Effects of plant spacing on evapotranspiration for estimating crop coefficient of Japonica rice

Augustine Ukpoju[1,*], *Taufiq* Yuliawan[1], and *Nazif* Ichwan[1], and *Hiroki* Oue[2]

[1] Graduate School of Agriculture, Ehime University, 3-5-7 Tarumi, Ehime, Japan
[2] The United Graduate School of Agriculture, Ehime University, 3-5-7 Tarumi, Ehime, Japan

Abstract. A field experiment was conducted to evaluate the evapotranspiration (ET), crop coefficient (Kc), and water use efficiency (WUE) of rice in two unique transplanting systems: Jejer Manten (JM) and Jajar Legowo (JL) under irrigated conditions. Research studies in Indonesia attribute JM and JL with high yields and water productivity compared to the conventional tile (TL) system using Indica rice. There is no scientific research on the effect of JM and JL on ET for estimating Kc in both Indica and Japonica rice. The aim of the study is to evaluate the influence of JM, JL, and TL on ET, Kc, and WUE of Japonica rice at different rice growth stages. Crop ET and water surface evaporation beneath the rice canopy (Ew) were measured by lysimeters installed in each transplanting system. The average of Kc was calculated at the vegetative, reproductive, and ripening stages. The yield was higher in JM and JL compared to TL. In terms of water conservation and efficiency, JL outperforms JM and TL due to lower ET, Kc values, and higher WUE. Selecting an appropriate transplanting system is subject to local conditions and water availability .

1 Introduction

Rice is a stable food in Japan and Indonesia [37, 52]. Six nations—China, India, Indonesia, Bangladesh, Vietnam, and Japan—produce and consume more than 90% of the world's rice, accounting for 80% of both global production and consumption [37]. The demand for rice in Asia is growing at 1.8% annually [37] due to increasing population, reduced farming population and urbanization. The quality and productivity of rice are both declining due to the recent trend of rising global temperatures on agriculture [51]. The change is affecting global water availability, changes in rainfall patterns, crop growth, and livestock production [6, 7]. To cope with climate changes, the knowledge of crop evapotranspiration (ET) mechanism is crucial for understanding plant-water requirements [3] for developing water management techniques to improve water use efficiency and reduce water consumption especially in paddy fields [29, 30, 31].

Evapotranspiration is a combination of soil surface evaporation and plant transpiration [70, 71]. Rice production is associated with significant global water use, with evapotranspiration from rice fields accounting for approximately 859 cubic kilometers per year [43]. It takes an average of 1,432 litres of evapotranspired water to produce 1 kg of

* Corresponding author: echibrainx@gmail.com

paddy rice [40, 43]. Experimental data from across Asia indicate that, on average, about 2,500 litres of water need to be supplied (by rainfall and/or irrigation) to a rice field to produce 1 kg of paddy rice [40, 43] but this can vary depending on various factors such as crop management, weather conditions, and soil properties. To ensure sustainable production of rice, accurate estimation of crop evapotranspiration ET is important for irrigation planning and scheduling [1, 2, 3, 4, 13, 53, 54]. Researchers have focused on improving the accuracy of various methods for estimating evapotranspiration over the last century. There are three methods of estimating evapotranspiration, the direct method, indirect method, and advance methods [53, 54,]. The use of lysimeter remains one of the most accurate direct methods for estimating evapotranspiration [44, 47] and they are categorised into weighing and non-weighing types. Lysimeters are used to measure crop evapotranspiration by taking account of the crop's transpiration and soil surface evaporation. Potential evapotranspiration (Ep) is a measure of the atmosphere's ability to evaporate and transpire water from the surface [20, 20, 48, 67, 68, 69]. It can be estimated via indirect methods, using empirical models such as the modified Penman Monteith FAO 56 method, Penman 1945 method, Blaney Criddle method, Hargreaves methods, Priestley-Taylor methods, and Thornthwaite method [45]. The performance of each model is dependent on the climatic conditions and data availability of the region [47, 53, 54]. Crop coefficient (Kc) is the ratio of crop ET to potential evapotranspiration (Ep) [20] derived empirically for each crop, based on lysimeter data and weather conditions of the region [47]. Kc values are specific to different crops and growth stages [14]. Rice has the highest Kc values compared to other crops [20] partly because of the high-water consumptive nature of rice. Kc estimation provides valuable information for determining crop water requirements, and for irrigation planning and management [12, 15].

