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ARTICLE

IoT-based smart crop-field monitoring of rice cultivation system for irrigation control and its effect on water footprint mitigation

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Abstract

Rice is the staple food and one of Thailand's economic crops. However, rice cultivation consumes a large amount of water. Therefore, it is necessary to reconsider the irrigation system's efficiency and the current rice cultivation data in Thailand. The purpose of this study was to evaluate the water-use efficiency of three irrigation methods, (1) modern irrigation system (MIS) using a self-developed Maxii Station (internet of things (IoT-based)) weather monitoring station, (2) alternate wetting and drying (AWD) and (3) basin irrigation, in the dry season rice cultivation (January–May) by tracing the water footprint. The results revealed that the field's actual water consumption was 7461, 5823, and 7612 m^3/ha for MIS, AWD, and basin irrigation, respectively. The theoretical water demand (7896 m^3/ha), calculated from CROPWAT 8.0, was in the vicinity of the MIS and basin irrigation. The rice productivity per area was 3.56, 1.71, and 2.56 tons/ha for MIS, AWD, and basin irrigation. These were lower than those usual due to high temperature affecting the rice's flowering stage. However, the MIS exhibited the most well grained, and the water footprint in the different rice-growing systems was 2343, 3924, and 3310 m^3/tons paddy for MIS, AWD, and basin irrigation, respectively. Moreover, the MIS could reduce the water footprint by 40.29% and 29.22% compared to AWD and basin irrigation, respectively.

Keywords Automation irrigation · IoT · Rice cultivation · Smart crop-field monitoring · Water footprint

Introduction

Rice is the staple food for over half the globe's population, especially for Asian countries. Asia accounts for about 90% of rice cultivation (Patil and Khan 2011; Das 2017), and more than 85% of the global available water is used for agricultural purposes, about 35% of that water is irrigation water, of which more than half is used for rice cultivation (Silalertruksa et al. 2017). The most common irrigation system for rice cultivation in Asia is basin irrigation, resulting in 1–3 m^3 of water to produce 1 kg of rice; this is 3–5 times more than the water used in corn and wheat cultivation, which take less than 1 m^3 to produce 1 kg of grain. The demand for water resources to support food production for the world's population needs increases, leading to a water insufficiency situation. Therefore, it is necessary to reconsider the irrigation system's efficiency for agricultural purposes.

In 2018, rice fields in Thailand occupied nearly 11 million ha, with an export value of more than 300 billion Thai baht. Generally, paddy rice is produced more than upland rice because of its high yield, but paddy rice consumes at least twice as much water as other grains. Currently, the irrigation water is insufficient, and this situation is becoming worse, especially in drought years when rainfall is below the average (Hydro and Agro Informatics Institute 2014; Office of Agricultural Economics 2019). Basin irrigation is the most commonly used irrigation method for the rice

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fields because it is convenient and can control many weeds (Maneepitak et al. 2019); however, the efficiency is relatively low. In addition to the irrigation efficiency, water footprint (WF) is another tool to assess water-use effectiveness in terms of sustainable water management. Hoekstra and Hung (2002) proposed the water footprint concept, which calculates water usage by direct and indirect consumption from the beginning until the end of each product or service production process with a life cycle assessment. This method measures the amount of water used and assesses the release of wastewater into the environment. It also shows the location and duration of water consumption and can be used as an indicator for water-use efficiency and sustainability of water resources (Hoekstra et al. 2011). The average water footprint of Thai rice is 1617 m^3/tons of grain [Chapagain and Hoekstra 2011], which is relatively high when compared to other grains such as wheat, corn, barley, and sugar cane which show a water footprint of 1300, 900, 1400, and 175 m^3/tons, respectively. [Hoekstra and Chapagain 2008] efficient rice production systems under water limit conditions with cost-effectiveness are continuously being developed. One of the famous water-saving methods is alternate wetting and drying (AWD) irrigation, which uses 15–57% of water less than that of the basin irrigation system. The AWD method can increase grain productivity because of the enhancement of root growth, but it has not been widely adopted because it does not significantly increase the yield. Moreover, AWD can also reduce the yield in certain conditions (Howell et al. 2015; Carrijo et al. 2017; Chu et al. 2018; Rungrat and Poothab 2019).

