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Using the Internet of Things to promote alternate wetting and drying irrigation for rice in Vietnam's Mekong Delta

Vu Bang Pham¹ · Thanh Tung Diep¹ · Karin Fock² · Thai Son Nguyen³

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Abstract

The livelihoods of millions of rice farmers in Vietnam's Mekong Delta have become increasingly vulnerable due to reduced rainfall and the resulting water stress. In this context, promoting water-saving practices, such as alternate wetting and drying technology, is vital to sustain rice production and enhance people's resilience to climatic changes in the Delta. Since this technology is not widely applied in the region, this study hypothesized that a precise water measurement using the Internet of Things technology could facilitate the uptake of the alternate wetting and drying rice cultivation practice. The study applied a rigorous research design to assess the differential benefits of applying the technology with sensors. Participating farmers were divided into three treatment groups that produced rice using either the continuously flooded irrigation technique, manual alternate wetting and drying tubes, or tubes with sensors. The on-farm trials' results showed that the precise water level measurements with the sensors allowed the farmers to maximize the benefits from alternate wetting and drying irrigation. The experimental results indicated an additional 13–20% of water savings over manual alternate wetting and drying. The technology also reduced irrigation energy costs by 25% and moderately enhanced rice yields by 2–11%. This pilot was the first to demonstrate in a large-scale open-field trial that it is feasible and beneficial for smallholder farmers to apply cutting-edge Internet of Things technology to increase water use efficiency in their rice farms. The technology adoption would significantly contribute to sustaining the agriculture-based livelihoods of people in the Delta.

Keywords AWD · IoT · Precision agriculture · Smart farming · Rice · Vietnam

1 Introduction

For 80% of the rural population in Vietnam, rice production constitutes their main livelihood (Nguyen 2016). Taking up 12% of Vietnam's land area, the Mekong Delta provides 50% of Vietnam's rice production, of which 90% is exported (IIUCN and VAWR 2016; Tong 2017).

Because of climate change, water shortages during the dry paddy season have recently been challenging for Vietnamese farmers (Nhan and Trung 2011). The 2016 drought due to El

Niño caused excessive heat and reduced rainfall, negatively impacting rice production. Thuy and Anh (2015) found that increased water stress reduced paddy yields in Vietnam's Mekong Delta. Experts warn that water scarcity in the next 10–20 years will adversely affect farmers in this region (World Bank 2019).

Promoting climate-smart cultivation practices that improve water use efficiency is critical for sustainable rice production (ADB 2019). Alternate wetting and drying (AWD) has been identified as a proven method for optimizing irrigation water use in rice production (Siopongco et al. 2013). First, the application of AWD technology in rice production results in water savings of up to 30% (Lampayan et al. 2015) compared to conventional flooded cultivation. The cost of rice cultivation decreases by reducing water consumption, labor costs, and electricity costs while maintaining yields (Lampayan et al. 2015). Furthermore, applying AWD also reduces greenhouse gas emissions (ADB 2019; Lampayan et al. 2015). Theoretically, precise water management under AWD can reduce emissions by up to 90% compared to the conventional

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practice (Adhya et al. 2014). Wang et al. (2020) suggested that the AWD practice saved water, enhanced yields, and mitigated GHG emissions in rice cultivation.

Despite the documented benefits from applying the AWD practice in rice production, farmers' adoption of the process remains limited. For example, farmers in Bangladesh did not replicate International Rice Research Institute's demonstration models due to an insufficient number of extension workers assisting farmers in applying the AWD technology (Kürschner et al. 2010). Lampayan et al. (2009) found that rice producers in the Philippines did not adopt AWD if they paid a fixed irrigation fee for each season. Similarly, Howell et al. (2015) argued that low or lack of direct incentives for farmers to save water was the primary reason for the technology's limited uptake. In most rice production areas in Vietnam, including the Mekong Delta, water-savings incentives are also weak. Farmers pay for water use by land area, not by volume (Yamaguchi et al. 2016).