Plant spacing is also an important agronomic factor [5, 55] that can influence evapotranspiration rates through competition for resources, vegetation characteristics, and management practices. Various researchers have tried to find the optimum plant spacing for rice, but rice evapotranspiration estimation is complicated by the impact of varied plant spacing, which is influenced by variables such climatic change, planting density, leaf area index, and water availability. The right plant spacing will allow for effective utilization of solar radiation for photosynthesis, soil nutrient and water [28].

The tile system (TL: 25 cm x 25 cm) has been the most conventional spacing for rice in many rice production countries especially Japan and Indonesia. Two unique transplanting system; Jejer Manten (JM), and Jajar Legowo (JL) have been attributed with high yield and water productivity in Indonesia [16, 17, 28, 61, 66]. This has prompted the government of Indonesia to promote the adoption of JM, and JL [18] mostly because of its associated advantages; increase in rice yield, higher plant densities per unit area (plants m^{-2}), increased border effects and larger solar interception due wilder rows between plants as compared to the tile (TL) system [16,17,18, 28, 61]. The spatial arrangement of JM, JL compared with TL is illustrated in Figure 1. The transplanted density occupied per square meter area were JL (21.26 plants m^{-2}), JM (19.01 plants m^{-2}), and TL (16.00 plants m^{-2}) as shown in Figure 1.

The impact of JM and JL was studied for the first-time using Japonica rice [18], and the results obtained were consistent with the studies using Indica rice cultivar [16, 17, 28, 61]. There is no research that estimates the crop coefficient of Jejer Manten (JM), and Jajar Legowo (JL) in both Japonica and Indica rice cultivars. This study will examine the water requirement for the consumptive needs of the Japonica rice under the different transplanting systems based on the estimated values of their evapotranspiration and crop coefficients. As the number of rice paddy acreage is decreasing in Japan due to industrialization, declining farming population, urbanization etc [38], JM and JL can improve rice production per unit area and conserve water use than the tile (TL) system practiced.

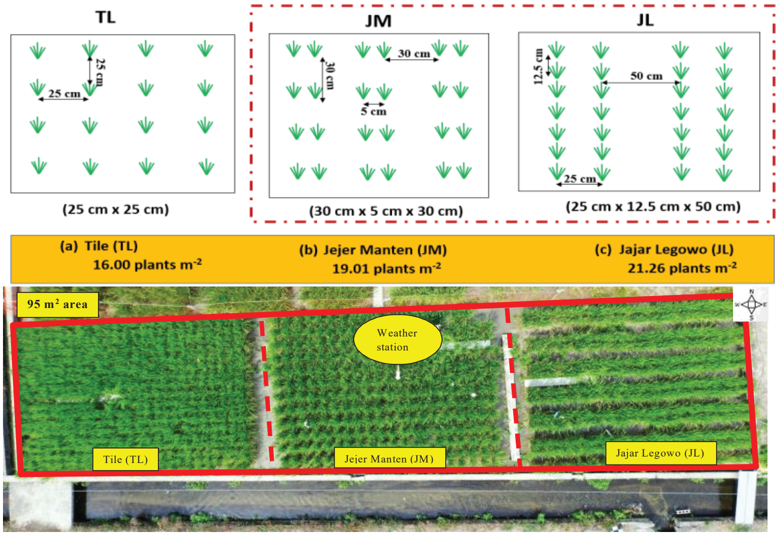


Fig 1. The spatial arrangement of JM, JL and TL and their planting densities per meter square (plants m^{-2}) and the Aerial view of the three transplanting systems divided into a 95 m^2 plot area