Additionally, AWD is appropriate only to the area where the source of irrigation water can be controlled. Therefore, improving irrigation systems to reduce water consumption and increase productivity is necessary. Moreover, modern agriculture is concerned about the environment, food safety, and resource-saving. Necessitating increased competitiveness and productivity also reduced costs, waste, and resource consumption during cultivation. Many factors are involved in developing modern agriculture, especially innovation and technology to monitor and/or control environmental factors, such as soil's nutrition, water, and weather (Rao and Sridhar 2018).

Internet of things (IoT) is one of the famous technologies that can solve diverse problems concurrently, such as labor, time, and environmental impact issues. In addition, proper control of temperature and relative humidity can improve the average growth rate of leaf area and give higher irrigation efficiency (Xu et al. 2014; Liao et al. 2017). Therefore, the modern irrigation system (MIS) with IoT control was developed. This research was a comparative study of three irrigation methods: modern irrigation system (MIS), alternate wetting and drying (AWD) system, and basin irrigation system investigated together with various environmental parameters such as air temperature humidity and soil moisture. The water efficiency of each irrigation system by using water footprint (WF) was evaluated.

Methodology

Scope of the experiment

Seed selection and preparation

Pathum Thani 1 is a famous day-neutral fragrant rice that can be grown year-round. In this experiment, the seed was soaked in clean water for 24 h and afterward dried by incubating for a whole night to ensure small shoots appeared. The seed tray was then put into a rice husk ash mixed with fine soil to a height of 20–23 mm. The prepared seeds were sprinkled at approximately 200 g per tray. Watering was done daily. The rice seeds were maintained under these conditions for 20 days before use.

Water consumption for rice cultivation

The amount of water usage for Pathum Thani 1 production was observed at an irrigation area of Mae Lao Water Transmission and Maintenance (19°44′31.2"N 99°42′31.3"E), Mae Lao District, Chiang Rai Province. The modern irrigation system (MIS) with IoT control, alternate wetting and drying (AWD), and basin irrigation were operated. In order to evaluate and compare the water consumption and productivity, this experiment was conducted during the dry season (January–May), 2019. Primary and secondary data were collected daily.

Climate, rain, soil, and plant coefficient (Kc) were initially defined by the CROPWAT 8.0 program (FAO, 2015a). The remaining dataset was adjusted according to the installed stations at the experimental plot (self-developed Maxii station), including humidity, temperature, wind speed, radiation, and rainfall. The reference crop evapotranspiration (Et_o) was obtained by calculating water consumption based on the Penman–Monteith model using meteorological data from the Maxii station.

Experimental design

Randomized complete block design (RCBD) was planned for the modern irrigation system (MIS), alternate wetting and drying (AWD), and basin irrigation treatments (Fig. 1). All treatments were performed in a trial plot size 5 m^2, triplicate per replicate.

(a) (b) (c)

Fig. 1 Rice field, **a** modern irrigation system (MIS), **b** alternate wetting and drying (AWD), and **c** basin irrigation

Modern irrigation system (MIS)

