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A Model of Evapotranspirative Irrigation to Manage the Various Water Levels in the System of Rice Intensification (SRI) and Its Effect on Crop and Water Productivities

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Abstract: Evapotranspirative irrigation is a simple idea in a watering field based on the actual evapotranspiration rate, by operating an automatic floating valve in the inlet without electric power to manage water levels. The current study introduces a model of evapotranspirative irrigation and its application under different water levels. The objectives were (1) to evaluate the performances of evapotranspirative irrigation under various irrigation regimes, and to (2) to observe crop and water productivities of the system of rice intensification (SRI) as affected by different types of irrigation. The experiment was performed during one rice planting season, starting from July to November 2020, with three irrigation regimes, i.e., continuous flooded (CFI), moderate flooded (MFI) and water-saving irrigation (WSI). Good performance of the system was achieved; low root mean square error (RMSE) was indicated between observed water level and the set point in all irrigation regimes. Developing a better drainage system can improve the system. Among the regimes, the WSI regime was most effective in water use. It was able to increase water productivity by up to 14.5% while maintaining the crop yield. In addition, it has the highest water-use efficiency index. The index was 34% and 52% higher than those of the MFI and CFI regimes, respectively. Accordingly, the evapotranspirative irrigation was effective in controlling various water levels, and we recommend the system implemented at the field levels.

Keywords: evapotranspiration; irrigation regime; paddy field; water level; water use efficiency

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1. Introduction

Rice is the main staple food in Indonesia and many countries worldwide; its demand has steadily increased in recent decades as the population grows. Water availability is a key component for rice production, but its sustained availability remains uncertain, due to increased water use from other sectors [1], thus threatening the irrigation water supply [2,3]. Moreover, current practices of continuously flooded farming have worsened water availability. Although conventional flooded irrigation systems may increase yield [4], their design is not efficient, which reduces water productivity [5] and promotes more greenhouse gas emissions, especially methane gas [6].

Intermittent irrigation is an alternative irrigation strategy that typically saves more water and is sometimes integrated with an adaptive rice farming called System of Rice Intensification (SRI) [7]. Previous studies have proven that SRI application increased rice yield [8,9], thus raising water productivity [10–12]. SRI is also recognized to be more environmentally friendly [13] because of its ability to suppress methane gas emission [14,15], which potentially reduces global warming potential (GWP) [16]. Therefore, this system is an appropriate choice for climate change adaptation and mitigation strategies [17] for the agricultural sector. By using the system, the field does not need to be flooded continuously, but rather it is possible to lower the water table and water level below the soil surface [18,19].

The main challenge in implementing the SRI system, like other precision farming techniques, is how to precisely control the water levels at the field, especially for farm-level farmers. So far, precision farming usually identically relates to irrigation automation that requires more cost investment of automated instruments and wireless sensor networks [20]. The idea requires installing water content sensors on rice fields, sending data wirelessly from the sensors to the running controller, then carrying out actions in opening/closing solenoid valves at the irrigation inlet [21]. Obviously, the technology is too expensive and is very difficult to be implemented by farmers. The technology may only be applied to farmsteads or agricultural industries with more capital to invest in technology and human resources.

In principle, the implementation of precision and smart agriculture does not necessarily require advanced automatic control technology. The principle is "to provide the right input, at the right place, at the right time, in the right amount, in the right way, using the right tools" [22]. Therefore, the implementation of precision farming remains a research challenge, especially when dealing with an applicable-efficient irrigation technology. Here, we propose a model, evapotranspirative irrigation technology. Principally, the field is watered based on the actual evapotranspiration rate by operating a simple automatic floating valve. The valve will automatically open or close with mechanical principles according to the desired water level; this idea is more straightforward than piped irrigation systems [23]. The inlet holes in the piped irrigation systems are replaced with float valves, while irrigation canals are replaced with pipelines and high investment costs. While the concept of evapotranspirative irrigation does not require modification of the irrigation canals, it modifies the inlet valve with an automatic float system. This system does not need electric power, but uses a simple mechanical principle to open and close the valve.

Theoretically, an evapotranspirative irrigation system is elaborated from the concept of evaporative irrigation [24]. The functional design has been designed and developed [25], as well as tested for lettuce plants [26]. However, the system has not been tested with various irrigation regimes with different water levels under specific weather conditions for SRI paddy cultivation. Subsequently, its effect on crop and water productivities would require observation. Therefore, the objectives of this study were to (1) evaluate the performances of evapotranspirative irrigation with different irrigation regimes under specific weather condition, and to (2) observe crop and water productivities on SRI paddy cultivation at different regimes.

2. Materials and Methods

2.1. Study Site

The research was a laboratory-scale experiment, which was conducted in one rice planting season from July to November 2020. We carried out an experiment in the Kinjiro Farm (coordinates 6.59° S, 106.77° E), Bogor, West Java, Indonesia. Rice seed was sown on 5 July 2020 and was planted on 19 July 2020. After 112 days of cultivation, the grains were harvested on 10 November 2020.

In a preliminary study, we sampled soils with three replicates on 0–30 cm. From the samples, we obtained information on soil properties at the study site. Typically, soil texture was characterized as a clay loam with a silt content more than 40%. Detailed soil physical properties are presented in Table 1.

Table 1. Soil physical properties of the field location.

No.	Parameter	Value	Unit	Method
1	Dry bulk density	0.89 ± 0.03	g/cm^3	Gravimetric
2	Particle density	2.18 ± 0.15	g/cm^3	Pycnometer
3	C-organic	6.11 ± 0.15	%	Loss on ignition
4	Organic content	10.55 ± 0.27	%	(LOI)
5	Soil texture			
	Sand	22 ± 7.2	%	Pipette
	Silt	44 ± 5.0	%	
	Clay	34 ± 3.5	%	
	Soil texture	Clay loam		
6	Water contents at:			Pressure plate
	pF 1/h = 10 cm H_2O	0.529 ± 0.006	cm^3/cm^3	
	pF 2/h = 100 cm H_2O	0.434 ± 0.013	cm^3/cm^3	
	pF 2.54/h = 347 cm H_2O	0.378 ± 0.018	cm^3/cm^3	
	pF 4.2/h = 15,849 cm H_2O	0.212 ± 0.009	cm^3/cm^3	

Note: Three soil samples were collected and were analyzed in a certified laboratory. The data in the table are the mean ± SD.

2.2. Experimental Design

The model of evapotranspirative irrigation was applied in the lab-scale experiment. A miniature paddy field with the dimensions of 4 m × 4 m and 0.5 m in height was used for each irrigation regime (Figure 1). Additionally, there was drainage storage with the dimensions of 0.5 m × 2 m × 0.5 m connected to the outlet's miniature paddy field model. However, the drainage was not controlled, and the water flowed naturally. In the inlet, there was a simple automatic float valve. The valve is equipped with a floating cylinder that pushes the valve upward when the water level rises to a particular level, thereby closing the valve. On the other hand, when the water level drops (in this case—caused by evapotranspiration), the floating cylinder will also go down, caused by the valve opening (Figure 1). The bucket was covered with a transparent fiberglass cover to minimize evaporation.

