Functional design of smart evaporative irrigation for mina-padi system in Indonesia

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Abstract. The smart evaporative irrigation is offered as an appropriate option in regulating irrigation water more effective. Smart means the system of irrigation is automatically controlled by a floating ball valve based on evaporation and evapotranspiration rate without electrical power. The objective was to evaluate the functional design of the evaporative irrigation on water demand aspect particularly for Mina-padi (paddy-fish farming). The system was evaluated based on the experimental field in the lab-scale since 10 July 2020. There were three irrigation regimes, i.e., continuous flooded (CR), wet (WR), and dry (LR) regimes. During the vegetative growth stage, the smart evaporative irrigation worked well. The irrigation was supplied by a floating ball valve automatically according to the evapotranspiration rate. The actual water levels were well kept and fitted to the setpoint as indicated by low mean absolute error (MAE). The CR regime needs more irrigation water and evaporated more water through the evapotranspiration process. Its rate was highest ranged between 5.81 – 6.6 mm/day. On the other hand, the LR regime has the lowest evapotranspiration rate in between 1.65 – 4.09 mm/day. The irrigation control system became crucial for control the evapotranspiration rate in which less irrigation water evaporate less water.

1. Introduction
As the main crop in Indonesia, rice is cultivated in the largest area of agriculture. The extent of paddy fields is recorded at 7.4 million ha in 2019. Paddy field is known as the highest agricultural water consumption because flooding irrigation is commonly used by the farmers. However, this method does not always have a linear correlation to the increasing in rice yield [1]. Previous studies in Indonesia showed flooding irrigation reduced 28% of yield compared to water-saving irrigation with the System of Rice Intensification [2]. Also, percolation, seepage, and runoff increased and caused losses of water [3, 4, 5].

To apply effective water used, some farmers combine rice cultivation to fish farming. This method is known as mina-padi (paddy-fish farming). Actually, this farming has been known a long time ago and provides carbohydrates and protein simultaneously. Also, this farming also provides many socio-economic benefits [6, 7]. A specific study in Yogyakarta province showed this farming increased farmers' income significantly; thus, it became the main factor to be adopted [8]. However, the system is known as wasteful in water used since more water is supplied in the system. Due to climate change and increasing of industrialization in Indonesia, water resources for agricultural use have become scarcer.
and limited, particularly in the dry season. Extreme drought occurred, so crop failure threat some paddy areas in Indonesia. Therefore, saving more irrigation water became urgent and are needed for sustainable rice farming in Indonesia.

In 2019, an evaporative irrigation idea was introduced as one alternative to water-saving irrigation [9]. This idea controls water supply by irrigation floating ball valve based on evaporation and evapotranspiration rate. This system doesn’t need electrical power to regulate the valve because it works automatically at a particular water level. So, it is called a “smart” system. However, there is no study reported evaluating this system yet. The objective of the study was to evaluate the functional design of the evaporative irrigation for paddy-fish farming with a closed system, particularly in the water demand aspect. The scope of evaluation aspects consisted of comparison actual water level and setpoint, the evapotranspiration rate of different irrigation schemes by performing water balance analysis.

2. Methodology

2.1. Field Design and Experiments

The evaporative irrigation was designed by adopting a closed system (recirculate water irrigation) as shown in Figure 1. Irrigated water was stored in a water tank and then supplied automatically to the field experiments by a floating ball valve. Water drainage from the field was drained to the fish pond. Three water regimes were set in this experiment; they are continuous flooded (CR), wet regime (WR), and dry regime (LR). The CR was set as a control treatment in which standing water (2 cm) was expecting during all days experiment. This regime is commonly applied by the farmers in Indonesia and known as conventional practice. WR was set as a moderate regime in which the water level was kept at the soil surface (0 cm) during the experiment. Meanwhile, LR was known as water-saving irrigation in which water level was kept 0 cm (at the soil surface) during 0-20 days after transplanting, and then water level was maintained at -5 cm (at 5 cm under the soil surface).