A smart monitoring procedure was developed and conducted for MIS in this study (See Fig. 2). Irrigation water volume was measured by a propeller-type flow meter. A capacitance probe was connected to the IoT device and measured soil moisture content with a manually adjust interval time (δ). The data were successfully used to determine the irrigation water requirements. To maintain adequate water requirements throughout the rice growth stage and to avoid anaerobic conditions in the top layer of soil, the soil moisture content (θ) was maintained between completely saturated soil ($\mathfrak{s}$) and field capacity ($\mathfrak{f}$) with the following relation:

$$\mathfrak{f} \leq \theta \leq \mathfrak{s} \tag{1}$$

Irrigation by spraying commenced when the soil moisture content decreased below the field capacity value. The main parameter for controlling periodical spraying was the air–water vapor pressure deficit (VPD; $\mathfrak{v}$) calculated as the following equations:

$$\mathfrak{v} = \left[\frac{(100 - RH)}{100}\right]\rho \tag{2}$$

$$\rho = 610.7 * 10^{\left[\frac{7.5T}{(237.3+T)}\right]} \tag{3}$$

ρ is the saturated vapor pressure (kPa), RH is the relative humidity (%), T is the air temperature at the experimental plot (°C).

To determine the irrigation period ($\mathfrak{t}$), our previous study model (Jarernkan 2019) was proposed as following:

$$\mathfrak{t} = (\delta - 2)log_e(\mathfrak{v}) + 1 \tag{4}$$

δ is the measurement interval time (min), (δ∈[2,10]) that set by user and $\mathfrak{v}$∈[1,3].

The irrigation treatment was automatically given through a sprinkler nozzle which applied raindrops over the rice leaves and soil surface. This system improves the rice's conditions to grow because it increases the moisture content in air and soil and decreases the canopy temperature evaporation rate. The power on/off was an internet-based command with sensors for humidity, temperature, wind speed, radiation, and rain.

Alternate wetting and drying (AWD)

AWD irrigation is a water management technique for the paddy field that is not continuously submerged for the whole period of rice production. In this study, the water level in the paddy field was controlled at 5 cm above ground level until the tillering stage (30-day-old rice), then irrigation stopped for 15 days as the first drying step. The second drying step, irrigation was stopped when the rice reached the maximum tillering stage (60-day-old rice) for 15 days (Royal Irrigation Department 2015). During the wetting periods, the water level was controlled between 5 and 10 cm height above ground level. The water level was monitored by four inches diameter PVC tubes with perforations.

Basin irrigation

Basin irrigation is a method for growing rice in lowland areas under flooded conditions, with a water level at 5–10 cm height above ground level (Department of Agriculture 2004). The water level was monitored by four inched diameter PVC tubes with perforations, as mentioned in AWD (from rice transplantation to 15 days before harvest).

The distribution of applied water for all experiments was the pressurized piping using a 1-inch PVC type class 13.5. The flow measuring was conducted using a 3/4-inch propeller-type flow meter with an accuracy of less than 1% error. Each flow meter was installed to the distribution pipe and located before discharge to each experimental plot. The flow volume was summarized every day. The average flow for each repetitive watering type was used as the water consumption for the rice cultivation system in this experiment.