Furthermore, a meta-analysis by Carrijo et al. (2017) suggested that an improper AWD practice can result in yield reduction. Another barrier to AWD's widespread adoption is the requirement to analyze the soil type before introducing the technology (Howell et al. 2015). The authors argued that applying AWD in areas with inappropriate soil types, such as sandy soils and heavy clay soils with shallow water tables, negatively affected crop yields. Other significant constraints to farmers' AWD adoption relate to the lack of information and extension services (Alauddin et al. 2020).

Various solutions exist to overcome these challenges and promote the uptake of AWD. For example, improved water governance with volumetric pricing would create an incentive for adopting AWD (Li and Barker 2004). Deploying local extension services and training to inform farmers about the implementation and benefits of AWD would also enhance technology uptake (Alauddin et al. 2020), and strengthening the capacities of extension service field staff would improve the transfer of AWD knowledge to farmers and increase their confidence in applying the technology (Kürschner et al. 2010).

The literature review provided by Fastellini and Schillaci (2020) shows that the application of sensors and the Internet of Things (IoT) for precision farming holds potential worldwide for improving economic profitability and environmental sustainability. The authors' results confirmed that precision farming and IoT technology contribute to enhancing crop yields, optimizing resource use, and increasing the resilience of producers and the agro-ecosystem. The same paper also pointed out that developed countries are more active in introducing IoT technology in agriculture (e.g., in commercial wine in France, maize in Northern Italy, cotton irrigation in the USA, and rice in Japan). Technology evolution in these countries is based on smart agriculture machinery systems and it aims to generate "big data" to increase production efficiency.

Despite this potential, the deployment of sensors and IoT technology in rice production has been limited. Most research focused on the technical aspects, such as describing the system's components and performance (Sekozawa 2010; Guitton et al. 2015; Kawakami et al. 2016; Fukushima et al. 2018; Li and He 2019). Other studies confirm that the IoT technology is technically feasible for rice but limited in its application to controlled experimental conditions on a small scale (Pfischer et al. 2011; Obota and Inyama 2013; Miskam et al. 2013). Chiaradia et al. (2015) identified the high investment cost as a significant challenge to developing a complete and integrated water management system in rice production using the IoT technology. A recent study found that biophysical and socio-economic challenges limit IoT applications in open fields (Alauddin et al. 2020).

A pilot was implemented in Vietnam's Mekong Delta to investigate the benefits of AWD with sensors (hereafter referred to as IoT AWD). The starting hypothesis on which the pilot was based was that the precise water measurements and convenience of the IoT technology could generate additional benefits over the conventional AWD practice, which would facilitate the adoption of AWD among smallholder farmers. To confirm this hypothesis, key performance indicators were measured and compared, including irrigation water savings, energy cost savings, and crop yields between IoT AWD and manual AWD plots. Farmers' perspectives on the benefits and challenges of applying sensors for automated irrigation were also investigated.

In the first section of this article, the pilot design and implementation are described, followed by a brief overview of the data collection and analysis methods. Subsequently, the results of key performance indicators are discussed before presenting the participating farmers' perceptions about the smart-sensor AWD technology. The article ends with conclusions.

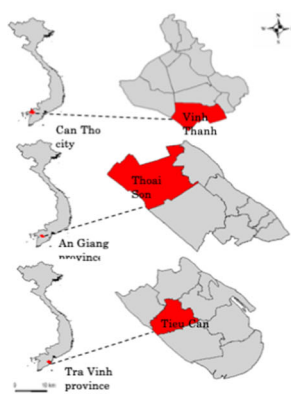
2 Materials and methods

2.1 Pilot design and implementation

Over 2 years, from September 2017 to August 2019, the pilot was implemented in three locations in Vietnam's Mekong Delta: Can Tho, Tra Vinh, and An Giang provinces, with 82 farmers and one farm enterprise (Fig. 1). These three locations with structural differences allowed an investigation of the benefits and challenges of introducing IoT AWD in diverse environments.