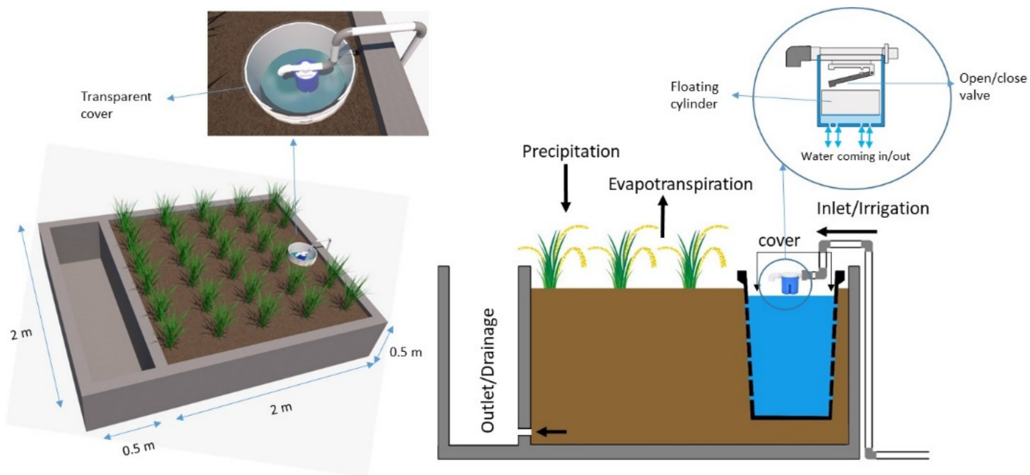


Figure 1. A miniature paddy field equipped with a simple automatic valve.

Here, we applied three water irrigation regimes with two replications, so there were six miniature paddy fields. The first regime was continuous flooded irrigation (CFI), where flooded water with 0–4 cm water level above the soil surface (the setpoint at 2 cm) was applied during planting season as control. The second regime was moderate flooded irrigation (MFI), where applied shallow flooded water with 0–2 cm water depth was used (the set point at 0 cm). The last regime was water-saving irrigation (WSI), which kept the water level at the soil surface (the set point at 0 cm) for 0–20 days after transplanting

(DAT), and then dropped 5 cm below the soil surface (the setpoint −5 cm). The WSI was selected based on the previous finding that revealed that the optimum water level for SRI to mitigate greenhouse gas emission was 5 cm below the soil surface [19].

In the rice cultivation, there were some components adopted, such as planting young seedlings (14 days after sowing), adding space between hills of 30 × 30 cm^2 and placing a single plant in each hill. This practice is known as the System of Rice Intensification (SRI), as commonly applied in Indonesia [27]. For the fertilizer application, all plots were supplied with the same doses, i.e., a combination of organic (1 ton compost/ha) and inorganic (100 kg/ha of urea, 75 kg/ha of phosphorus and 50 kg/ha of KCl) fertilizers.

2.3. Field Measurement

An automatic weather station (AWS) Vantage Pro2 product of Davis Instruments Corp. Inc., Hayward, CA, USA measured weather parameters such as air temperature, relative humidity, solar radiation and wind speed at 2 m height. The AWS has sensors such as air temperature and relative humidity, solar radiation and wind speed sensors, all connected to ISS (Integrated Suite Sensors) and then stored in the console. For the water level sensor, we used an e-Tape sensor water level where the output was voltage. Thus, we performed the calibration for this sensor. The water level measurement was stored in an Em50 Data Logger, a product of Meter Group Inc., NE Hopkins Ct, Pullman, WA, USA (previously known as Decagon Corp, Inc.). Both the Davis console and Em50 Data Logger were set and stored data within 15-minute time intervals.

We observed morphological characteristics of rice once in three days. In each plot, we measured plant height, tiller and panicles numbers with five replicates. On the harvesting day, we observed and weighed biomass (straw), grain, panicles number and weed in all plots. The grain yield, biomass weight and weed weight were converted to ton/ha. In addition, a single hill was randomly selected to observe root length among the regimes.

2.4. Water Balance Approach

Based on the schema in Figure 1, water balance analysis in each plot was analyzed by the following equation:

$$\Delta \mathrm{WL}(\mathrm{t}) = \mathrm{I}(\mathrm{t}) + \mathrm{P}(\mathrm{t}) - \mathrm{DR}(\mathrm{t}) - \mathrm{ETa}(\mathrm{t}) \quad (1)$$

where ΔWL is the change of water level in the bucket (mm), I is irrigation (mm), P is precipitation (mm), DR is drainage or overflow from the plot (mm) and ETa is actual evapotranspiration (mm). Here, the plot was designed with zero percolation and seepage. In the inlet and outlet, there was a water meter to measure irrigation and drainage. However, there was water loss by overflow when heavy rain events occurred and low pressure of water flow was not recorded. Therefore, the Excel Solver and ETa adjusted the parameters of I and DR by minimizing the following objective function:

$$\mathrm{F}(\mathrm{x}) = \sum_{\mathrm{t}=1}^{\mathrm{n}} |\Delta \mathrm{WL}_{\mathrm{o}}(\mathrm{t}) - \Delta \mathrm{WL}_{\mathrm{m}}(\mathrm{t})| \quad (2)$$

The constraints:

$$I \geq 0; DR \geq 0; ETa \geq 0 \quad (3)$$

where ΔWL_o is the change of observed water level (mm), and ΔWL_m is the change of estimated observed water level by the Excel Solver (mm), t is the day after transplanting (DAT) and n is total cultivation days. Since the Excel Solver only estimated 200 data in one process, the adjustment process was performed four times according to plant growth stages. They were initial (1–24 DAT), crop development (25–64 DAT), mid-season (65–87 DAT) and late-season stages (88–110 DAT).

Weather data were used to determine reference evapotranspiration according to a standard model by the FAO Penman-Monteith equation [28], which is derived based on the aerodynamic and canopy resistance, given by the following equation:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T_{ave}+273}u(e_s - e_a)}{\Delta + \gamma(1 + 0.34u)} \quad (4)$$

where ET_o is reference evapotranspiration on a daily basis (mm), R_n is net radiation received at crop surface (MJ/m^2/d), G is soil heat flux density (MJ/m^2/d), T_{ave} is air temperature (°C), u is wind speed at 2 m height (m/s), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), γ is psychrometric constant (kPa/°C) and Δ is the slope of vapor pressure curve (kPa/°C). The input data to calculate ET_o were solar radiation, minimum, average and maximum air temperature, relative humidity and wind speed at 2 m height on a daily basis. Moreover, the information regarding the location (elevation and latitude) was needed, as well as Julian's day. Detailed derived equations and their procedure calculations of ET_o can be referred to by Allen et al. [28].