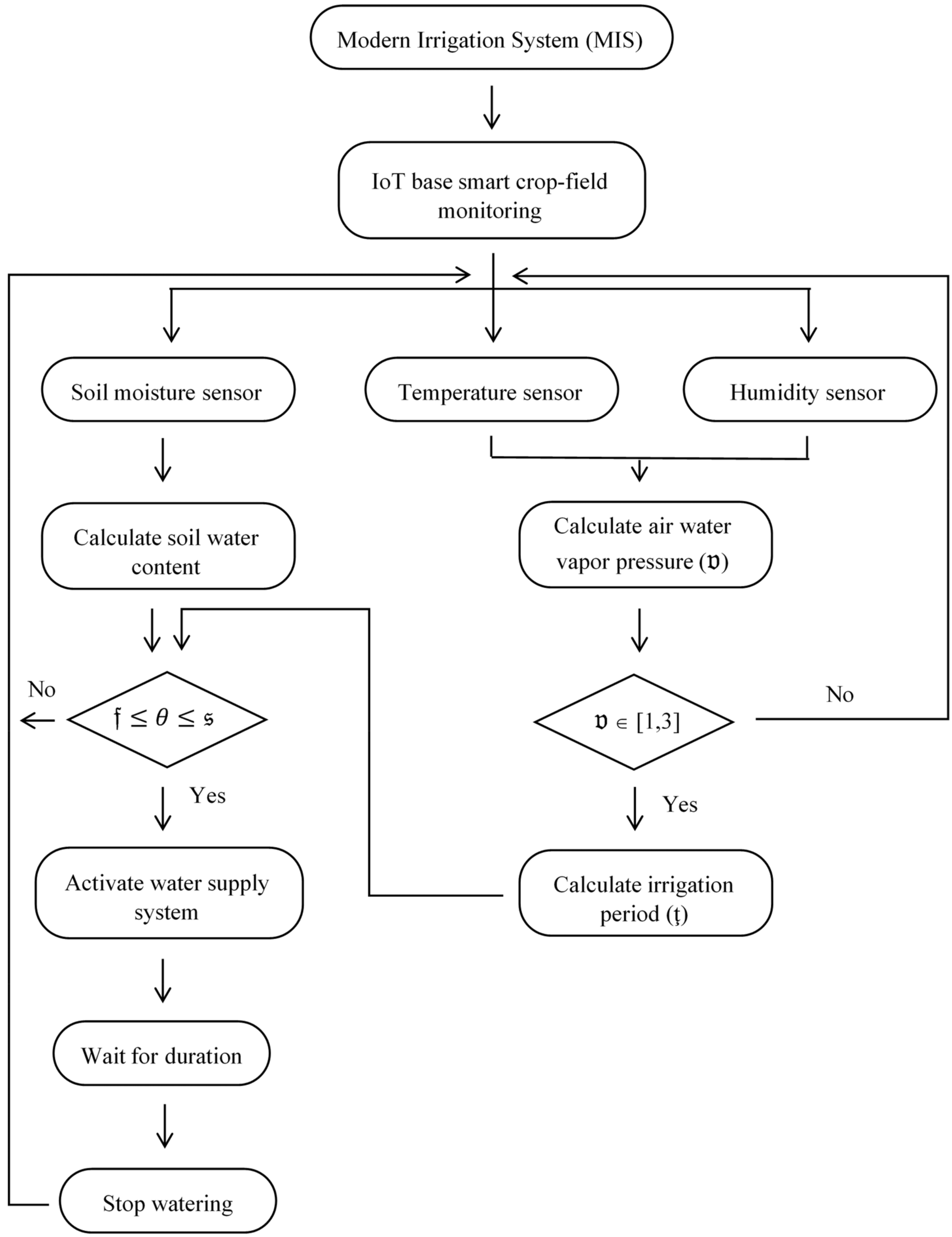

Fig. 2 The watering decision procedure of MIS

Analytical method

Theoretical calculation of crop water requirement

Consumptive use or crop evapotranspiration (ET) was calculated using the Penman–Monteith equation (CROPWAT 8.0) (FAO 2015b) by using weather data from CLIMWAT 2. and the Maxii station such as climate, reference crop evapotranspiration (Et_o), rain, and soil. Kc value was obtained from day-neutral rice varieties grown in Thailand. Using the basin irrigation technique, weekly irrigation data for the reference rice was received from the Bureau of Water Management and Hydrology (Royal Irrigation Department 2015). Then, the theoretical water usage data were compared to all tested irrigations' actual water consumption data.

Resource efficient assessment

1. Water consumption and productivity were calculated from the total amount of water used for seeding, plot preparation, and the freshwater requirements from the beginning of planting until the harvest period.
2. The yield of rice grain was reported at 15% moisture content.
3. In this study, Water Footprint (WF) that indicates as $WF_{consumption,}$ can be calculated from the following equation:

$$WF_{\text{consumption}} = \frac{CWU_{\text{green}} + CWU_{\text{blue}}}{Y} \quad (5)$$

When $WF_{consumption}$ = Water Footprint (m^3/ton paddy), CWU = Crop Water Use (m^3/ha), CWU_{green} = Effective rainfall from CROPWAT 8.0 with the weather, data from Maxii station (m^3/ha), CWU_{blue} = Experimental irrigation data (direct water use) and material used in cultivation system (indirect water used) (m^3/ha), Y = Yield of planting (ton paddy/ha).

