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Dynamics of Precision Irrigation Adoption based on Sensors among Small-Scale Rice Farmers a Multi-Site Case Study in Indonesia User Experiences of Drone-Based Land

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ABSTRACT

This study investigates the adoption dynamics of sensor-based precision irrigation and drone-assisted land management among smallholder rice farmers in Indonesia. Using a multi-site mixed methods case study with surveys, interviews, and field experiments, findings show that adoption of irrigation sensors is shaped by perceived technical benefits, investment costs, and extension support, while drone use is influenced by ease of operation and access to services. Economic analysis indicates that combining sensors and drones improves water efficiency by up to 27% and reduces labor costs by 15%. The study concludes that integrating these technologies can enhance the sustainability of small-scale rice farming and provides important policy and engineering implications for precision agriculture in Indonesia.

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INTRODUCTION

Precision agriculture is increasingly seen as one of the main solutions in responding to global challenges in the form of increasing food needs, limited water resources, and pressures on environmental sustainability. The development of sensor technology for soil moisture monitoring and drones for land mapping has been proven to make a significant contribution to water use efficiency, reduced labor costs, and increased crop productivity (Revolutionizing Agrotechnology, 2023). In Indonesia, the agricultural sector is still the backbone of the economy by absorbing more than a third of the national workforce, especially in the rice subsector. However, relatively stagnant productivity challenges, limited irrigation infrastructure, and high reliance on traditional methods make technology-based modernization efforts increasingly urgent (Fikri et al., 2023). This condition requires research that can explain the dynamics of the adoption of precision technology in a more contextual way, especially among small-scale rice farmers who still face limited financial and technical access.

Although the application of sensor-based precision irrigation has shown great potential in improving water efficiency by more than 20% in various international studies, its adoption rate in developing countries, including Indonesia, is still low (Zhang, 2024). Key factors influencing adoption include high initial investment costs, limited technical skills, and a lack of institutional support and training for farmers (Hussin et al., 2023; Kumar et al., 2022). On the other hand, the development of drones for agriculture also shows great potential in improving the effectiveness of land monitoring and crop health, but the use of this technology is still hampered by regulations, operational costs, and limited capacity of farmers in operating the device (Fikri et al., 2023; Lopez & Ramirez, 2021). Therefore, there is still a gap between the potential of the available technology and the reality of implementation on the ground, particularly at the smallholder level (Chen et al., 2023).

Previous studies have focused more on the technical aspects of sensors and drones separately, while integrative approaches that combine technical performance analysis with real experience of farmers in the field are still very limited. For example, studies on precision irrigation have been widely conducted at the level of large plantations and commercial farming systems (Mizik, 2023), but less explored how this technology can be adapted by smallholder farmers who have limited resources. Similarly, research related to drones in developing countries still tends to highlight their potential applications without delving into the user experience in diverse socio-economic contexts (Fikri et al., 2023). This shows that there is a research gap that needs to be filled, namely the need to understand the dynamics of precision technology adoption more comprehensively by taking into account technical, social, and economic factors simultaneously.

In addition, most previous studies have focused on quantitative analysis in the form of measurements of factors influencing technology adoption, but it is still rare that integrates a qualitative approach to explore subjective perceptions and real experiences of farmers in using new technologies (Hussin et al., 2023;

Zhang, 2024). In fact, in the context of agricultural innovation, user experience plays an important role in determining the sustainability of adoption, as perceptions of benefits, ease of use, and technical barriers often determine adoption decisions more than just economic calculations (Geng et al., 2024). Thus, research that simultaneously assesses the technical performance of sensors and drones and explores farmers' experiences in their application will provide a more complete understanding of the real conditions in the field (Fikri et al., 2023).

Based on these research gaps, this study was designed to analyze the dynamics of sensor-based precision irrigation adoption and explore the experiences of drone users in land management among small-scale rice farmers in Indonesia using a multi-location case study approach. By integrating quantitative and qualitative data, this study aims to identify the technical, social, and economic factors that play a role in encouraging or inhibiting technology adoption, as well as describing the reality of drone use by farmers in the field.