ET_o and ET_a can be used to determine and adjust crop coefficient (K_c) by the following equation:

$$K_c = \frac{ET_a}{ET_o} \quad (5)$$

Water productivity and water-use efficiency index were used to evaluate the performance of each regime. There are two definitions of water productivity adopted in this study. Firstly, water productivity is defined as total production per total water input; secondly, water productivity is total production per total water evaporated and transpired and they are expressed in g grain/kg water [29]. Meanwhile, the water-use efficiency index is crop yield per unit of water supplied [30]. Accordingly, the equation of water productivity and water-use efficiency index is given by the following equation:

$$\mathrm{WP_{I+P}} = \frac{100\mathrm{Y}}{\mathrm{I+P}} \quad (6)$$

$$\mathrm{WP_{ETa}} = \frac{100\mathrm{Y}}{\mathrm{ETa}} \quad (7)$$

$$\mathrm{WUE} = \frac{100\mathrm{Y}}{\mathrm{I}} \quad (8)$$

where Y is grain yield (ton/ha), 100 is a conversion factor, $\mathrm{WP_{I+P}}$ is water productivity by total inflow (irrigation and precipitation) (g grain/kg water), $\mathrm{WP_{ETa}}$ is water productivity by actual evapotranspiration (g grain/kg water) and WUE is water use efficiency index (g grain/kg water).

The water level of the setpoint was compared to the observed to evaluate the performance of evapotranspirative irrigation by root mean square error (*RMSE*):

$$RMSE = \sqrt{\sum_{i=1}^{n}\frac{(WL_{set} - WL_o)^2}{n}} \quad (9)$$

where WL_{set} is water level setpoint (cm), WL_o is actual water level (cm) and n is cultivation days.

A significant test was performed by a single factor analysis of variance (ANOVA) to elucidate the effects of irrigation regimes on crop performance, water productivities and water use efficiency. The differences among regimes on all parameters' means were then compared using the least significant difference (LSD) at the 0.05 probability level (α = 0.05).

2.5. Weather Condition during the Season

Figure 2 shows the fluctuations in weather parameters, especially air temperature, relative humidity and wind speed. Air temperature is presented in minimum, maximum and average values. Despite fluctuating, air temperature conditions remain relatively constant throughout the growing season. It can be referred to as the gradient value of the linear equation, which was relatively low (<0.01). The maximum air temperature reaches 36.3 °C, while the minimum and average air temperatures reach 20.5 °C and 26.8 °C, respectively.

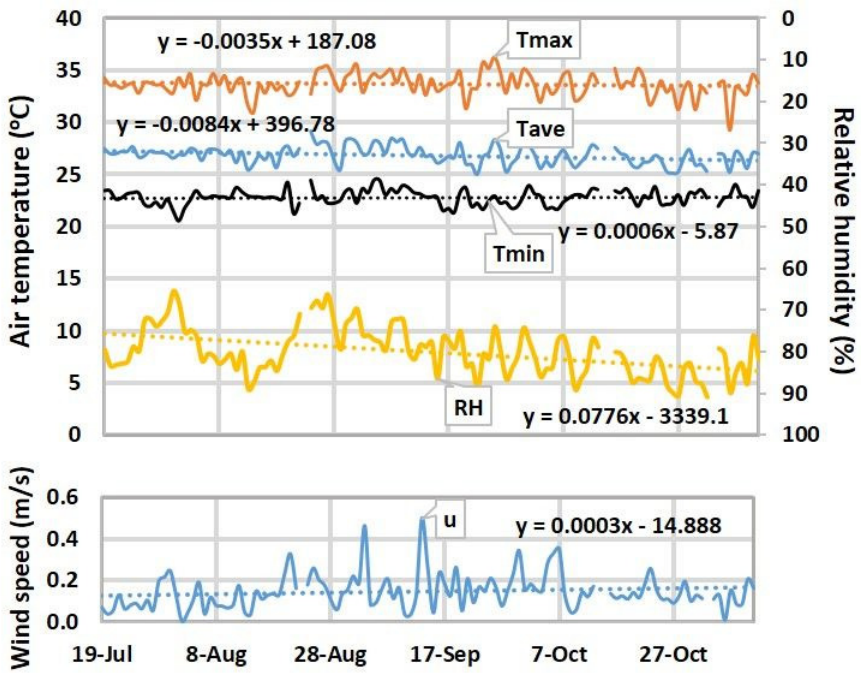


Figure 2. Air temperature, relative humidity, and wind speed fluctuations during planting season.

On the other hand, the relative humidity was found to decrease slightly. The gradient value was higher than the linear equations of air temperature; however, the value was low (<0.1). During one growing season, the consecutive minimum, average and maximum relative humidity values were 65.4%, 80.1%, and 91.0%, respectively. For the wind speed, the fluctuation was between 0 and 0.5 m/s, which indicated low wind speed in the field location (<1 m/s). In addition, its gradient was also relatively low (<0.01) by means there that even fluctuated; however, there was no significant change in the trends. The minimum, average and maximum wind speed values were 0, 0.1, and 0.5 m/s, respectively.

Another parameter, solar radiation, also showed a slightly decreasing trend, as depicted in Figure 3. The reference evapotranspiration is also presented in the figure. At the beginning of the growing season, solar radiation reached around 15 MJ/m^2/d with reference evapotranspiration of 3 mm. Then, the reference evapotranspiration and solar radiation fluctuated; however, the trend was similar to other weather parameters. The gradient of the linear equation was low (<0.01), which represented no significance in raising and decreasing those parameters. At the end of the season, the value of solar radiation was around 14 MJ/m^2/d with reference evapotranspiration being lower than 3 mm. The maximum, average and minimum values of solar radiation were 19.9, 14.1 and 5.9 MJ/m^2/d, respectively. At the same time, the reference evapotranspiration values were 1.1, 2.9, and 4.2 mm for minimum, average and maximum, respectively.

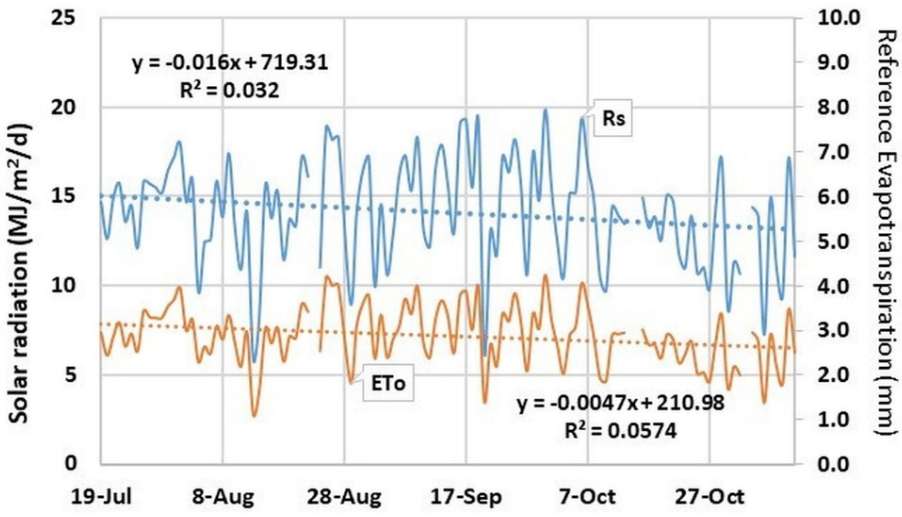


Figure 3. Solar radiation and reference evapotranspiration fluctuation during the planting season.