In this study, the scope of WF evaluation was Life Cycle Assessment (LCA) base method (Mekonnen and Hoekstra 2011) from cultivation to harvesting following the previously mentioned. Therefore, direct water consumption and indirect water consumption from the material used (see Table 1.) in each step of the rice cultivation system were recorded. WF was calculated in terms of m^3/ton of paddy grain as a functional unit.

Table 1 Considered resources in the rice cultivation system

The material used in the rice cultivation system	Unit
Grain	Kg
Diesel	L
Organic fertilizers	Kg
Chemical fertilizer 46–0-0	Kg
Chemical fertilizer 16–20-0	Kg
Pesticides	Kg

Results and discussion

Water consumption

The study of the theoretical water requirement calculated using CROPWAT 8.0 with the weather data from the in-field weather station, Maxii station, for the whole process of rice production was 7896 m^3/ha. The results indicated that the water consumption of MIS (7461 m^3/ha) and basin irrigation (7612 m^3/ha) were close to the theoretical water demand. However, the theoretical water requirement using the weather data generated by the CLIMWAT database program, which Royal Irrigation Department generally uses to support the water allocation, was 5765 m^3/ha. It was lower than those of the in-field water consumption and theoretical water requirement calculated using the weather data from the in-field weather station. This was probably due to the unstable weather caused by climate change and the higher than average temperature during the experimental period causing the different water requirements. However, the water consumption in-field study of rice production for AWD irrigation was 5823 m^3/ha. The water consumption of MIS was slightly lower than that of basin irrigation because MIS was real-time water management using the VPD values, which were calculated from relative humidity, temperature, and saturated vapor pressure. In this study, the VPDs were adjusted between 1 and 3 kPa, suitable for the opening and closing stomata of rice [Ohsumi et al. 2008].

In general, the life cycle of the rice cultivation system includes four major stages such as seed preparation, vegetative phase, reproductive phase, and ripening phase (Fig. 3a). For Pathum Thani 1, seed preparation starts from land preparation by plowing until transplantation which takes about 17 days. The vegetative phase begins from rice transplanting until the maximum tillering stage, which takes about 50 days. After that, the reproduction phase starts from panicle initiation to the booting stage and the flowering stage, which takes approximately 30 days. Finally, the ripening phase starts from the milky stage until harvesting, taking about 30 days (Department of Agriculture 2004).

The water consumption for seed and soil preparation of all irrigation techniques was 29.44 mm (Fig. 3b) because of the controlled variables, including plot preparation, seeding rate, experimental plots size, and preparing in nursery house as the farmer's method, outside the field. As a result, all irrigation systems had the same soil and climate