In Can Tho, the Khiet Tam Cooperative (10° 14' 08.3" N 105° 10' 49.9" E) participated in the pilot. Its farmers were well-positioned to apply manual and IoT AWD. The cooperative owned harvesters and drying and storage facilities that were acquired through a previous ADB project. The same

Fig. 1 Map of the project locations. Source: adapted from the original shapefiles acquired from gadm.org, accessed in March 2020.



project also enabled the farmers to laser level their fields and introduced them to manual AWD. The cooperative actively supported its members with input provision and marketing. In Can Tho, all participating farmers had autonomous access to irrigation. With an average of 2.2 ha, the smallholder farmers' field sizes in Can Tho are above average. The pilot plots had slight acidic alluvial (clay loam) soil with good water-holding capacity, and acid sulfate soil layer was located deep within the topsoil.

In contrast to Can Tho, the Tra Vinh site illustrated the real-life challenge of implementing AWD with smallholder farmers with suboptimal conditions for AWD. The Phu Can Cooperative (9° 47' 52.3" N 106° 09' 43.1" E) participated in the Tra Vinh pilot. Its farmers had no prior experience with manual AWD and imperfectly leveled and smaller fields (0.9 ha on average). The cooperative was not as well equipped as the one in Can Tho, and its services focused mostly on organizing farming inputs. The site featured a central water pump, and the commune set a fixed irrigation schedule at the beginning of each crop season. When the central pump was operated, it filled the main canal and secondary canals on both sides with water. Farmers with plots adjacent to the secondary canals received water by manually opening valves to their fields. These farmers could make independent irrigation decisions because the commune cooperated with the pilot project and allowed the pump operator to run the central pump at the farmers' request. However, automatically triggering an individual pump was not possible for the farmers. The farmers whose plots were not connected to the secondary canals received water through field-to-field irrigation by temporarily opening field boundaries and closing them when enough water was obtained. This practice put limitations on the farmers' ability to control the irrigation schedule and amount, and they tried to overcome this challenge by collaborating within their respective farmer groups. The pilot plots were situated on the sand ridge (described as sandy soil) that had weak water-holding capacity.

In An Giang, the pilot worked with a commercial rice-producing company (10° 14' 08.3" N 105° 10' 49.9" E). The

expectation was that they would serve as an example for a modern rice-farming environment with larger plots, laser-leveled fields, and individually controllable and automatically controlled pump operations. In practice, however, it was challenging to establish optimal conditions for AWD. Although the average field size was larger (4.3 ha), the resources for laser leveling could not be committed, and the fields remained imperfectly leveled. The irrigation infrastructure was also sub-optimal, with pump capacity limitations occasionally compromising the irrigation schedule and the available water amount for the AWD plots. The pilot plots were characterized by strong acid sulfate soil. The topsoil consisted of clay soil with organic matter, which ensured good water-holding capacity.

The participating farmers in each location were divided into three treatment groups that produced rice using either continuously flooded irrigation, or manual AWD, or IoT AWD technology. In the on-farm trials, there were no cases where one farmer performed more than one treatment plot.

The pilot was carried out in four phases (Table 1). The first two experimental field trial phases cultivated 12 plots. The two on-farm field trial phases included 147 plots (62 in phase 3 and 85 in phase 4) in three different locations. On 94 plots, the farmers applied IoT AWD. To establish the counterfactual across the treatments, farmers applied conventional flooded irrigation on 28 plots and manual AWD on 25 plots. Parcels in one location were selected close to each other to minimize the risk of external factors unevenly affecting the key outcome indicators' measurement.

2.1.1 Internet of Things solution

The employed IoT solution comprised four components: solar-powered water-level sensors ("smart" AWD tube), a controller/gateway, and a cloud platform, as well as mobile and web-based end-user applications (Fig. 2).