The linear relationship between the reference evapotranspiration and the weather parameters is presented in Figure 4. Among the four parameters, solar radiation has the most substantial relationship to the reference evapotranspiration, represented by the highest R^2 value. The value of R^2 was close to 0.95, indicating that solar radiation has the highest contribution to the variability of evapotranspiration. The second parameter that has a major influence on the reference evapotranspiration was relative humidity, followed by the air temperature and the wind speed. This relationship indicated that solar radiation most influences the evapotranspiration process through the soil surface and plants [31]. Based on the sensitivity analysis study, solar radiation is the most sensitive parameter to changes in evapotranspiration [32].

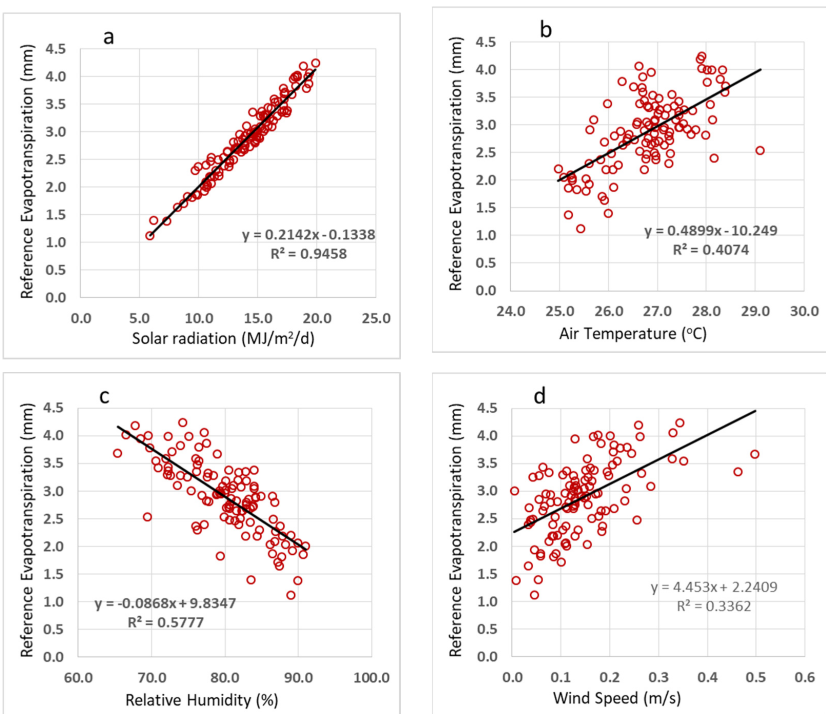
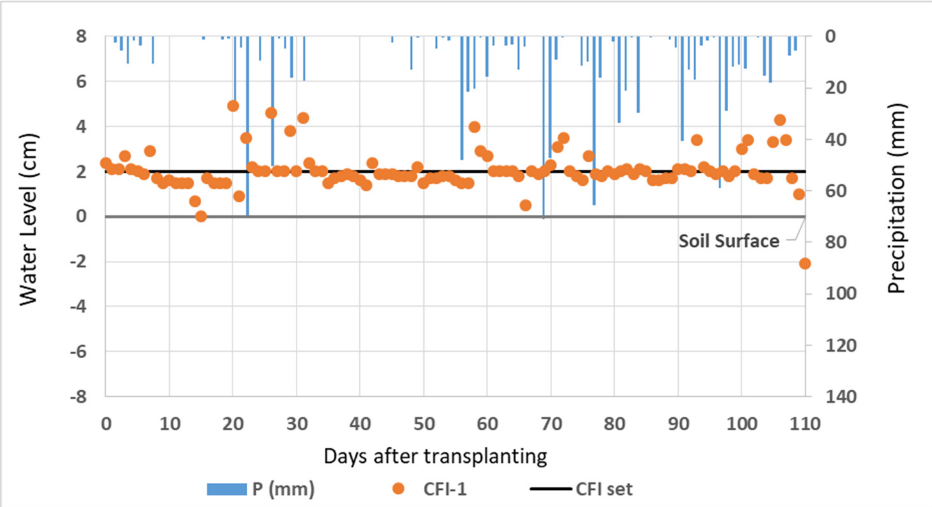


Figure 4. The linear correlation among reference evapotranspiration and weather parameters: (**a**) reference evapotranspiration vs. solar radiation; (**b**) reference evapotranspiration vs. air temperature; (**c**) reference evapotranspiration vs. relative humidity; (**d**) reference evapotranspiration vs. wind speed.

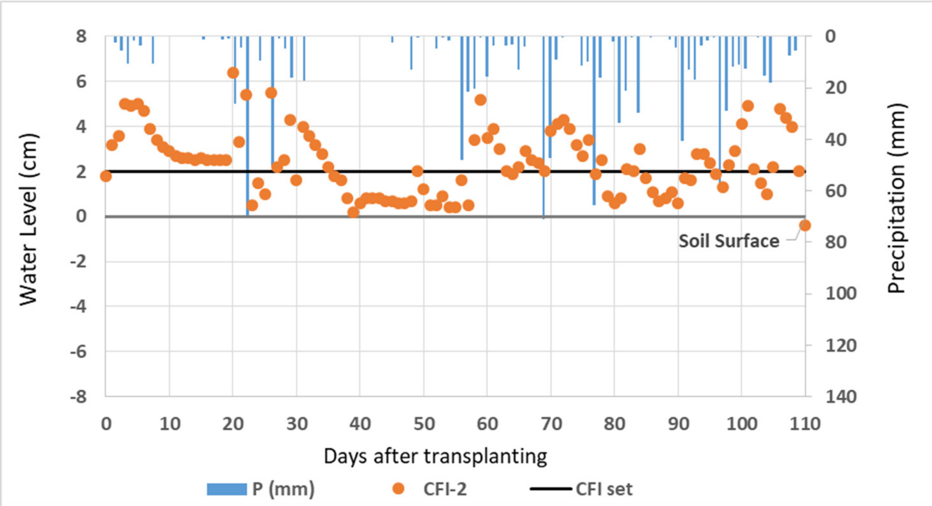
3. Results

3.1. Performance of Evapotranspirative Irrigation

The actual condition of the water levels in the CFI regime for replications 1 and 2 (CFI-1 and CFI-2) are presented in Figure 5. In this regime, inundation with a water level of 2 cm above the soil surface was used as the set point. The water level fluctuated and was close to the set point; however, high fluctuation occurred when there was a high rain intensity event. There was a significant increase in water level, especially at 20 DAT, both in CFI-1 and CFI-2. Heavy rainfall of 26.2 cm caused an increase in water level from 1.5 cm to 4.9 cm in CFI-1 and from 2.5 cm to 6.4 cm in CFI-2. The same situation occurred at 26 DAT when 50.2 mm of rainfall contributed to raising in water level from 2 cm to 4.6 cm of CFI-1 and 1 cm to 5.5 cm of CFI-2.