The main objective of this study is to provide a comprehensive understanding of the linkages between the adoption of sensor technology in precision irrigation and farmers' experiences in utilizing drones for land management. Thus, this study is expected to fill the literature gap regarding the integration of technical and social analysis in the context of small-scale rice farming in Indonesia, as well as make a theoretical contribution to the development of precision agricultural engineering.

In addition to the theoretical contribution, this research also has a significant practical contribution. Empirical findings on the dynamics of sensor adoption and drone use experience will provide important input for policy makers, agricultural extension workers, and technology developers in designing technology implementation strategies that are more adaptive to the needs of smallholder farmers. The results of the research are also expected to strengthen the direction of agricultural transformation policies towards sustainable smart farming in Indonesia, as well as provide technical and social recommendations that can increase the effectiveness of agricultural modernization programs at the local and national levels.

THEORETICAL REVIEW

Sensor-Based Precision Irrigation

Precision irrigation has become one of the major innovations in the field of agricultural engineering due to its ability to improve water use efficiency and maintain land productivity. Sensor-based technology used in precision irrigation systems is able to monitor soil moisture in real-time so that watering decisions can be made more accurately compared to conventional methods. Research shows that the use of soil sensors is able to reduce water consumption and at the same time increase crop yields, especially in rice plants that have quite high water needs (Mizik, 2023; Singh et al., 2022). However, the adoption of this technology among smallholders is still relatively low, especially in developing countries such as Indonesia, due to limited capital, lack of technological literacy, and lack of institutional support (Hussin et al., 2023).

The Use of Drones in Precision Agriculture

In addition to sensors, the use of drones in agriculture is also increasingly widespread and is considered an important part of precision agriculture. Drones are able to map land conditions, monitor plant growth, and spray pesticides more efficiently. In the context of rice land management, drones can assist smallholders in identifying areas that need special interventions, so that resources can be allocated more appropriately (Fikri et al., 2023; Torres et al., 2021). However, drone adoption faces challenges in the form of high equipment costs, limited technical skills of farmers in operating the devices, and regulations that have not fully supported their widespread use in the agricultural sector (Revolutionizing Agrotechnology, 2023; Li & Zhao, 2022).

Limitations of Previous Studies

Previous studies have mostly focused on the technical effectiveness of each technology, both sensors and drones, without examining in depth how farmers' experience in implementing the two innovations simultaneously. In fact, social aspects and user experience are important factors that determine the sustainability of technology adoption. Previous research has highlighted more economic benefits or increased yields, but it is still rare to assess farmers' perceptions of ease of use, the relevance of technology to local conditions, and the institutional support available (Hussin et al., 2023). Other research also emphasizes the importance of understanding farmers' perceptions in determining technological sustainability (Fikri et al., 2023). Recent studies have found that the success of precision agriculture adoption is strongly influenced by socio-cultural factors at the local level (Kumar & Devi, 2022). Meanwhile, other research shows that institutional support and community-based service models can accelerate technology adoption among smallholder farmers (Lopez et al., 2021).

Research Gaps in Small-Scale Farmers

There is also a research gap related to the context of small-scale rice farmers, where most studies on precision irrigation and drones are conducted on a large-scale farm or in pilot projects supported by external funding (Mizik, 2023). This condition is different from the reality of smallholders in Indonesia who have limited access to capital, training, and technological infrastructure (Rahman et al., 2024). Therefore, research on the dynamics of the adoption of sensor-based precision irrigation and the experience of using drones among smallholder farmers is important to answer the challenges of implementing modern technology in the local context.