One solar-powered "smart" AWD tube was installed in each IoT AWD plot. Using laser technology, it measured every 5 min the water level from 15 cm below ground up to 5 cm

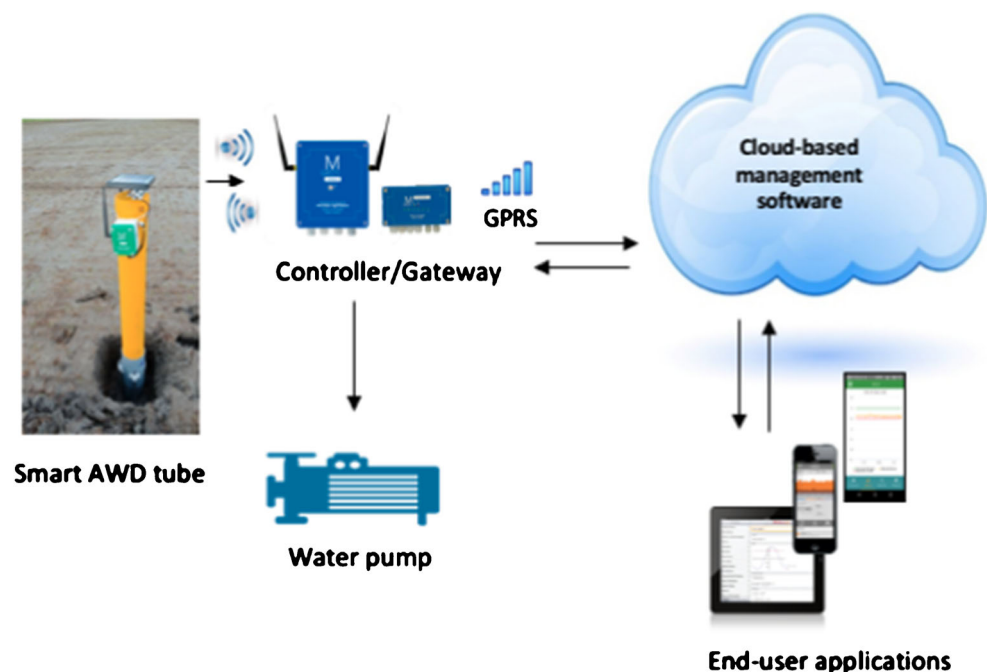
Table 1 Description of plot design in experimental field trials and on-farm trials. Man. AWD, manual alternate wetting and drying; IoT AWD, Internet of Things alternate wetting and drying.

Category	Can Tho	Tra Vinh	An Giang
Soil type	Clay loam	Sandy	Clay and acid sulfate
Rice crops per year (crop)	3	3	3
Field leveling	Perfect (laser leveled)	Imperfect (manual leveled)	Imperfect (manual leveled)
Autonomous water access	Yes	No	Yes
Experimental trial 1: winter-spring 2017 crop season			
Control treatment	None	1 plot (0.3 ha)	None
Man. AWD treatment	None	1 plot (0.3 ha)	None
IoT AWD treatment	None	1 plot (0.3 ha)	None
Experimental trial 2: spring-summer 2018 crop season			
Control treatment	1 plot (1.0 ha)	1 plot (0.3 ha)	1 plot (0.5 ha)
Man. AWD treatment	1 plot (1.0 ha)	1 plot (0.6 ha)	1 plot (0.6 ha)
IoT AWD treatment	1 plot (1.0 ha)	1 plot (0.4 ha)	1 plot (0.4 ha)
On-farm trial 1: summer-autumn 2018 crop season			
Control treatment	4 plots (4.0 ha)	11 plots (3.3 ha)	1 plot (3.0 ha)
Man. AWD treatment	3 plots (3.0 ha)	9 plots (3.5 ha)	1 plot (3.0 ha)
IoT AWD treatment	13 plots (13.0 ha)	19 plots (9.6 ha)	1 plot (7.0 ha)
On-farm trial 2: winter-spring 2019 crop season			
Control treatment	5 plots (5.0 ha)	6 plots (3.0 ha)	1 plot (3.0 ha)
Man. AWD treatment	5 plots (5.0 ha)	6 plots (2.3 ha)	1 plot (3.0 ha)
IoT AWD treatment	20 plots (20.0 ha)	40 plots (22.6 ha)	1 plot (7.0 ha)

above ground at a resolution of 0.1 cm. The tube transmitted the water level data in real time using a wireless LoRa connection. This connection is ideal for outside IoT applications because of its long transmission distance range and low power consumption (coverage range of up to 20 km and less than 14

dB transmission power (Kolobe et al. 2020; Ali et al. 2019)). The controller or gateway sent the data to the cloud-based data management software via an Internet connection (GPRS/3G). The cloud-based data management received and stored the data, then provided monitoring, control, and statistic functions