2 Material and Method

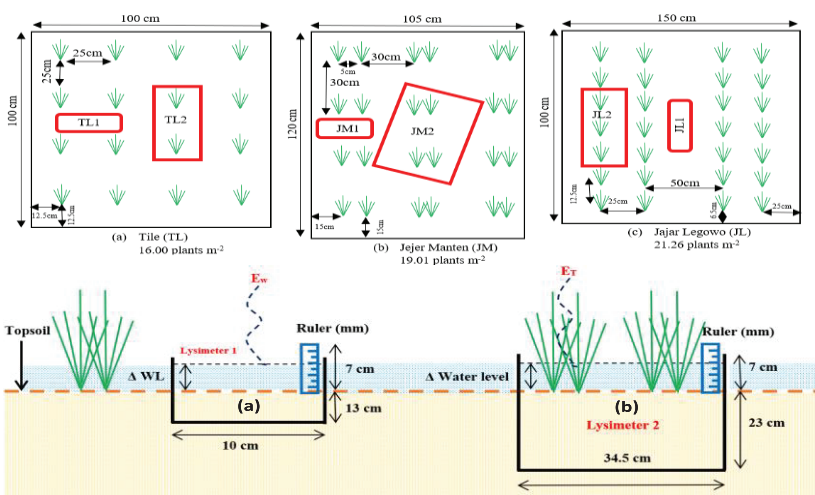


Fig 2. Lysimeter arrangements (TL1, JM1, JL1 are lysimeters installed to measure surface evaporation (Ew), TL2, JM2, JL2 are lysimeters to measure crop ET)

The field experiment was conducted in one rice planting season from May to October 2022 at the Faculty of Agriculture, Ehime University, Japan (33°50'16.2' 'N, 132°47'31.8 '' E). It was carried out on a plot area of 95 m^2 divided into three transplanting spacing systems; Jajar Legowo (JL: 25 cm x 12.5 cm x 50 cm), Jejer Manten (JM: 30 cm x 5 cm x 30 cm) and conventional tile (TL: 25 cm x 25 cm) as shown in Figure 2. A rice (Oryza sativa subsp. japonica) cultivar "Nikomaru" [19] was used. The rice cultivar was pre-germinated, and the seeds were sown from May 29, and transplanted into three different planting systems on June 18, 2022. 4:6:4 g m^{-2} of NPK was applied a day before transplanting. The grains were harvested 111 days after transplanting (DAT) on October 7, 2022. The field was characterized by sandy loamy soil. The water level was maintained at approximately 3-5 cm during the vegetative phase of the rice. Mid-season drainage was observed from 15 to 25 July 2022. Mid-season drainage is usually practiced in rice fields in Japan to re-oxidize the soil, remove toxic substances such as sulfide, and prevent excessive vegetative overgrowth [20]. A weather station comprising HMP-155 Vaisala, a CNR-4 net radiometer, and ATMOS-41 was installed to measure the microclimatic conditions in the rice field, such as hourly and daily air temperature, wind speed, relative humidity, solar radiation, and precipitation. Two non-weighted lysimeters were installed 10 DAT in each transplanting system to measure ET and Ew as shown in Figure 2. Daily potential evapotranspiration (Ep) was estimated using Penman 1948 equation [20]. The crop coefficients Kc for TL, JM, and JL were calculated at the initial stage, crop development, mid-season, and last season stages.

2.1 Lysimeter installations and measurements

The dimensions of the lysimeters are represented in Table 1. In Figure 3, TL2, JM2 and JL2 lysimeters were arranged to accommodate the required numbers of rice plants for measuring ET within each transplanting system. The conditions in the lysimeter (soil moisture, soil depth, plant spacing, plant health) were carefully maintained to match the conditions of the field. Lysimeters TL1, JM1 and JL1 were placed to capture the natural soil surface evaporation in each transplanting system. The lysimeters were buried at depth such that 7 - 10 cm is left above the soil. They were filled with soil proportional to the level of soil outside the lysimeters within each planting system as shown in Figure 2. Lysimeter (1) was used to measure evaporation Ew, while the lysimeter (2) was used to measure crop evapotranspiration ET.