METHODOLOGY

Types and Approaches to Research

This study uses a mixed methods approach with a multi-site case study design. A quantitative approach was used to measure the adoption rate of sensor-based precision irrigation as well as evaluate the economic and technical impact of the use of the technology, while a qualitative approach was used to explore farmers' experiences in the application of drones for rice land management. The selection of a multi-site case study design was carried out to gain a more comprehensive understanding of the dynamics of technology adoption in diverse social, economic, and agroecological contexts in Indonesia (Creswell & Creswell, 2023). The mixed methods approach is considered effective because it is able to combine the strength of quantitative and qualitative data in a more balanced manner (Fetters, 2020). In addition, the use of multi-site case study designs has also been shown to enrich cross-context understanding and improve the external validity of research (Snyder, 2022).

Population and Sampling Techniques

The study population is small-scale rice farmers in the three main rice-producing provinces in Indonesia, namely Central Java, South Sulawesi, and North Sumatra. The sampling technique used is purposive sampling, with the criteria of farmers who have experience using sensors for irrigation or drones in land management. The quantitative sample count involved 180 respondents selected for the survey, while the qualitative participants consisted of 24 key informants, including pioneer farmers using technology, agricultural extension workers, and technical service providers. The selection of this sample was based on considerations of the relevance of information and the representation of variation in experience across the three study sites (Etikan & Bala, 2022).

Data Collection Techniques

Quantitative data was collected through a structured questionnaire that included indicators of technology adoption, perception of technical benefits, investment costs, as well as institutional support. The questionnaire instrument was adapted from previous research related to the adoption of precision agricultural technology and adjusted to the local context (Mizik, 2023). Qualitative data was obtained through semi-structured interviews to explore the experiences, perceptions, and challenges of using drones in rice land management. In addition, field experiments were carried out in the form of testing soil moisture sensors to measure the accuracy of moisture monitoring, as well as mapping drone imagery to assess the effectiveness of monitoring plant growth. The validity of the quantitative instrument was tested through the validity of the content by involving agricultural engineering experts, while reliability was measured using Cronbach's Alpha with a minimum value of 0.70 as a good reliability indicator (Hair et al., 2021).

Research Procedure

The research stage begins with a literature study to identify relevant variables in the adoption of sensor and drone technologies. Next, a pre-survey was conducted on 20 farmers outside the main research site to test the instruments. The main survey was conducted for three months with the help of trained enumerators. In-depth interviews were conducted in parallel with the selection of key informants who were considered representative in each province. Field experiments were carried out on selected farmers' land to test the performance of sensors and the accuracy of drones in mapping crop conditions.

All data is encrypted and stored anonymously to maintain respondent confidentiality.

Data Analysis Techniques

Quantitative data were analyzed using logistic regression to examine the factors influencing the adoption of irrigation sensors, as well as cost-benefit analysis to assess the economic efficiency of the use of the technology. The analysis was performed with SPSS 26 software and Microsoft Excel. Qualitative data were analyzed using thematic analysis with open, axial, and selective coding steps to identify patterns of farmers' experiences in the use of drones. Quantitative and qualitative results are then integrated to obtain a more holistic picture of the dynamics of the adoption of precision agriculture technology in small-scale rice farmers (Nowell et al., 2022).

RESEARCH RESULTS

Sensor-Based Precision Irrigation Adoption Rate

The results of a survey of 180 smallholders in Indonesia's three main rice-producing provinces show that the adoption rate of sensor-based precision irrigation is still relatively low. Of the total respondents, only 38% have tried using sensors to aid decision-making in irrigation practices, while the rest still rely on conventional methods based on experience and visual forecasting. These findings are in line with the phenomenon of low penetration of precision technology in developing countries, which are often constrained by investment costs, limited technical knowledge, and lack of institutional support.

Logistic regression analysis conducted to identify factors influencing adoption showed that the perception of technical benefits was the most dominant factor with a significance level of $p < 0.01$. Farmers who consider that sensors are able to improve water use efficiency and maintain land productivity are more likely to adopt this technology than farmers who are still skeptical of its benefits. The investment cost factor was also shown to be significant ($p < 0.05$), where farmers with better access to capital had a higher likelihood of adoption. Meanwhile, extension support also plays an important role ($p < 0.05$), with the results of the analysis showing that farmers who receive technical training or guidance have a 1.7 times higher probability of adopting sensor technology compared to those who do not receive such support.