Fig. 2 Key components of the IoT solution.



for the end-users, and allowed the defining of the specific optimum water levels for different soil types and rice varieties (i.e., AWD schedules). The end-user applications provided an interface for the users to operate their farm irrigation and comply with AWD principles. The application ran on both Android and iOS. When connected to the Internet, the users could remotely monitor the actual water levels and trigger individual pumps without visiting their rice fields.

2.2 Data collection and approaches to analysis

The research employed mixed methods to measure the outcome indicators, including farm records (or crop diaries), qualitative interviews (focus group discussions and key informant interviews), and a quantitative household survey.

2.2.1 Farm records

A detailed crop diary was used to capture the farming inputs. At the beginning of the crop season, the participating farmers were instructed on using the diary to regularly record all the input quantities and costs that occurred during the crop season. The inputs included irrigation water, fertilizer, pesticides, and labor. The project field coordinator regularly validated the entries. The grain yields were calculated from five 5 m² crop cuts, selected randomly along a cross-diagonal transect, in each plot on the harvesting day. The mean moisture content was then calculated, and the grain yields were determined at 14% moisture content.

At the end of each phase, the collected data were entered into an Excel-based form. Descriptive analyses were used to analyze the input costs to identify significant differences between the treatments and locations. Relevant statistical tests, such as one-way ANOVA test and a two-sample t test, were also employed to confirm the differences.

2.2.2 Qualitative interviews

At the end of phase 4, three separate focus group discussions with farmers of three different treatments were conducted at each of the Tra Vinh and Can Tho sites. Five farmers in each group with varying backgrounds, such as education level, farming experience, and farm size, were interviewed. The qualitative interviews focused on the participating farmers' perception of the IoT AWD technology, their intention to adopt it, and their willingness to pay for it. The interviews also explored incentive policies and support mechanisms to enable farmers to apply the technology in the future.

The key informant interviews covered the farmers' propensity to continue using the sensors, and the incentive policies and support that would help them and the cooperatives to apply the technology in rice cultivation. The interviewed stakeholders included policymakers, agronomist experts, and

the farm operator in An Giang (the enterprise's representative). The interview with the enterprise's representative also helped the researchers to understand how the user, as a company not an individual farmer, perceives the benefits of the IoT AWD technology. Findings from focus groups and key informant interviews were used to corroborate the results from farm records and the quantitative household survey.

2.2.3 Quantitative household surveys

Quantitative household surveys were conducted at the end of the pilot. All 82 participating farmers were interviewed (30 in Can Tho, 52 in Tra Vinh). Of these 82 farmers, 60 were exposed to the IoT AWD technology; 11 implemented manual AWD; and 11 applied conventional flooded irrigation. The survey captured the farmers' perceptions, their attitudes toward adopting or continuing AWD or IoT AWD, the driving factors, the adoption barriers, and the desired support for adoption. The collected data were entered into Excel and cleaned and analyzed using STATA version 14. The ordinary least squares (OLS) regression was applied to identify the yield determinants, whereas the one-way ANOVA test and the two-sample t test were used to confirm the differences in the results of key performance indicators across the treatments and locations. The findings and results from the quantitative surveys were compared with and verified by the findings from the qualitative interviews and farm records. The data from the quantitative household surveys were linked to the farm record database using the farmer ID.

3 Results and discussion

This section reports the results from the on-farm trials. The results from the experimental field trials were dropped because the trials were conducted in a controlled research setting to test the sensors and finalize the IoT solution. Nevertheless, the data from the experimental field trials were used to assess the water savings for IoT AWD compared to manual AWD.