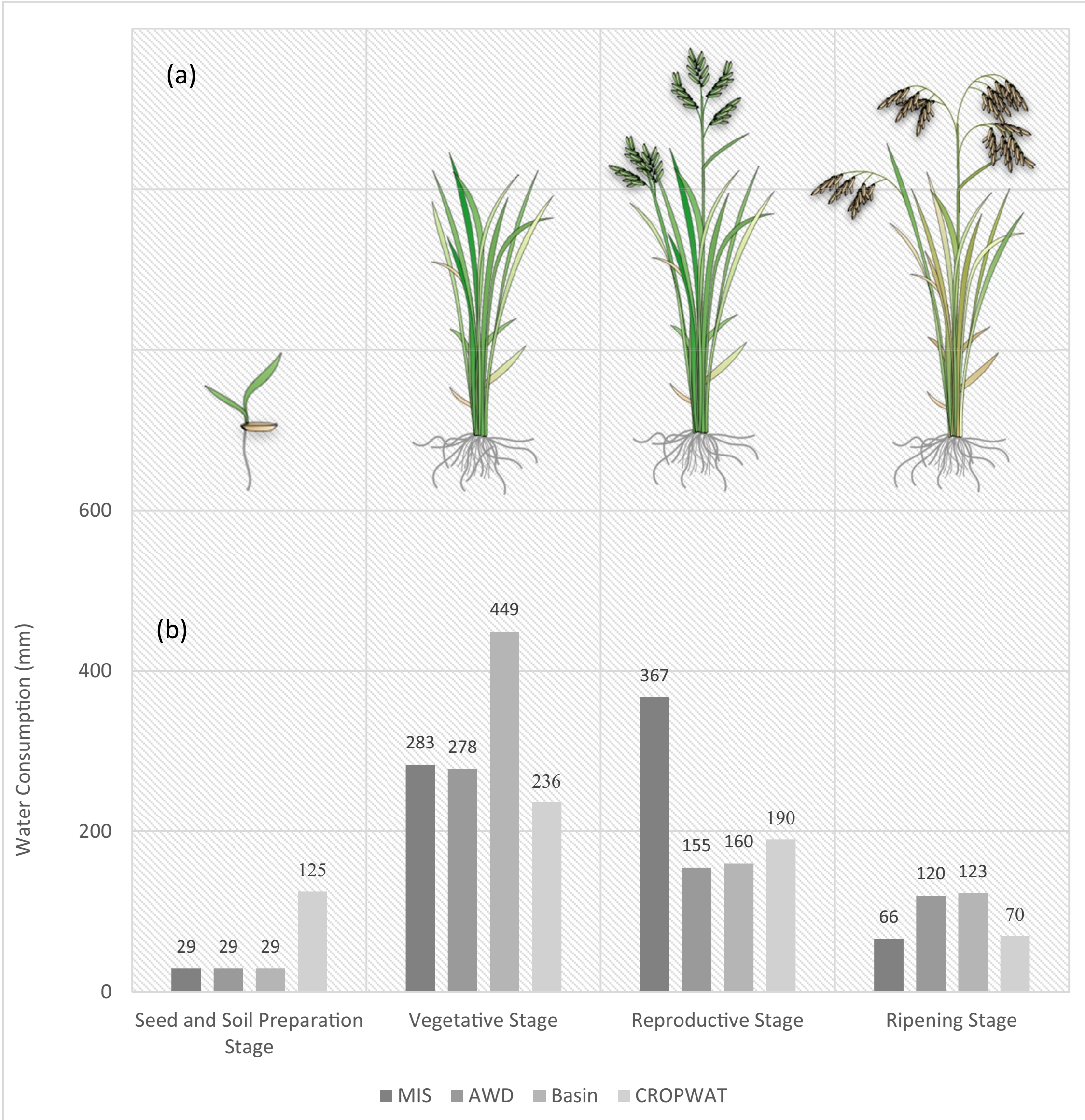

Fig. 3 Water consumption at each stage of rice growth of the modern irrigation-based IoT, wet and dry irrigation, and basin irrigation and compared to CROPWAT

characteristics, important factors for water consumption. (Allen et al. 1988). Therefore, the practical and theoretical water demand showed an obvious difference. Plot preparation in nursery houses could reduce water consumption in this step compared to the default program method.