On the other hand, the variables of the farmer's age and land area did not have a significant effect on the adoption decision ($p > 0.05$). These findings are interesting because they show that although it is often assumed that younger farmers are faster to adopt innovation, in these cases the age factor is not the main determinant. Similarly, land ownership extent does not necessarily correlate with the adoption of sensor technology, indicating that adoption motivation is more influenced by perceptions of direct benefits and external support than by the structural condition of the land.

In summary, technical, economic, and institutional factors have an important role in driving the adoption of irrigation sensors, while demographic factors and business scale have not proven significant. These findings underscore the importance of intervention strategies in the form of targeted counseling and affordable financing schemes so that smallholders can more easily access and adopt sensor technology in their daily irrigation practices.

Table 1. Results of Logistic Regression Analysis of Determinants of Sensor-Based Precision Irrigation Adoption

Determinants of Adoption	Signifikansi (p-value)	Information
Perceived technical benefits	< 0.01	Highly influential
Investment costs	< 0.05	Influential
Counseling support	< 0.05	Influential
Age of the farmer	> 0.05	Insignificant
Land	> 0.05	Insignificant

Drone User Experience in Land Management

The results of in-depth interviews with 24 key informants revealed that the use of drones in rice land management is perceived to provide real benefits to smallholders, especially in land mapping, early detection of pest attacks, and monitoring plant growth in the vegetative phase. Most farmers state that the use of drones helps reduce work time in the field and provides visual information that is difficult to obtain through manual observation. This is especially felt during the planting season, when the area of land that must be monitored is large enough and the available labor is limited. A farmer in Central Java stated: "*Before there were drones, I had to walk around the fields for almost two hours every morning to check the condition of the crops. Now with a drone, I can see the condition of the land in just about 20 minutes*" (Informant JT-07, interview April 14, 2025).

In addition to the benefits of time efficiency, drones are also considered helpful in reducing uncertainty in decision-making. An informant from North Sumatra, for example, emphasized that the resulting drone images can show areas of land that are experiencing drought or inundation more clearly: "*If you look at it directly, sometimes not everyone is caught, but with drones I can tell which parts of the rice fields are lacking water. So it can be quickly directed to irrigation*" (Informant SU-05, interview April 28, 2025). This shows that drones play an important role in supporting the application of precision farming principles, albeit at the smallholder level.

However, behind these benefits, there are a number of obstacles faced by farmers in the use of drones. The main obstacle is the limited operational capabilities, especially for farmers with older age and limited digital skills. Some farmers admitted that they still depend on external operators or young people in the village who are more familiar with technology. An agricultural extension worker in South Sulawesi said: "*Farmers here are actually happy with the results of drones, but most of them do not dare to operate them themselves for fear of damage. So usually they ask for help from farmer groups or service providers*" (Informant SS-03, interview May 6, 2025).

The cost factor is also a significant obstacle. The relatively high price of drones makes it impossible for most smallholders to buy independently. Alternatively, some farmer groups are trying to implement a joint venture system or hire the services of a drone operator. However, the rental cost which ranges from IDR 300,000 to IDR 500,000 per mapping session is considered quite burdensome, especially for farmers with limited land area. A farmer in South Sulawesi stated: "*If you have to buy it yourself, it's obvious that you can't afford it. Even if you rent frequently, the cost becomes large. So we usually use it only for the planting season*" (Informant SS-09, interview May 10, 2025).

The availability of technical support is also a key determinant of the sustainability of drone use. Farmers in areas with good access to technical services, such as Central Java which has extension workers and active technology communities, tend to use drones more often in a sustainable manner. In contrast, in rural areas far from service centers, the use of drones is still sporadic and relies on training opportunities from projects or universities. This was confirmed by one of the informants in North Sumatra: "*If there are technicians or campus people coming, we can learn. But if there is none, drones are usually only stored*" (SU-11 informant, interview April 30, 2025).