3.1 Plots with sensors used less irrigation water than plots with manual alternate wetting and drying

Irrigation water savings were measured in experimental control trials in phases 1 and 2, where the compliance with the irrigation schedule was more closely monitored and enforced so that farmers followed the irrigation schedule properly. The average volume of irrigation water was calculated based on the capacity of the pump and irrigation duration that was recorded in the crop diary. Regarding the automated irrigation under IoT AWD, the IoT system stored the irrigation history on the website.

The precise water level measurements with IoT allowed farmers to maximize the water-saving benefits from the AWD technology. Results from experimental field trials indicate an additional 13–20% of water over manual AWD (Table 2).

The observation that IoT AWD allows for extra water savings compared to manual AWD was confirmed by the feedback provided by the farmers. In particular, they expressed that the measurements were more precise using IoT AWD and that they trusted the data. The quantitative survey results indicated that almost all farmers (93%) noticed additional irrigation water savings when applying IoT AWD (Section 3.4).

Farmers with prior exposure to AWD technology and individual pump control (in Can Tho) gained even more water savings when applying the technology. The technology helped them to be more confident with AWD, resulting in using less irrigation water. Operating individual pumps enabled them to apply a higher level of precision than farmers in Tra Vinh. The farm enterprise in An Giang did not follow the AWD irrigation schedule well because of conflicting instructions from the enterprise to the farm operator. The farm operator also stated that he lacked the confidence to leave the field dry to the suggested level, expecting there to be water stress on for the rice plants in the fields' high areas. These shortcomings in following the AWD schedule, unlevelled plots, and insufficient pump capacity negatively affected the AWD performance; therefore, An Giang received less water savings than the other two sites.

3.2 Plots with sensors saved irrigation energy cost over manual alternate wetting and drying in sites with individual irrigation control and consistent application of the alternate wetting and drying schedule

The IoT plots generated energy cost savings over manual AWD plots in Can Tho, where farmers operated individual pumps and saw high additional water savings with IoT AWD (Table 3). In particular, the irrigation energy cost savings amounted to 24% in the first on-farm trial and 25% in the

second on-farm trial. For Tra Vinh with a central irrigation system, no systematic energy usage reduction could be established. In An Giang, IoT AWD resulted in an additional saving of 48% over manual AWD in the on-farm trial 1, but no difference in the on-farm trial 2. A one-way ANOVA test, using farm record data from the on-farm trial 2, confirmed that irrigation costs across three treatments were significantly different ($P < 0.01$). With the removal of the irrigation cost figure in Tra Vinh site, a two-sample *t* test also confirmed the significant difference between Can Tho and An Giang ($P < 0.01$).

These results showed that while IoT generates water and electricity savings beyond the manual practice, the savings are minor and inconsistent in production environments that are not entirely suitable for AWD. In Can Tho, farmers with prior exposure to AWD technology, leveled fields, and individual pump control could apply a high level of precision, resulting in more water savings, whereas in An Giang, where the conditions were not conducive for AWD, such as unlevelled fields and insufficient pump capacity, the farm operator realized the smallest water savings.

3.3 Plots with sensors realized moderately higher yields than manual alternate wetting and drying

In the second on-farm trial, the IoT AWD plots generated 11% higher yields than the manual AWD in Can Tho. The difference was minimal in Tra Vinh (3%) and An Giang (2%) with inconsistent application of the IoT and manual AWD technology (Table 4). In the first on-farm trial, the yields were 4% higher on IoT plots, except in Tra Vinh (−12%). In Tra Vinh, heavy rains during the flowering stage depressed the IoT yields but had no negative effect on the other treatments, which commenced some days later, confirming the climate challenge of using precision water technology in outdoor environments that cannot be fully controlled.

The one-way ANOVA test results showed that the yield difference across the three treatments was significant at the 0.55% level. The findings were comparable to previous studies. For example, Nhan et al. (2016) concluded that AWD with a safe groundwater threshold of −15 cm did not significantly affect grain yields. A study by Lampayan et al. (2009) in the Philippines also reached similar conclusions.