Table 1. Lysimeter dimensions

Category	Allocation	Dimension (L x B x D) cm	Purpose
Lysimeter 1	TL1, JM1 and JL1	(45 cm × 34.5 cm × 30 cm)	Ew
Lysimeter 2	TL2, JM2 and JL2	(60 cm × 10 cm × 20 cm)	ET

There were three hills of plant in JL2, two hills in TL2 and four hills in JM2. Each hill had three seedlings. The water level in the rice field and lysimeters were maintained within 1-5 cm depth. A secondary irrigation canal was used to supply water to the rice fields. Rulers were installed in all lysimeters to measure the differences in water level observed every morning and evening, which is expressed in millimeters per day. The irrigation supply was stopped 10 days before harvest.

2.2 Estimating actual evapotranspiration ET

Non-weighing lysimeters are inexpensive and can be fitted within any rice field. Figure 2 illustrates the mechanism for estimating ET. Crop type and crop root depth are factors to consider when choosing the appropriate lysimeter to measure ET. Measuring crop ET using this method can be strenuous but effectively accurate. Daily Ew and crop ET were determined by capturing the slightest changes in daily water levels within the rice field and lysimeters at 7 AM and 6 PM during the rice growing season. The difference in water levels was calculated and expressed in millimeters per day (mm d^{-1}). Some data weren't captured due to weather conditions (nonstop rains and typhoons).

2.3 Potential evapotranspiration Ep

Hourly potential evapotranspiration (Ep) was estimated using the original Penman 1948 equation (Eq. 1) [20, 67]. Daily net solar radiation (Rn) comprising of (downward shortwave solar radiation (*St*), upper shortwave solar radiation (*aSt*), longwave upper solar radiation (*Lu*) and longwave downward solar radiation (*Ld*)) were measured by CRN4. Heat stored in surface water (ΔW) was measured as a function of Water temperature (Tw) and water depth within each transplanting system. ATMOS 41 was used to obtain weather data on the experimental field. A soil heat plate was buried 5 cm beneath the soil surfaces to estimate soil heat flux (G), also surface water temperature (Tw) was measured by floating 5TE/5TM in each transplanting system as illustrated in Figure 3.

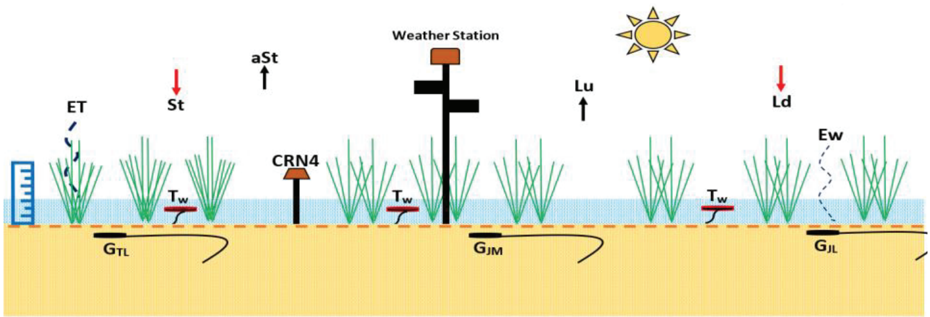


Fig 3. Weather station and sensory installations

The original Penman 1948 empirical model combines the energy balance and aerodynamic approaches into a single equation that expresses the evapotranspiration rate (Ep) as a function of net radiation, soil heat flux, air temperature, vapor pressure deficit, wind speed, and aerodynamic resistance (Eq. 1) [20, 48, 67, 68, 69].

$$LEpen = \frac{\Delta(Rn - G - \Delta W) + \gamma f(u) * (esat(Ta) - ea)}{\Delta + \gamma} \quad (1)$$