Overall, farmers' experience shows that the benefits of drones are highly appreciated, especially in terms of time efficiency and accuracy of information, but operational barriers, costs, and access to technical services are limiting factors. From a sustainability perspective, this study confirms that the sustainability of drone use at the smallholder level is largely determined by operational ease and external technical support. These findings are consistent with the results of qualitative analysis that show that social and institutional factors are just as important as technical factors in determining the sustainability level of drone adoption.

Field Experiment Results: Water Efficiency and Drone Accuracy

The results of field experiments conducted at three research sites show that the use of soil moisture sensors is able to have a real impact on the efficiency of water use in small-scale rice cultivation. Based on measurements made during one growing season, the average water use efficiency increased by 27.0% compared to conventional irrigation practices. On land using traditional methods, the volume of water used per hectare reaches an average of 13,200 m^3 per season, while with the help of sensors, this figure can be reduced to 9,630 m^3 without reducing production. This data shows that the use of sensors is not only relevant in the context of saving water resources, but also able to maintain productivity stability in smallholder rice fields.

In addition, yields from land using sensors showed no significant differences in productivity compared to conventionally managed land. The average productivity is in the range of 6.1 tons per hectare for land with sensors and 6.0 tons per hectare for land without sensors. Thus, the water savings obtained from the use of sensors do not negatively impact rice production, but rather increase the input efficiency in the production system. This proves that sensor technology has the potential to improve the sustainability of agricultural systems through optimizing the use of limited resources.

Field experiments also include trials of the use of drones in land mapping and crop growth monitoring. The results of the analysis showed that the drone images obtained had a spatial accuracy rate of 92.0%, which is high enough to support decision-making processes related to land management, such as the identification of areas of inundation, drought, or pest attacks. This accuracy was verified by comparing the results of drone imagery with direct measurements in the field (ground truthing) at 50 sample points at each research site. The high level of conformity shows that drones can be used as a reliable tool in supporting the implementation of precision agriculture, especially for smallholders who need quick and precise information in managing their land.

Furthermore, the use of drones has also been proven to be able to reduce the need for labor in land monitoring. Before the existence of drones, monitoring an area of one hectare of land took an average of 1.5–2 hours per day, while with the help of drones that time could be cut to just 20–30 minutes. This efficiency has a direct impact on reducing farmers' workload while increasing accuracy in detecting problems on the land. Thus, the combination of using soil moisture sensors and drones not only results in efficiency in water use, but also efficiency in labor use.

Overall, the findings of these field experiments indicate that the integration of sensors and drones has a strategic contribution to improving resource efficiency in small-scale rice farming systems. Sensors serve to optimize water use and maintain productivity, while drones provide accurate spatial information to support land management decision-making. The synergy of these two technologies provides a strong foundation for the implementation of more inclusive and sustainable precision agriculture in Indonesia.

Table 2. Comparison of Water Use Efficiency and Productivity between Conventional and Sensor-Based Methods

Parameter	Conventional Methods	Sensor-Based	Difference (%)
Water volume per hectare (m^3/season)	13.200	9.630	–27.0
Productivity (tons/ha)	6.0	6.1	+1,7
Irrigation monitoring time (hours/ha/day)	1,5–2,0	0.5–1.0	–50.0

Source: Primary data processed (2025)

Table 3. Drone Image Accuracy against Ground Truthing

Research Location	Number of Sample Points	Suitability Rate (%)	Average Accuracy (%)
Central Java	50	91.8	
Sulawesi Selatan	50	92.3	

Research Location	Number of Sample Points	Suitability Rate (%)	Average Accuracy (%)
North Sumatra	50	91.9	
Average	**150**		**92.0**

Source: Primary data processed (2025)

Economic Analysis of the Use of Sensors and Drones

The results of the cost-benefit analysis show that the application of sensor and drone technology to small-scale rice farming systems provides significant economic benefits, although it requires a relatively high initial investment. The use of soil moisture sensors has been proven to reduce operational costs related to water use, while drones contribute to saving time in land monitoring and pest control. Cumulatively, these two technologies resulted in an average reduction in labor costs of 15.0% per planting season, mainly due to the reduced need for manual monitoring and the efficiency of labor distribution in the field.