(**a**)

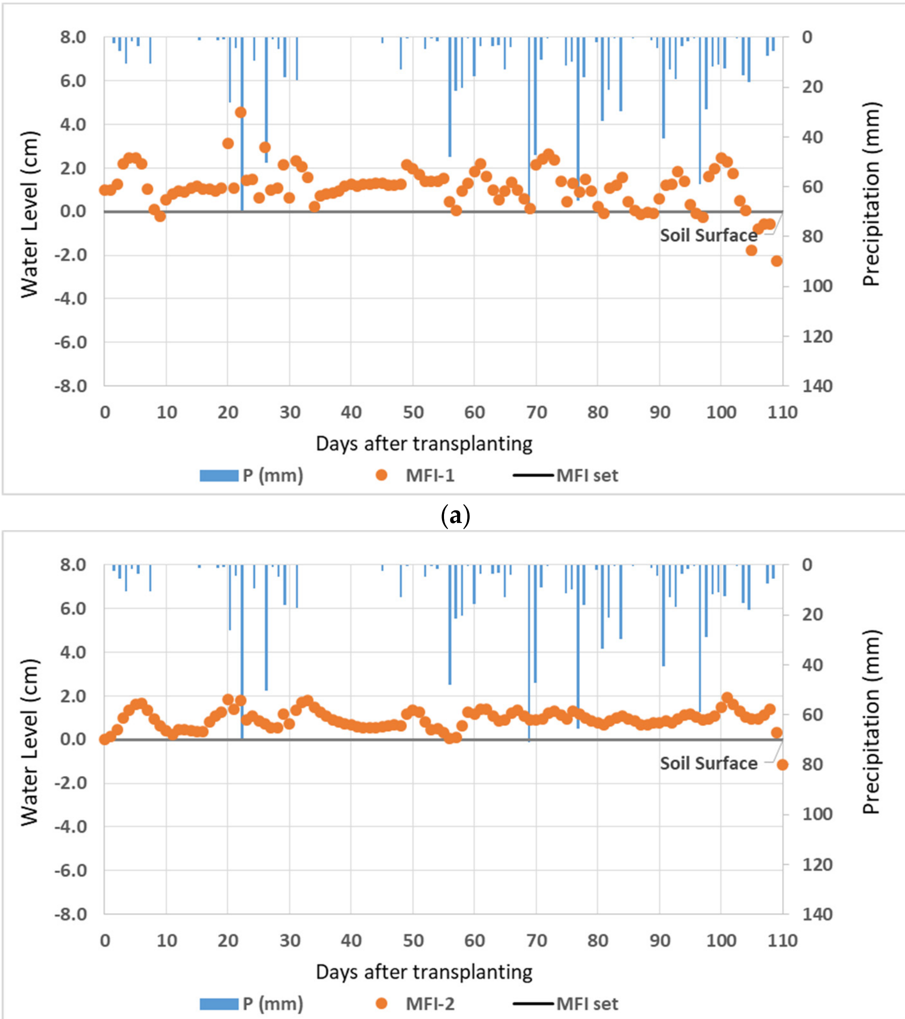


(**b**)

Figure 5. The actual field condition of water levels: (**a**) CFI-1; (**b**) CFI-2.

On the other hand, water levels tend to be lower when no rain event occurs for several days. As at 32–42 DAT, the water level decreased from 3.6 cm to 0.8 cm. Although it was set at the same setpoint, CFI-1 showed better performance. The average water levels were 2 cm and 2.4 cm for CFI-1 and CFI-2, respectively. Even though they fluctuated, the water levels were close to the desired level, indicating that the evapotranspirative control system worked well in this regime.

Figure 6 shows the fluctuations in water levels of the MFI regime in both the first replication (MFI-1) and the second one (MFI-2). The actual water levels fluctuated and were a little bit far from the set point. The actual water level is higher than that of the setpoint, particularly MFI-2. The water levels were lower to the setpoint only at the end of the growing season. When rainfall with high intensity occurred, it caused water levels in the field to increase. As at 22 DAT, after 70.8 mm of rain, the water level increased by 4.6 cm and 1.8 cm for MFI-1 and MFI-2, respectively. As per the same situation on the CFI regime, lower water levels generally occurred when no rain event happened, such as from 32 to 42 DAT. At this time, the water level tended to decrease from 1.8 cm to 0.5 cm. The average water levels were 1 cm and 0.9 cm for MFI-1 and MFI-2, respectively. This indicated that the evapotranspiration control system was slightly accurate in controlling the water level.



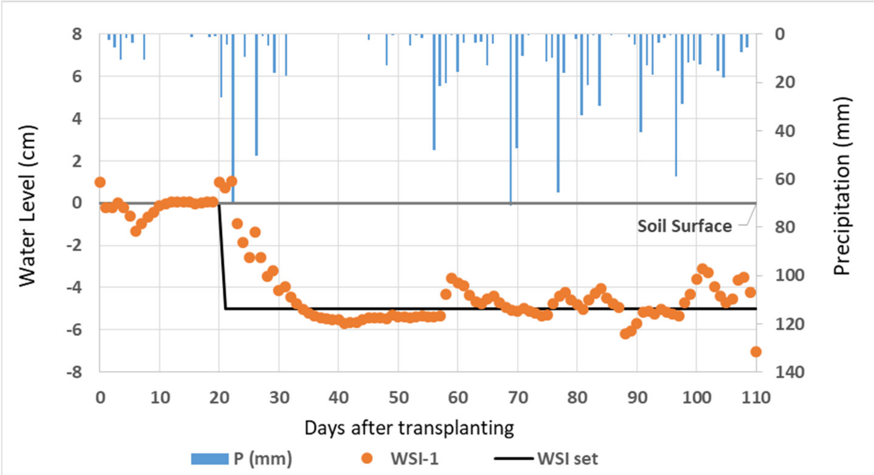
(**a**)

(**b**)

Figure 6. The actual field condition of water levels: (**a**) MFI-1; (**b**) MFI-2.

As previously mentioned, there were two setpoints in the WSI regime, i.e., 0 cm at 0–20 DAT and −5 cm afterward. As presented in Figure 7, the water level in both the first replication (WSI-1) and second replication (WSI-2) was well controlled at 0–20 DAT with the first set point. There were no significant fluctuations, and the water levels were close to the setpoint even though there was low rain intensity. The average water level in this phase is −0.1 and 0.5 cm for WSI-1 and WSI-2, respectively. Then, high fluctuation occurred when the water level was dropped to −5 cm. In this period, as per the same situation in two other regimes, high rainfall events occurred. The average water levels in the stage were

−4.6 cm and −3.3 cm for WSI-1 and WSI-2, respectively. These results indicated that the performance of WSI was slightly accurate, and both plots can be conditioned to be drier than the other two regimes.