In the vegetative stage, basin irrigation showed the highest value of water consumption at 448.92 mm. The water consumption of MIS, AWD, and theoretical calculation was 283.19, 277.92 and 236.00 mm. However, the plant height and leaf area index (LAI) of the rice in the maximum tillering stage of MIS were slightly higher than those of AWD and basin irrigation. The plant height of rice irrigated by using MIS was 123.69 and 115.28% of the height of rice which was irrigated with the AWD and basin method, respectively. Likewise, the LAI of rice irrigated with MIS was 104.63 and 101.50% of the LAI of rice irrigated with AWD and basin method, respectively. The MIS showed the highest water consumption at 367.31 mm in the reproductive phase, while AWD and basin irrigation was 160.00 mm and 154.96 mm, respectively. By theory, the rice would require water, about 190.00 mm. The reason might be because of the VPD management of the MIS in the range of 1–3 kPa since the average maximum day temperature was high, about 42 °C.

Nevertheless, this may cause that the yield and the yield components of rice that were irrigated with MIS methods

Table 2 Plant height, grain yield, and yield components of rice irrigated by MIS, AWD, and basin irrigation

Treatments	Plant height (cm)	Grain yield (tons/ha)	Grain number per panicle	Panicles	Unfilled grain (%)
MIS	70.23 a	3.56 a	129	25.70	37.16
AWD	56.78 b	1.71 c	114	23.13	51.44
Basin	60.92 b	2.56 b	126	25.80	45.95

Means followed by the same letter are not significantly different at the 5% level by DMRT

were higher than those of AWD and basin irrigation. The rice yield (Table 2), which was irrigated with MIS, was higher than those of AWD and basin irrigation at 108.19 and 139.06%, respectively. In addition, the yield components such as grain number per panicle, number of panicles, and unfilled grain (%) were in the same trend. The yield of rice irrigated with MIS gave the highest data, followed by basin irrigation and AWD, respectively. Finally, the water consumption in the ripening phase of the MIS was 66.21 mm, complementary to the theoretical water rice demand at 70.00 mm. Again, water usage of the wet and dry irrigation and basin irrigation were close to each other at 120.00 and 122.84 mm, respectively (Fig. 3b). Since IoT based on MIS was smart crop-field monitoring and automating irrigation based on many related factors such as soil moisture, temperature, light intensity, etcetera, it can provide the closest irrigation water usage to the theoretical water rice demand in normal condition.

Water footprint (WF)

Resource data of all irrigation systems were analyzed and WF values computed. The total yield (at 15% moisture content) per productive unit results suggested that Pathum Thani 1 rice at the irrigation area of Mae Lao Water Transmission and Maintenance using MIS gave the best yield at 3.56 tons/ha. This was followed by basin irrigation and wet and dry irrigation at 2.56 and 1.71 tons/ha, respectively (Table 2). In this study, all irrigation methods had less grain yield than the general average yield of Pathum Thani 1 rice in Thailand, which is 4.45 tons/ha (Department of Agriculture 2004) because of the delay in planting and the rice flowering stage occurred during the dry season, causing some partial sterility due to high-temperature stress (Jagadish et al. 2008). The result of yield components showed that grain number per panicle and number of panicles were not significantly different. However, the percent of unfilled rice grain irrigated by AWD method was significantly higher than those of the MIS and basin method.