The simulation of cost and benefit calculations was carried out taking into account the average price of sensor devices and drones in the local market in 2025, coupled with annual maintenance costs. The simulation results show that if technology is used individually by farmers, the break-even point period can only be reached after more than 6 planting seasons. However, when technology is adopted through collective schemes based on farmer groups or sharing services, the break-even period can be shortened to 3–4 planting seasons. This condition is caused by the distribution of initial investment costs among group members, so that the burden per individual becomes lighter and the use of technology becomes more optimal.

In addition, the cost-benefit analysis also showed that the use of sensors was able to increase water use efficiency by an average of 27.0%. This efficiency directly contributes to reduced energy costs for water pumps, especially in areas with irrigation systems that rely on borewells. Water efficiency also has an indirect impact in the form of crop productivity resilience in the dry season, which has the potential to reduce the risk of losses due to crop failure. Thus, the economic benefits are not only limited to input cost savings, but also include reduced production risks.

The use of drones, although not directly resulting in an increase in rice productivity in the short term, has been shown to be helpful in reducing potential losses due to delayed pest detection and water shortages. With an image accuracy rate of up to 92.0%, drones allow farmers to intervene in a timely manner, so that the cost of pest control or irrigation correction can be reduced. A farmer in Central Java revealed: "*If we use drones, we can quickly know which rice fields are affected by pests. So the medicine is not wasteful because it is only used where it is necessary.*" (Informant JT-12, interview April 18, 2025). This shows that the economic benefits of drones are more preventive, which has an impact on medium-term efficiency.

Overall, these findings confirm that the integration of sensors and drones provides significant economic benefits and can improve the sustainability of small-scale rice farming, especially if organized in the form of farmer group-based institutions. The collective strategy not only lowers the burden of investment costs, but also strengthens farmers' access to technical support and equipment maintenance. Thus, this study shows that the successful adoption of precision technology at the smallholder level is greatly influenced by the institutional model used, not just by the readiness of individual farmers.

Table 4. Summary of Economic Analysis of Sensor and Drone Use

Economic Analysis Components	Average Score	Impact
Water use efficiency	+27.0%	Positive on energy and input costs
Reduced labor costs	–15.0%	Positive through energy savings
Break-even period	3–4 growing seasons (collective)	Feasible if based on farmer groups

Source: Primary data processed (2025)

Variation of Results Between Research Locations

The results showed that there was a difference in the level of adoption and experience of using sensor-based precision irrigation technology and drones between the research sites. In Central Java Province, the highest rate of censorship adoption was recorded, which was 45.0% of the total respondents. This figure is much higher than South Sulawesi at 34.0% and North Sumatra at 33.0%. The high adoption rate in Central Java is mainly due to the intensity of extension activities, pilot programs that are more often carried out by universities and research institutions, and relatively more established institutional support. Agricultural extension workers in the region are actively facilitating training on the use of sensors, giving farmers more confidence to adopt new technologies.

In contrast, the adoption rate of censorship in South Sulawesi and North Sumatra is still relatively low. This is influenced by limited access to equipment, high investment costs, and lack of ongoing technical counseling. Farmers in the region rely more on traditional methods due to limited information and the lack of consistent institutional support. A farmer in South Sulawesi said: "*We have heard about censorship, but the tools are rare in villages. If there is no assistance from the government or farmer groups, it will be difficult to be able to buy*" (Informant SS-07, interview May 7, 2025). This confirms that the difference in adoption is not only due to individual readiness, but is also determined by the supporting ecosystem in each region.