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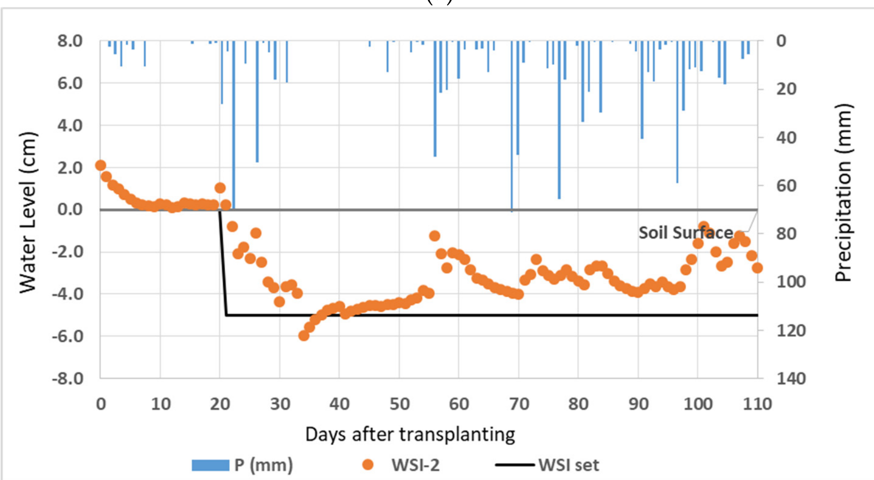

(**b**)

Figure 7. The actual field condition of water levels: (**a**) WSI-1; (**b**) WSI-2.

RMSE values of the CFI regime showed the lowest level, indicating that the CFI plot was the best in controlling water level (Table 2). Its values were 1.17 cm, 15%, and 26% lower than that of MFI and WSI plots; however, the differences were not significant. The water level can generally be controlled as their values close to the setpoint, with RMSE below 1.6 cm. The biggest challenge in implementing the evapotranspirative irrigation was high rain intensity during one growing season. In hydrology, rainfall is always correlated to the water level as many models have been developed [33,34]; thus, rainfall becomes the most important factor in predicting water level under natural conditions.

Table 2. The performances of evapotranspirative irrigation in each regime.

Irrigation Regimes	RMSE (cm)
CFI	1.17 ± 0.42a
MFI	1.37 ± 0.49a
WSI	1.57 ± 0.47a

Note: The presented data are the mean ± SD, where different letters in a row indicate a significant difference at $\alpha < 0.05$ level.

Precipitation contributed to most of the water balance component by 79–88% of the inflow (Table 3). The largest contribution of precipitation was found in the WSI regime with less irrigation water. However, the rainfall affected more drainage or water loss. It was counted for 67–69% of outflow. For irrigation, CFI requires the most irrigation water to maintain flooded conditions in the field. The CFI regime required 27% and 49% more irrigation water than the MSI and WSI regimes. Flooded conditions in the CFI and MSI regimes also contributed to the higher value of actual evapotranspiration. The values were about 8% higher than that of the WSI regime. High actual evapotranspiration also correlated with higher crop coefficients in the CFI and MSI regimes. Several studies have shown similar results; flooding increases water used through actual evapotranspiration and consequently increases the crop coefficients [35–37].

Table 3. Water budget in each regime.

Water Balance Components	CFI	MSI	WSI
Inflow			
Precipitation (mm)	957.6 ± 0a	957.6 ± 0a	957.6 ± 0a
Irrigation (mm)	260.7 ± 10.9a	189.4 ± 13.9b	133.3 ± 2.1c
Outflow			
Actual evapotranspiration (mm)	364.6 ± 1.2a	363.5 ± 11.0a	333.4 ± 4.4b
Drainage/overflow (mm)	877.1 ± 2.2a	843.6 ± 71.3a	824.0 ± 26.6a
Total water storage (mm)	23.4 ± 14.2a	60.1 ± 66.8a	66.5 ± 24.3a
Average of crop coefficient	1.09 ± 0.00a	1.09 ± 0.04a	0.99 ± 0.01a

Note: The presented data are the mean ± SD, where a different letter in a row indicates a significant difference at $\alpha < 0.05$ level.

3.2. Effects of Irrigation Regimes on Crop and Water Productivities

Plant height during one growing season in the three regimes is presented in Figure 8. At 10 DAT, the average plant height of the CFI, MFI, and WSI regimes was 26.5 cm, 23.4 cm, and 22.3 cm, respectively. The higher plant height of the CFI regime showed that standing water in the initial growth stage stimulated the crop to grow taller. At the beginning of the mid-season stage (64 DAT), there was a proportional and consistent increase in plant height of 98.8 cm under the CFI regime, while in the MFI and WSI regimes they were, consecutively, 93.4 cm and 92.2 cm. Finally, the highest average plant height at the end of the season was found in the CFI regime. It was 3.2% and 4.8% higher than those of the MFI and WSI regimes, respectively.

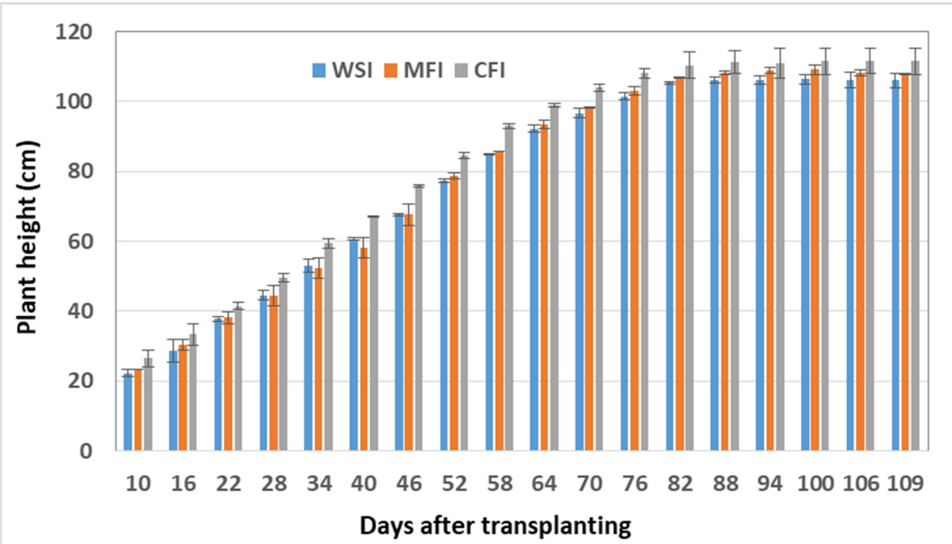

Figure 8. The Average plant height among the regimes.

Comparable results in the number of tillers were found among the regimes, particularly in the early growth stage. At 10 DAT, the regimes produced the same number of tillers (Figure 9). A significant increase in the number of tillers occurred from the vegetative growth stage (25–30 DAT). In this phase, the number of tillers was 11, 8, and 8 in the CFI, MFI, and WSI regimes, respectively. The tiller formation ended at 70 DAT in the generative state, in which the paddies focused on grain filling. An appealing occurrence happened at the end of the late-season stage, where the MFI regime produced more tillers than the two other regimes. The number of tillers in the MFI regime was 34. It was 3.8% and 10.8% greater than the CFI and WSI regimes, respectively. Thus, saturated soil conditions (water level at soil the soil surface) were more effective in tillers formation.