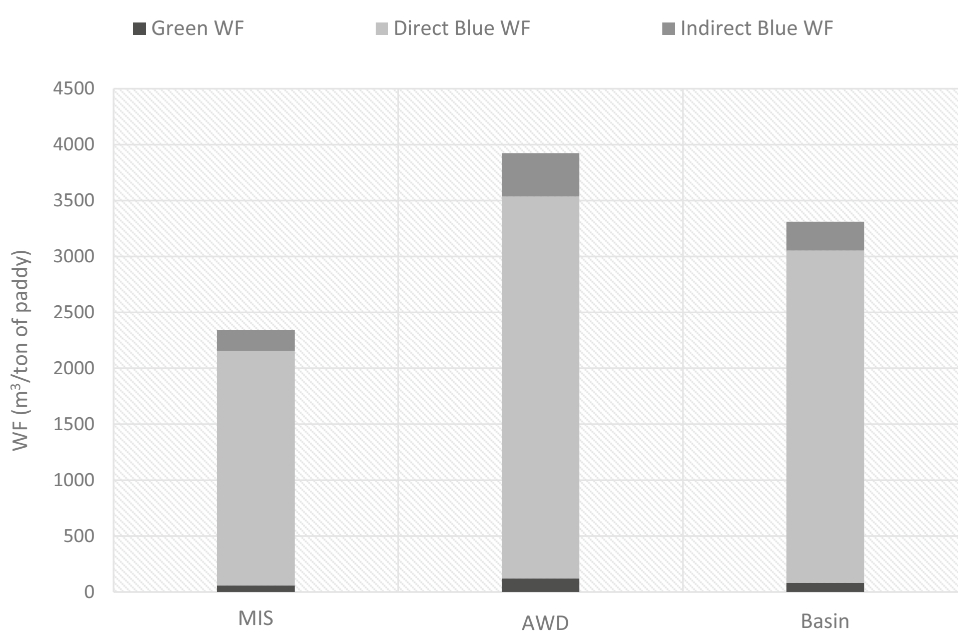

Fig. 4 Water foot print of rice cultivation system which irrigated by MIS, AWD and basin irrigation

Consequently, the highest WF was found in the AWD process, followed by basin irrigation and MIS at 3924, 3,310, and 2343 m^3/ton paddy, respectively (Fig. 4). The direct blue WF is the main part of the rice cultivation system. The result demonstrates that using irrigation water during rice cultivation by using the smart monitoring system and the IoT water irrigation method is more efficient than other techniques. The significant differences in WF from irrigation are because the cultivation was performed in the dry season. The extremely hot weather during the flowering period and the loam soil in the experimental plot may have played significant productivity yield and water irrigation roles. In addition, the WF from leaching requirement in rice cultivation systems usually involves fertilizing the fields. The dissolving of fertilizers into the natural water resources might happen due to excess fertilizer usage for the crop requirement. Thus, rice fertilizer demand was calculated theoretically to prevent excess fertilizer. From the collecting data in this study, no sewage was discharged; this may be due to the drought and high temperature, causing water evaporation before rice harvesting. Therefore, WF assessment is one of the guidelines for determining irrigation schedules and planning effective water resource management for the entire system and contributing to future sustainability in water management.

Conclusion

The results of the study reflect the efficiency of water resource utilization in the rice cultivation system in the dry season. The effectiveness was considered through the productivity, water, and resources used in rice cultivation systems based on water footprint evaluation. The theoretical crop water requirement was calculated and compared to the field water consumption. It was found that the theoretical crop water requirement calculated using the field weather data was closer to the actual field experimental result than that obtained from the calculation by the CLIMWAT database program. However, rice planting in the dry season consumes a lot of irrigation water and results in lower productivity because of the hot weather. Although the water consumption of AWD was the lowest, this type of irrigation had the highest affected rice production at high temperatures. The IoT-based smart crop-field monitoring and automation irrigation system of MIS, therefore, has been developed to manage the water consumption of rice. The algorithm is related to one of the transpiration factors, VPD. MIS method affects water consumption and water footprint. This irrigation method can reduce the effect of alleviating the sterility of pollen grain due to high temperatures. Therefore, the efficiency of water consumption in terms of water footprint for the MIS based on IoT has the lowest water footprint, 40.29% and 29.22% lower than those of AWD and basin irrigation, respectively. These results emphasized that the water footprint can be used effectively as a tool for water management in rice planting systems or other field crops for sustainability in the agricultural water management sector. It was not the water consumption projection but it also reflects the effectiveness of water resource management in the agricultural sector. The planning for rice planting systems or other field crops toward sustainability required a holistic view based on a cost–benefit approach. The increase of the rice crop cycle each year including planting in the dry season may not provide the higher annual productivity as found in this study; however, increase water footprint and may result in more water stress in the future.

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