![Figure 1. Design of the evaporative irrigation for paddy-fish farming by adopting a closed system.](image)

The experiment was started on 10 July 2020 at the Kinjiro Farm located in Bogor, West Java, Indonesia. For rice farming, we adopted the System of Rice Intensification (SRI) elements, such as young seedling (14 days sowing), wider spacing (30 x 30 cm²), and single transplanting in each hill [10]. In addition, we used some sensors and data loggers to collect the field data. They are consisted of weather sensors to collect rain and reference evapotranspiration (ETo), water level, and soil moisture sensors. Each sensor was set in 15 minutes interval, and all data were stored in the data loggers. Weather sensors consisted of air temperature and humidity sensor, rain gauge, solar radiation sensor, wind speed, and direction sensor. Reference crop evapotranspiration was determined by the Penman-Monteith model as FAO’s standard model [11]. In addition, irrigation and drainage were measured by the water meter.
2.2. Water Balance Analysis

The water balance was performed in each regime on a daily basis by the following equation:

\[ h(t + \Delta t) = h(t) + \Delta h \]  \hspace{1cm} (1)

\[ \frac{\Delta h}{\Delta t} = (R - RO - ET) \pm Q \pm S \]  \hspace{1cm} (2)

Where, \( h \) is water level (in mm), \( \Delta h \) is the change of water level (in mm), \( R \) is rainfall (in mm), \( RO \) is runoff (in mm), \( ET \) is actual evapotranspiration (in mm), \( Q \) is irrigation/drainage (in mm), \( S \) is seepage (in mm), and \( t \) is time (day).

This analysis was performed to determine ET in each water regime, and then compare the results among the regimes. Also, total water balance components were compared among the regimes. The evapotranspiration rate was determined according to the accumulative evapotranspiration. This accumulative was plotted to the graph and then fitted with the third-order polynomial equation by the following:

\[ Y = ax^3 + bx^2 + cx + d \]  \hspace{1cm} (3)

\( Y \) is accumulative evapotranspiration, \( x \) is time (day), and \( a, b, c \) and \( d \) are constant. The evapotranspiration rate was then calculated based on the first derivative of Equation 3.

2.3. Evaluation of evaporative irrigation

The effectiveness of the evaporative irrigation was determined by mean absolute error (MAE) by the following equation:

\[ MAE = \frac{1}{N} \sum_{i=1}^{N} \left| WL_o - WL_{set} \right| \]  \hspace{1cm} (4)

Where \( WL_o \) is observed water level (in cm), \( WL_{set} \) is the expected water level (setpoint) (in cm), \( N \) is the number of data. MAE is known as dimensioned evaluations showing the average error of the observed and expected data. It is appropriately used in climate and natural science applications and has an advantage, more realistic average error measure, and unambiguous like root mean square error (RMSE) [12].

2.4. Limitation of study

The current study only presented the hydrological aspect of the evaporative irrigation, including its performance. The analysis was limited in the vegetative plant growth phase (0-50 days after transplanting). Plant and fish growth performances, including yield in each irrigation regime, were planned for the next phase of the study.

3. Results and Discussion

3.1. Actual Field Condition

The actual and expected (setpoint) water levels were presented in Figure 2. In some days, the actual water level was fitted to the setpoint for all regimes. In the early vegetative stage (10 days), the CR regime’s water level was easier maintained than two other regimes. The average actual water level was 2.05 cm above the soil surface. On the other hand, the water level in both the WR and LR regimes fluctuated, and the averages were 1.04 cm and 0.47 cm, respectively. The system worked well as indicated closer values between actual and setpoint in all regimes on the late vegetative stage (35-45 days after transplanting). The average WL values were 1.8 cm, 0.54 cm, and -5.59 cm for the CR, WR, and LR regimes, respectively. It was indicated the system worked well when no rain event occurred.
However, the evaporative irrigation was seemingly not working well on the rainy days for all regimes. The water level increased dramatically when heavy rain occurred. During rainy days, MAE values were higher than those during sunny days for all irrigation treatments (Table 1). Similar results were also found by a previous study that error was significantly increased during rainy days [13]. Although using a fuzzy control system, the water level increased incredibly as well as the error during rainy days. It showed the control system automatically by both the controller machine and the evaporative system was less effective in the rainy days. It is recommended to control the drainage rate, such as applying a subsurface drainage system [14]; thus, the water level can be well maintained in the rainy days. Overall, the evaporative irrigation was satisfactorily applied indicated low MAE (<1.3 cm) for all regimes.