Where, LE_{pen} is hourly potential evapotranspiration in W m^{-2}. The slope of saturation vapour pressure curve at the air temperature (Δ) is the sum of the net solar radiation (Rn) in W m^{-2}, soil heat flux (G) in W m^{-2} and heat stored in water surface (ΔW). The wind function (f(u)) is defined by Penman as (0.26(1+0.537*u*)); where *u,* is the wind speed measured 2 m above the ground, γ is psychometric constant 0.66 hPa/^{O}C, esat (Ta), is the saturation vapour pressure in kPa at mean air temperature Ta, ea, is the actual vapour pressure in kPa.
The heat stored in water surface (ΔW), expressed in W m^{-2}

$$C_w \rho_w d_w \frac{\partial T_w}{\partial t} \quad (2)$$

Where, c_w is the specific heat of water (c_w = 4.18 J kg. K^{-1}), d_w is the depth of the water surface beneath the canopy, ρ_w is the density of water, kg m^{-3}, and T_w is the temperature of the water at the time *t*, (°C). Hourly values of Ep were calculated using the Penman 1948 equation then converted from Wm^{-2} to mm h^{-1} by multiplying LEpen by 3.6h divided L to give ET in mm h^{-1}. Where is the latent heat L (J g^{-1}). L is equal to (2499-2.512T). T is the average of the minimum and maximum temperature during the experiment.

2.4 Crop coefficients

The crop coefficient (Kc) represents the physical and physiological qualities of the crop under investigation in comparison to the reference crop, such as ground cover, canopy attributes, aerodynamic resistance [53], leaf area, plant height, crop characteristics, irrigation system, rate of crop development, crop planting date, soil, and climate conditions, and field management processes [22][23][24][25]. Kc values vary throughout the crop's growth stages, with lower values during the initial stage, increased values during the mid-season, and a decline at the late season stages [23][24][25]. The length of each growth stage depends on various factors such as crop type, planting date, climatical conditions, cultural practices etc [22]. It is important to continously observe the condition of the field so as to accurately determine the growth stage of the crop while adjusting the empirical Kc values [22]. For the estimation of Kc, the FAO-56 definition [26] was applied, which is defined Kc the ratio of (ET/Ep) [26].

$$Kc = \frac{ET}{Ep} \tag{3}$$

ET is the crop evapotranspiration (ET) measured in millimeters per day (mmd^{-1}) and Ep is potential evapotranspiration (Ep) in mmd^{-1}. We obtained Kc values for all crop growth stages; initial stage (7−21 DAT), crop development stage (22−61 DAT), mid-season stage (62-91 DAT), and late season stage (92-110 DAT) Figure 4.

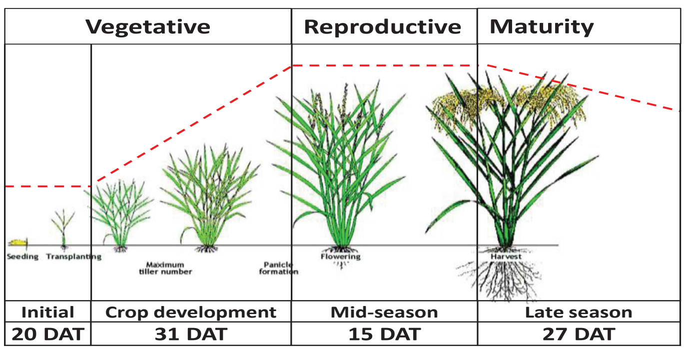


Fig 4. Rice growths and crop coefficient Kc in the four growth stages within TL, JM and JL

2.5 Water use efficiency within each planting system

Water use efficiency (WUE) is defined as the amount of carbon assimilated as biomass or grain produced per unit of water used by the crop [32]. The concept of water use efficiency (WUE) was proposed by [33], which demonstrates that water use and plant productivity are related. They coined the word "WUE" to describe how much biomass a plant produces for every unit of water it uses. Since then, several original articles and reviews have been written on the subject, with [34] being the most recent. Therefore, water-use efficiency is expressed in equation form as follows :

$$WUE = \frac{Dry\ weight\ production}{Evapotranspiration\ ET} \tag{4}$$

Where, dry weight production is the yield in kilogram per hectare ($Kg\ ha^{-1}$), ET is the total evapotranspiration expressed in millimeters gotten from daily lysimeter observations. Water use efficiency (WUE) was estimated between TL, JM, and JL from 10 DAT.