Table 5 shows the findings of the ordinary least squares (OLS) regression analysis. The R-square for the model was 0.3127, and the adjusted R-square was 0.2577. The results indicate that four of the six variables were statistically significant. The demographic characteristics of the households, including age and the educational background of the household head, significantly and positively affected the yield. Furthermore, farmers with larger plots realized higher yields. However, it is surprising that the results do not establish the significant influence of fertilizer and pesticide costs on the

Table 2 Average volume ($\text{m}^3/\text{ha}/\text{crop}$) of irrigation water. Man. AWD, manual alternate wetting and drying; IoT AWD, Internet of Things alternate wetting and drying.

Treatments	Project sites		
	Can Tho	Tra Vinh	An Giang
IoT AWD	1100	1430	1645
Man. AWD	1375	1673	1891
Control treatment	2063	2192	2364
Water savings over Man. AWD	−20%	−15%	−13%

Table 3 Irrigation energy cost (Vietnam dong per ha; the exchange rate of VND versus USD was 23,181). Man. AWD, manual alternate wetting and drying; IoT AWD, Internet of Things alternate wetting and drying.

Treatments	On-farm trial 1		On-farm trial 2	
	Can Tho	An Giang	Can Tho	An Giang
IoT AWD	115	47	79	183
Man. AWD	152	91	106	177
Control treatment	176	136	230	292
Energy cost savings (IoT AWD—Man. AWD)	−24%	−48%	−25%	0%
ANOVA test result—treatments (Prob > F)			0.0021	
Two-sample t test result—locations (Pro T < t)			0.0036	

yield. However, when analyzing the effect of the cost of fertilizer and pesticides on yields separately, the fertilizer cost increased yields, while the pesticide cost did not have any influence. Last, the cost of seeds was highly significant and negatively affected yields. This observation implies that using more seeds did not result in higher yields. Although this conclusion might vary by region or seed varieties, it confirms the appropriateness of advanced agronomic rice production practices in Vietnam, with strong recommendation for reducing the seed input (Yamaguchi et al. 2016; Tran and Le 2019).

3.4 Farmers had positive perceptions about smart-sensor alternate wetting and drying technology

The interviews with the farmers who were exposed to the IoT AWD technology investigated their perceptions of the technology. The farmers confirmed that the application of IoT increased the benefits of the AWD technology. More specifically, 93% realized additional water savings over manual AWD; 80% benefited from extra irrigation cost savings; and 73% perceived that precise water management with the help of IoT resulted in superior plant health. Moreover, the farmers found

the IoT system easy to use and valued its accuracy and convenience. The vast majority (96%) experienced the IoT system as reliable; 70% found the IoT system easy to use; 88% trusted its measurements; and 73% expressed that it gave them increased confidence in applying AWD.

Most IoT system users did not report significant technical challenges with the technology. The reported challenges were that IoT AWD required leveling and training in using the system (expressed by 63% of farmers). Except for the prerequisite of 3G or WIFI accessibility (70%), the aspects associated with the technology itself, such as maintenance (38%), changing the battery (20%), troubleshooting (29%), and system outages (14%), did not pose a challenge for most IoT users.

The vast majority of farmers (95%) would like to use or continue using the IoT system in the coming crop season, irrespective of the technology used in the past. The main reason is that the system helped increase their confidence in the AWD irrigation practice, as stated by almost all farmers (98%). Most of the farmers (95%) believed that IoT should be widely used, and almost 80% anticipated that the IoT would be the future of farming.

Table 4 Average grain yields (ton/ha) at 14% moisture content. Man. AWD, manual alternate wetting and drying; IoT AWD, Internet of Things alternate wetting and drying.