Meanwhile, the use of drones shows a different pattern. Although Central Java has a higher rate of sensor adoption, reports of drone use are more common in North Sumatra. This condition occurs due to the support of commercial drone service providers who are already operating in the area. The presence of this service provider makes farmers not need to buy drones individually, but rather simply rent them when needed. This rent-based service model lowers cost barriers and improves technology accessibility. An informant in North Sumatra explained: "*If it is a drone, we usually rent it from a service provider. It is cheaper because it is only used when planting and when there is a pest attack*" (Informant SU-04, interview April 25, 2025). This suggests that the existence of a modern agricultural services market can be one of the important factors accelerating the adoption of drones.

In addition to the cost and support factors of counseling, the institutional social aspect also plays an important role in shaping the variation between locations. In Central Java, farmer groups play an active role as mediators in the provision of sensor equipment and technical training. A collective-based use scheme allows investment costs to be borne together, making technology more accessible. In contrast, in South Sulawesi, the involvement of farmer groups is still limited, so adoption tends to be individual and sporadic. This makes the level of sustainability of using technology lower than other regions.

This variation also reflects differences in the readiness of the support services ecosystem. In areas with access to intensive counseling, university support, and private sector involvement in the provision of technology services, the adoption and sustainability of the use of sensors and drones is higher. In contrast, in areas where technical and institutional access is still limited, precision technology is still considered foreign and difficult to adopt widely. Thus, the results of this study confirm that the successful implementation of precision technology at the smallholder level cannot be separated from the institutional context and service ecosystem in each location.

Table 5. Variation in Sensor Adoption and Use Rates between Research Sites

Research Location	Sensor Adoption (%)	Drone Usage (%)	Key Supporting Factors
Central Java	45.0	28.0	Intensive counseling, institutional support for farmer groups
Sulawesi Selatan	34.0	22.0	Limited access to equipment, lack of training
North Sumatra	33.0	36.0	Commercial drone service provider support, easy rental access

Source: Primary data processed (2025)

DISCUSSION

The results of this study show that the use of soil moisture sensors is able to increase water use efficiency by up to 27.0 percent without reducing crop yields. These findings reinforce the theory of precision agriculture that emphasizes the importance of sensor technology in optimizing the use of inputs, particularly water, to maintain productivity. Previous studies have also emphasized that sensors can help reduce water waste while maintaining agricultural yields (Mizik, 2023; Hussin et al., 2023). However, this research makes a new contribution because it was conducted in the context of small-scale rice farmers in Indonesia, who are usually underrepresented in technology-based precision research. Thus, this study expands the understanding of the effectiveness of censorship on the real conditions of smallholders.

Logistic regression analysis showed that the perception of technical benefits, investment costs, and extension support were significant factors influencing farmers' decision to adopt sensor technology. This is in line with the concept of innovation diffusion which explains that relative superiority, external support, and ease of use are important factors in the adoption process (Montes de Oca Munguia et al., 2021). The results of this study also show concrete data that farmers who receive training are 1.7 times more likely to adopt censorship compared to farmers who do not receive support. These findings show that institutional aspects and technical guidance have a crucial role in accelerating the adoption of precision agriculture technologies.

Farmers' experience in using drones also provides important insights. Drones have been proven to help farmers in land mapping, pest detection, and crop growth monitoring with an image accuracy of 92.0 percent. This technology significantly reduces the fieldwork time, which usually takes hours, to only about 20–30 minutes per hectare. However, drone adoption is still hampered by limited operational skills, high purchase costs, and limited access to technical services in rural areas. This shows that while drone technology has great potential, its sustainability is highly dependent on the availability of technical support and an affordable service model. These findings are in line with previous research that emphasizes that social barriers and costs often determine the success of technology adoption more than technical aspects alone (Fikri et al., 2023; Guebsi et al., 2024).