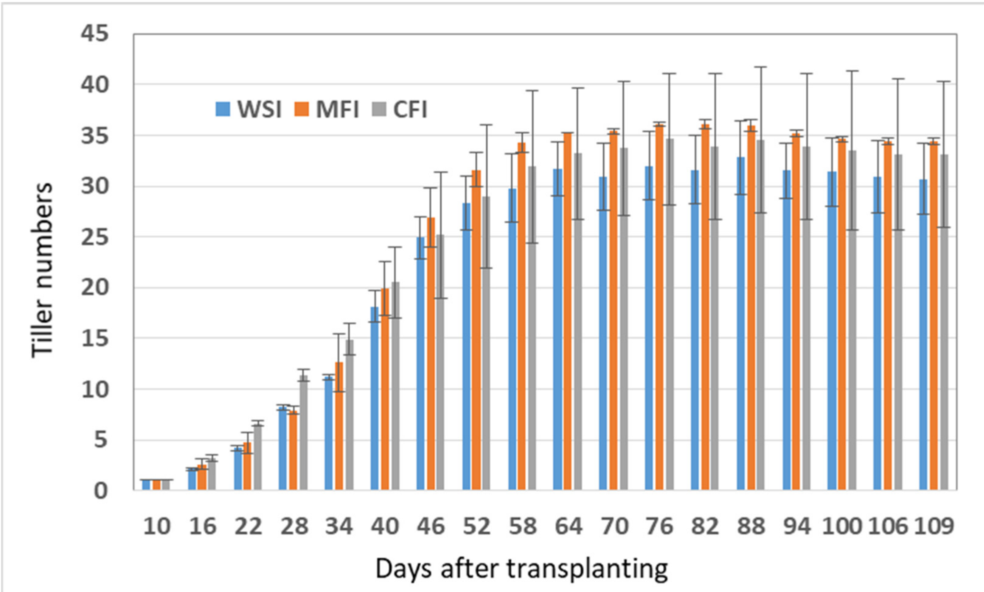

Figure 9. The average plant height among the regimes.

Based on statistical analysis, there was no significant difference in crop growth performance, including in plant height, number of tillers, number of panicles, biomass (straw) weight and grain yield (Table 4). Indeed, the CFI regime produced the highest plant height, which correlated to the heaviest straw weight. However, it was only about 5.6% higher than those of the others two regimes. Meanwhile, the MFI regime, although it produced lower plant heights than the CFI regime, it produced the greatest number of tillers and number of panicles. Its quantity was 5–10% higher than those of the CFI and WSI regimes, respectively. The exciting things occurred in the WSI regime that produced the highest grain yield. Although not significant, it was 6% and 7.5% higher than the CFI and MFI regimes, respectively. The increased grain yield seems to be due to the high grain density [38].

Table 4. Yield, water productivity, and water use efficiency among the regimes.

Parameters	CFI	MFI	WSI
Plant height (cm)	111.4 ± 3.7a	107.8 ± 0.3a	106.0 ± 2.0a
Number of tillers	33.0 ± 7.4a	34.4 ± 0.3a	30.7 ± 3.5a
Number of panicles	32.4 ± 6.8a	34.3 ± 0.1a	29.5 ± 4.1a
Biomass (straw) (ton/ha)	21.5 ± 0.7a	20.3 ± 1.4a	20.6 ± 0.7a
Grain yield (ton/ha)	6.3 ± 0.9a	6.2 ± 0.2a	6.7 ± 0.4a
Weed (ton/ha)	0.6 ± 0.8a	0.8 ± 0.4a	3.7 ± 0.6b
Root length (cm)	9.0	16.0	27.0
Water productivities:			
WP_{I+P} (g grain/kg water)	0.52 ± 0.08a	0.54 ± 0.02a	0.61 ± 0.04a
WP_{ETa} (g grain/kg water)	1.72 ± 0.25a	1.71 ± 0.10a	2.01 ± 0.10a
WUE (g grain/kg water)	2.41 ± 0.46a	3.30 ± 0.34a	5.02 ± 0.23b

Note: The presented data are the mean ± SD, where the different letters in a row indicate a significant difference at $\alpha < 0.05$ level.

However, the WSI regime produced the heaviest weeds biomass, reaching 3.7 tons/ha. Therefore, it was challenging to implement water-saving irrigation such as intermittent irrigation of the SRI method [39]. The WSI regime produced weed biomass more than three-times higher than the other regimes, and they were significantly different (Table 4 and Figure 10). Indeed, rice inundation was an alternative to prevent weed growth, especially in the vegetative phase [40]. However, as previously mentioned, it was wasteful in the water use since the paddies supplied more than they needed.

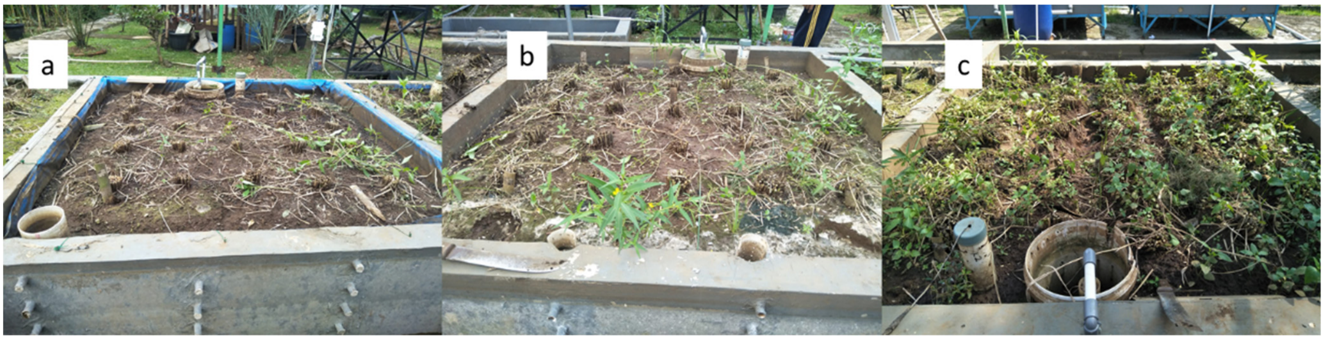

Figure 10. Weed collection after harvesting in each regime: (**a**) CFI; (**b**) MFI; (**c**) WSI.

The drier fields with the low water level caused the roots to grow more profound, as in the WSI regime (Figure 11). This situation is in line with the previous observations by Setiawan et al. [18] and Aziez et al. [41]. The water deficit conditions spur roots to grow vertically downwards in deeper soil layers to get water or nutrients. Deeper root formation may cause stronger paddy growth in the SRI with intermittent irrigation than in conventional farming with continuously flooded irrigation. Hence, SRI plant growth may be better than conventional systems with continuous waterlogging [42]. On the other hand, when the field is flooded, the roots grow sideways horizontally around the soil surface, as found in the CFI regime (Figure 11).