3 Results and Discussions

The average solar radiation (st) during the experiment was 186 $W\ m^{-2}$. The total precipitation was 473.11 mm and mean relative humidity was 79.34 %. Figure 5 describes the weather conditions during the experiment.

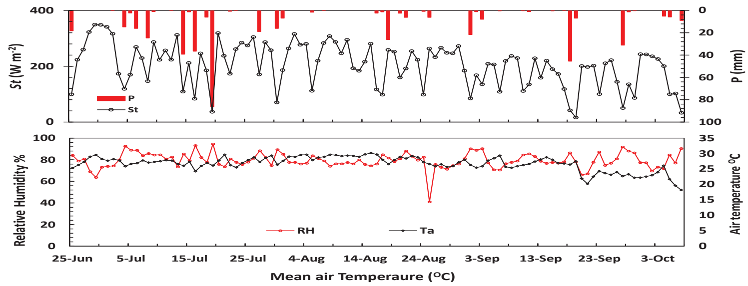


Fig 5. Daily variation of precipitation (P), solar radiation (*St*), relative humidity *(RH)*, air temperature *(Ta)* and wind speed (*u*).

3.1 Data Analysis

Analysis of variance (ANOVA), T-test and linear regression were used to find the relationship between plant density and yield, to compare crop ET, Ew, Kc and Ep of each transplanting system at a significance level of 5%.

3.2 The relationship between plant spacing, plant density, leaf area index (LAI) and evapotranspiration ET

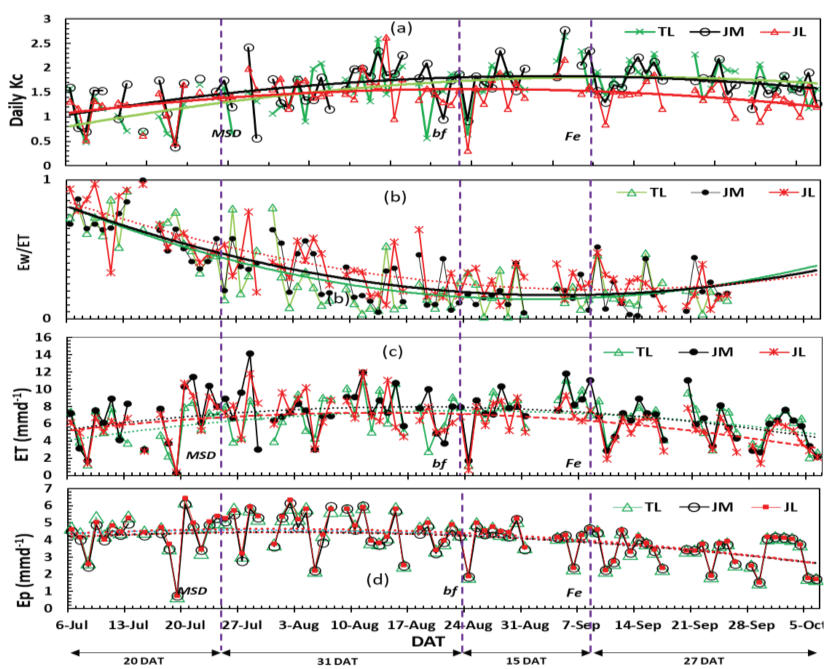
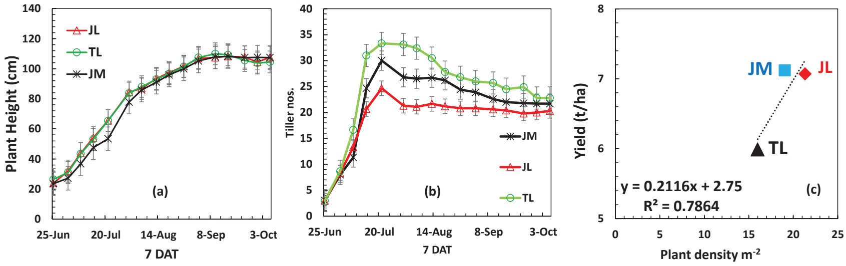