Economic analysis shows that the use of sensors and drones can reduce labor costs by an average of 15.0 percent per planting season. Although the initial investment cost is considerable, the calculation simulations show that break-even points can be reached in 3 to 4 growing seasons if the technology is used collectively through farmer groups or service-sharing schemes. These findings confirm that the collective institutional model is the most feasible strategy to increase the sustainability of precision technology adoption among smallholders. These results are also in line with international studies that emphasize the importance of community-based models in driving the adoption of expensive agricultural technologies (Amoussouhoui et al., 2024).

The study also found variation between locations. Central Java has the highest censorship adoption rate at 45.0 percent, while South Sulawesi and North Sumatra only reach 34.0 percent and 33.0 percent. This difference is mainly due to the intensity of counseling and the better institutional strength in Central Java. On the other hand, the use of drones is relatively higher in North Sumatra due to the existence of commercial drone service providers that provide rental services at affordable prices. This variation suggests that institutional factors and the service ecosystem are strongly determining the speed of adoption of precision technologies. Thus, the adoption policy strategy must be adjusted to local conditions and cannot be generalized to all regions.

This research certainly has limitations. Experimental data was only conducted in one planting season, so the long-term effects on productivity and sustainability of the system could not be ascertained. In addition, the number of key informants for interviews is still limited so a more diverse user experience has not been fully explored. Economic analysis also does not include aspects of equipment depreciation and long-term maintenance costs. Therefore, further research needs to be carried out longitudinally, involving more informants from various social groups, and taking into account the useful life of the equipment in the cost-benefit analysis.

Overall, the study shows that the integration of sensors and drones has the potential to improve resource use efficiency, lower labor costs, and provide accurate spatial information support for smallholder farmers. However, successful adoption does not depend only on the technology itself, but on institutional support, technical services, and collective strategies that are able to lower cost and skill barriers. The contribution of this research lies in providing empirical evidence in the context of small-scale Indonesian rice farmers, as well as providing a scientific basis for the development of more inclusive and sustainable precision agriculture policies.

CONCLUSIONS AND RECOMMENDATIONS

This study confirms that the application of precision agriculture technology in the form of irrigation sensors and drones has strategic potential in improving the sustainability of small-scale rice farming in Indonesia. The results showed that the use of soil moisture sensors was able to increase water use efficiency by up to 27.0 percent, while drones were proven to provide spatial imagery with 92.0 percent accuracy that supports proper land management decision-making. In addition, economic analysis shows a reduction in labor costs by 15.0 percent per planting season and the potential to reach break-even in 3 to 4 planting seasons if technology is adopted through a collective model based on farmer groups.

The main determining factors in the adoption of this technology are the perception of technical benefits, investment costs, and counseling support. Farmers who are trained are more likely to adopt the sensors, while the experience of using drones is strongly influenced by ease of operation and access to technical services. The difference in adoption rates between locations also shows that the success of precision technology implementation is highly dependent on the local ecosystem, including the intensity of outreach and the presence of technology service providers.

The theoretical contribution of this research lies in strengthening the empirical evidence regarding the dynamics of the adoption of precision technology among smallholder rice farmers, which has been rarely researched. From a practical point of view, these findings provide an important basis for the formulation of more inclusive precision agriculture policies, emphasizing the need for institutional strengthening of farmer groups, sustainable technical support, and community-based service models that can reduce cost barriers. Overall, the integration of irrigation sensors and drones has proven to not only provide technical benefits, but can also be a strategic instrument in supporting food security and resource efficiency in Indonesia's small-scale rice farming sector.

FURTHER STUDY

For further study, it is important to examine the scalability and long-term sustainability of precision agriculture technologies, particularly in diverse rice farming contexts across Indonesia. Future research could focus on evaluating the socio-economic impacts of collective adoption models, including their effectiveness in reducing investment risks and enhancing farmer cooperation. In addition, studies on the role of government policies, private sector involvement, and digital infrastructure development are needed to better understand the enabling ecosystem for technology adoption. Comparative research across different regions may also provide insights into how local socio-cultural and ecological conditions influence adoption patterns and the overall effectiveness of precision agriculture in smallholder settings.

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