3.2. Water Balance Components
Table 2 showed water balance components in all irrigation regimes. It was clear that the CR regime needs more water irrigation, among others. It was about 1.01% and 24.62% higher than those of the WR and LR regimes, respectively. The difference in water irrigation between the CR and WR regimes indicated the WR was less effective in water use due to more water drained in this regime. The same case also occurred in the LR regime. It was recorded the regimes drained 26.4% and 25.2% higher than that of the CR regime. In addition, the LR regime contributed more water losses by seepage and
drainage. The seepage happened because there was a leak in this experimental plot as well as uncounted water.

Table 2. Water balance component of each irrigation regime.

| Components            | Water regime |
|-----------------------|--------------|
|                       | CR           | WR           | LR           |
| Rainfall (mm)         | 269.4        | 269.4        | 269.4        |
| Irrigation (mm)       | 325.4        | 322.1        | 245.3        |
| Drainage (mm)         | 284.0        | 386.0        | 379.8        |
| Evapotranspiration (mm)| 314.8        | 212.5        | 126.9        |
| Seepage (mm)          | 0.0          | 0.0          | 48.0         |
| Uncounted water (mm)  | 4.0          | 7.0          | 40.0         |

According to Table 2, water losses through drainage and seepage contributed 47.75%, 65.26%, and 83.12% of inflow for the CR, WR, and LR regimes, respectively. As previously mention that the water irrigation was supplied according to the evapotranspiration rate operated by the floating ball valve; thus, most of the water losses from the rainfall. The total evapotranspiration in the CR regime was highest than in other regimes. The regime evaporated water through evaporation and transpiration of 32.50% and 59.69% higher. The total evapotranspiration in this regime was 314.8 mm, while other regimes were 212.5 mm and 126.9 mm for the WR and LR regimes, respectively. It was pointed out that standing water contributed more water loss by evaporation and evapotranspiration. Similar results also showed a previous study [15] that reported continuous flooding increased significant evaporation, particularly in the dry season.

3.3. Evapotranspiration rate

The cumulative evapotranspiration was fitted by the third-order polynomial equation, as showed in Figure 3. The coefficient determination ($R^2$) in all regimes were high (> 0.9), and the model can be accepted. According to the Equation, the evapotranspiration rate was well determined. It was clear that the evapotranspiration rate in the CR regime was highest. The evapotranspiration rate was ranged between 5.81 – 6.6 mm/day. On the other hand, the LR regime evaporated water at the lowest rate. The interval was 1.65 – 4.09 mm/day. Meanwhile, the WR regime’s evapotranspiration rate reached a moderate level ranged in between of 3.49 – 5.01 mm/day.

The trend of the evapotranspiration rate among the regimes was quite different. The CR regime showed a raised rate, particularly after 20 days. For the WR and LR regimes, the maximum rate occurred in the early vegetative stage. The WR regime’s trend showed a decreasing rate until the end of the stage, while the LR regime showed a rising movement after 30 days (Figure 3). Under the same climate, available water became the main factor that affected the evaporation rate from the field. The current study showed that less irrigation water decreased the evapotranspiration rate. Therefore, the irrigation control system became key to control evapotranspiration [16].
Figure 3. Cumulative evapotranspiration and evapotranspiration rate among the regimes: a) CR regime, b) WR regime, c) LR regime

4. Conclusion
The developed smart evaporative irrigation worked properly for *Mina-padi* farming in Indonesia. The indicator was by low mean absolute error (MAE) on three water irrigation regimes, namely: continuous flooded (CR), wet (WR), and dry (LR) regimes. Based on water balance analysis, the LR regime needs less water compared to those CR and WR regime. Also, the LR regime has the lowest evapotranspiration rate in between 1.65 – 4.09 mm/day. It is essential for further study to observe plant and fish growth under different water irrigation regimes and evapotranspiration rates.

Acknowledgments
The current study was fully funded by the Ministry of Research and Technology/National Research and Innovation Agency under research project with the title “Developing Smart Evaporative Irrigation for Precision Farming with more Environmental Friendly by using Artificial Intelligence” according to contract number of 2521/IT3.L.1/PN/2020.

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