Figure 11. Root development of randomized hill of paddy in each regime: (**a**) CFI; (**b**) MFI; (**c**) WSI.

The minimum water irrigation in the WSI regime had implications in increasing water productivities, both in terms of total inflow (WP_{I+P}) and actual evapotranspiration (WP_{ETa}). WP_{I+P} of the WSI regime increased up to 14%; however, it was not significant because precipitation became dominant in water inflow. The same is true for water productivity from the perspective of plant evapotranspiration. Although actual evapotranspiration was the lowest, the WP_{ETa} of WSI regime still increased up to 14.5% since the highest grain yield. Moreover, the WSI regime had the highest water use efficiency index due to the lowest irrigation. Its value index was 34% and 52% higher than those of the MFI and CFI regimes. This lead showed that maintaining water level at the soil surface at the beginning of plant growth is one alternative to raise water-use efficiency. This result is similar to that from an alternate wet and dry irrigation (AWD) experiment conducted previously to improve water use efficiency [43].

4. Discussion

Along with the effect of climate change, water resource availability changes and tends to decrease, particularly in runoff and water levels due to changes in the hydrological cycle [44]. Climate change is commonly characterized by increasing temperatures, rainfall patterns and the frequent occurrence of extreme weather [45]. The concept of evapotranspirative irrigation is an effort to find an adaptive strategy to climate change and easier application in the fields. The performance showed it was satisfactory with fairly small RMSE values (Table 2). However, the system inaccuracies were raised when there was a heavy rainfall event (Figures 5–7), and therefore precipitation became a constraining factor affecting the performance. The precipitation was also found as the main factor that reduced accuracy in water level control application in Indonesia [46,47].

Although we utilized advanced technology such as sensors, actuators and microcontrollers, inaccuracies were found during rainfall whenever the drainage system was not controlled properly. Sirait et al. [46] developed a solar power pipe irrigation automation system to control water levels. The performance of the system was very satisfactory from the beginning and early late-season; however, error increased, as raising the gap between setpoint and observed water level in the late season since the heavy rain event. An identical situation was found by Nurfaijah et al. [47]. They developed an on-off water level control system by utilizing an Arduino microcontroller for three irrigation regimes. There was an increase in error during the precipitation. Therefore, it is highly recommended to control the drainage rate for areas with high rainfall, such as by utilizing a subsurface drainage system [48]. The subsurface drainage technology was able to increase water-use efficiency up to 20% while maintaining the yield [49].

Among the regimes, the evapotranspirative irrigation was suitable with the WSI regime in producing more rice. The key to increasing grain yield was seemingly attributed to the lower water level below the soil surface after 20 DAT. The field was on aerobic conditions that allowed more oxygen availability in the soil [50]. In addition, in the initial stage, the field was wet. Thus, the WSI regime was similar to the moderate wetting and drying regime (MWD) [51] or alternate wetting and drying irrigation (AWDI) [52]. The regime was effective in water use and able to increase the yield [53]. The key in increasing grain yield is increasing oxidation activity in roots, raising the photosynthetic rate in leaves and increasing enzyme activities in the converting process of sucrose to starch in rice grains [51]. Moreover, the system allows the roots to grow larger. It will transport cytokinins through the xylem to the leaves in maintaining the photosynthesis process [54]. The longer root, as presented in Figure 11, seemingly shows more activities inside under the WSI regime. More biomass and grain were also developed when more oxygen absorption occurred by root activities, particularly in the reproductive stage [55].

However, the aerobic condition also has potential yield reduction when the lower water level is not well controlled, causing the extreme driest of the soil. Setiawan et al. [18] reported that the yield could be maintained at a water level of 3.2–7 cm below the soil surface. However, if the water level is deeper than those intervals of water levels, it can significantly reduce the yield due to stress on the crop. Based on a field experiment by Zhang et al. [51], the yield reduction of 32% occurred when the soil was extremely dry. The reason is due to abiotic factors such as increased soil pH, ammonia toxicity and nutritional deficiencies in aerobic conditions [56]. In addition, aerobic conditions also stimulate significant weed growth, as shown in Figure 10. More weed production can potentially reduce the yield, thus integrated weed management became important to deal with this obstacle [57]. In Indonesia, weed growth can be suppressed using an active herbicide containing 10% ethyl pyrazosulfuron applied after tillage and a mechanical power weeder [58].

Under the absence of inundation, such as in the WSI regime, the rate of evapotranspiration is low [25]; consequently, the total actual evapotranspiration was lowest compared to the two other regimes (Table 3). Then, the average actual coefficient of this regime was also lowest. The finding was supported by Linquist et al. [37]. They performed a 3-year field experiment and found that continuously flooded irrigation resulted in higher actual evapotranspiration and crop coefficient than that drier, and vice versa. Kadiyala et al. [59] recorded a 19% lower crop coefficient in aerobic conditions. Commonly, the lower the actual evapotranspiration, the lower the yield [18,60], according to the basic equation reported by van Lier et al. [61]. However, several experiments showed different results [10,62–64]. It seems there is an inconsistent correlation between crop coefficient and grain yield. According to Zhang et al. [65], the relationship between evapotranspiration and yield can be represented by a parabolic trend. By means, the higher evapotranspiration may lead to higher yield within a particular range. Then, after the parabolic peak point, the opposite trend is found. It is important to optimize the irrigation regime to find the peak point of actual evapotranspiration and yield so that water can be efficiently used.

The WSI regime improved water productivities and a significant water-use efficiency index. The similar result was also found by Choudhury et al. [66], that SRI improved water productivity both in evapotranspiration and total water supplied perspectives. In addition, the SRI saves 18–21% of water input [67]; thus, the regime is suitable for the areas with limited water resources such as upland and in combination with SRI cultivation [68]. The strategies to improve those two parameters are by reducing percolation and evaporation. Percolation can be reduced by minimizing the inundation water level (or at least at saturated level) and increasing the duration of unsaturated conditions at 80–90% field capacity water content [69]. In other words, the water level should be kept between 0 and 5 cm on the surface [70]. Under this setup, plant growth was not significantly impaired (Figure 8), and it is an effective strategy to reduce evaporation from the soil surface [71].

5. Conclusions

A model of evapotranspirative irrigation has reasonable prospects of application because of its simplicity and easiness of use. Good performance of the system was achieved as indicated by low RMSE in all irrigation regimes during one rice planting season. The performance can be improved by developing a better drainage system. According to the experiment under the developed technology, the water-saving irrigation (WSI) regime of the system of rice intensification (SRI) was most efficient in water use. It was able to increase water productivity by up to 14.5% without reducing the yield. In addition, it has the highest water-use efficiency index, which is 34% and 52% higher than the moderate flooded irrigation (MFI) and continuous flooded irrigation (CFI) regimes. In the near future, the system should be implemented at the field levels under various climate conditions.

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