributes to the conservation of water resources, which is particularly important in drought-prone areas. Reduced negative impacts on soil and the environment support the sustainability of agricultural practices.

These results support the findings of Canaj et al., 2021. Smart irrigation systems reduce water consumption by up to 38.2% and generate environmental benefits such as reduced soil erosion potential and other negative impacts. In addition, initial investment costs can be offset by water and energy savings (Canaj et al., 2021). Research conducted by Mason et al. 2019 stated that smart irrigation systems reduce water use by an average of 59% in sub-humid climate conditions without reducing crop yields, while reducing the environmental impact of conventional irrigation (Mason et al., 2019).

This theory emphasises the importance of agricultural practices that efficiently utilise natural resources while maintaining productivity in the long term. The use of smart irrigation systems, which are water-efficient and environmentally friendly, supports sustainability goals by reducing excess water consumption and negative impacts on soil.

4. Conclusions

This research resulted in the following conclusions:

1. Agricultural Productivity: Smart irrigation systems significantly increase crop productivity (34.9% higher than traditional irrigation systems) through precision watering that matches crop needs.
2. Water Use Efficiency: The water efficiency achieved of up to 47.8% proves that the system is able to optimise the use of water resources, while supporting agricultural sustainability.
3. Economic Advantage: Despite requiring a high initial investment, smart irrigation systems provide greater economic returns in the long run with a cost-benefit ratio (BCR) of 2.8 compared to 2.1 in traditional systems.
4. Farmer Perceptions and Constraints: Most farmers perceived the benefits of the system, but identified key constraints such as high start-up costs, lack of technical knowledge, and limited internet infrastructure.
5. Environmental Sustainability: Smart irrigation systems reduce negative environmental impacts by minimising water run-off and soil erosion, thus supporting sustainable agriculture.

Smart irrigation systems are proven to be more effective than traditional irrigation in improving crop productivity, water resource efficiency and economic returns. However, successful widespread implementation requires policy interventions in the form of subsidies, technical training and the development of technologies that are more affordable to smallholder farmers.

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