Treatments	On-farm trial 2						On-farm trial 1					
	Can Tho		Tra Vinh		An Giang		Can Tho		Tra Vinh		An Giang	
	Yield	SD	Yield	SD	Yield	SD	Yield	SD	Yield	SD	Yield	SD
IoT AWD	7.14	0.57	7.49	0.98	3.15	< 0.01	6.11	0.07	4.68	0.33	4.46	< 0.01
Man. AWD	6.45	0.21	7.26	0.70	3.10	< 0.01	5.88	0.10	5.31	0.49	4.30	< 0.01
Control treatment	5.92	0.23	7.00	0.95	3.20	< 0.01	5.96	0.06	4.84	0.41	4.27	< 0.01
Difference (IoT AWD—Man. AWD)	11%		3%		2%		4%		−12%		4%	
ANOVA												
Treatments (Prob > F)	0.0055											

Table 5 Ordinary least square regression results to identify the determinants of yield.

Number of obs.	= 82	F (6,75)	= 5.69	R-squared	= 0.3127
Root MSE	= 0.77644	Prob > F	= 0.0001	Adj R-squared	= 0.2577
Actual grain yields	Coef.	Std. Err.	t	P > t	[95% Conf. interval]
Seed	−3.418862	0.7257213	−4.71	0.000	−4.864 −1.973151
Fertilizer and pesticide cost	0.0820207	0.0518978	1.58	0.118	−0.0213651 0.1854065
Rental cost	0.0143203	0.2102083	0.07	0.946	−0.4044361 0.4330767
Age	0.014795	0.0073299	2.02	0.047	0.0001932 0.0293968
Educational background	0.2414482	0.1270902	1.90	0.061	−0.0117284 0.4946248
Plot area (ha)	1.098615	0.4845913	2.27	0.026	0.1332598 2.06397

4 Conclusion

In this paper, the differential benefits of using IoT for applying AWD technology and farmers' perceptions of the technology were investigated. The results showed that farmers can maximize the water-saving benefits from AWD technology through precise water level measurements with IoT. They also realized a significant reduction in irrigation energy costs over manual AWD when applying the IoT technology in farms with individual irrigation control and strict compliance with the AWD schedule. The comparison in grain yields among the treatments revealed that the IoT technology slightly enhanced the grain yields over the manual AWD in conducive conditions for AWD. The pilot is the first to demonstrate that IoT for AWD in rice production is technically feasible in large-scale open-field conditions and, given farmers' wide acceptance of the solution, has the potential for facilitating the uptake of the AWD practice. Despite vast interest in IoT technology, it should only be promoted in locations with conducive conditions for AWD, such as well-leveled fields, independent access to the irrigation water source, and an additional infrastructure for automation, namely electricity and Internet connectivity. Subsequent research will undertake the cost-benefit analyses of investments in the IoT technology to investigate its financial and economic feasibility, which is critical for evaluating the technology's overall feasibility.

A limitation of this study is the small sample size for the household survey. The sample size consisted of smallholder farmers who were exposed to either the manual AWD or the IoT AWD technology in two study areas, which may not be representative of the whole of Vietnam's Mekong Delta. This limitation did not allow us to provide a more in-depth analysis. Therefore, the result interpretation remains rather descriptive.

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Data availability statement and code availability statement The datasets generated during the current study are available from the corresponding author on reasonable request.

Authors' contributions Conceptualization, D.T.T. and N.T.S.; methodology, D.T.T. and P.V.B.; formal analysis, D.T.T., K.F., and P.V.B.; investigation, P.V.B. and K.F.; writing—original draft, P.V.B.; writing—review and editing, K.F. and D.T.T.; supervision, D.T.T.; project administration, P.V.B.; funding acquisition, P.V.B. and D.T.T.

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Declarations

Ethics declaration The study is not clinical and human participants are only required to expose to the IoT technology and involve in a face-to-face survey aimed at understanding the perception of smallholder farmers who are exposed to the technology. Therefore, approval of such a specific protocol from an ethical committee is not binding under the current legal framework, as declared by the Head of Tra Vinh University's Department of Science and Technology.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

Disclaimer The views expressed in this article do not necessarily reflect the views of Tra Vinh University or the World Bank.

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