Fig 5. Daily variations of (a) crop coefficeint Kc (b) Ew/ET (c) crop evapotranspiration ET (d) potential evapotanspiration Ep in four growth stages. initial stage (7−21 DAT), crop development stage (22−61 DAT), mid-season stage (62-91 DAT), and late season stage (92-110 DAT). *MSD* is denoted as the mid-season period, *bf* as before flag extension and *fe* as full flowering

The results of ET, Ep, Kc, Ew/ET and Ew were different for each growth stages and transplanting systems. The effect of different plant spacing for estimating rice evapotranspiration is a complex issue influenced by factors such as climate change, planting density, leaf area index, and water availability. To understand the influence of the aforementioned factors, we estimated the averages of ET, Ep, Kc, Ew/ET and Ew during the rice growth stages; initial stage (7−21 DAT), crop development stage (22−61 DAT), mid-season stage (62-91 DAT), and late season stage (92-110 DAT) in Figure 5. The ratio of Ew/ET should not exceed 1 [75]. At the initial stages, the average values of Ew/ET was 0.61 for TL, 0.61 for JM and 0.68 for JL. And at the ripening stages, Ew/ET was 0.18 for TL, 0.19 for JM and 0.20 for JL. The values of Ew/ET are important for precision agriculture and irrigation management.

3.2.1 Effect of plant spacing and density on rice growth characteristics

The yield and plant growth characteristics (plant height, number of tillers, yield…) were measured and compared within the three transplanting systems. The plant density per unit area recorded during the experiment was 21.26 plants m^{-2} for JL, 19.01 plants m^{-2} for JM, and 16.00 plants m^{-2} for TL. There was no significant difference in plant heights amongst the three transplanting systems [16, 17, 18]. According to [50], the number of hills per unit of ground area is determined by spacing and nitrogen. The larger the plant population pe unit area, the smaller the number of tillers per hill obtained. This was evident in the difference in tillering numbers amongst TL, JM, and JL in Figure 8. TL had the lowest plants per unit area but the highest tiller numbers per hill. Likewise, JL has the highest plant per unit area but the lowest number of tillers per hill. This agrees with [50, 58, 61, 63] and corresponding studies by [16, 17, 18, 61]. The influence of higher plant density resulted in JM having the highest yield 7.21 t ha-1, followed by JL 7.08 t ha-1, and TL 5.99 t ha-1[18]. This is also consistent with previous studies [16, 17, 28]. The yield difference between JM and JL was statistically insignificant and significantly different compared to TL. A significant correlation existed between the various plant densities and yields (p <0.002, R2 = 0.7) in Figure 7.



kly variations of (a) plant height and (b) tiller numbers and (c) relationship between plant density and yield.

3.2.2 The influence of plant density, leaf index area (LAI) on ET

The spatial arrangements of JM and JL could significantly enhance solar radiation interception between rows, increase aeration, increased border effects and Increase LAI, and ET compared to TL [16, 18, 58]. The daily estimated of ET, The JM and JL system had the highest plant density, indicating a greater number of plants per unit area. This impacted the crop yield potential, as higher plant density often results in increased production. However, the effect of plant density may vary depending on local conditions, soil management, cultural practices, crop type and water availability [61, 62, 64, 65]. Previous studies have examined the influence of optimizing plant density and spacing in relationship to yield and LAI of various crops [61, 62, 64, 65]. A study by [64] on maize found that LAI and yield increased with the increase in plant density. In a recent study using Japonica rice (Nikomaru) [18] found that JM and JL plant density could improve canopy structure, improve border effects, improve leaf angle of inclination, increase LAI, and solar radiation absorption and, as a result, higher evapotranspiration ET [3, 18, 35, 55, 58, 59, 63]. The influence of the transplanting systems on ET and LAI can be seen in Figure 8 above. Plant population and tillering is said to have an impact on plants' LAI and ET [63, 64, 65], however, tillering decreases with increase in plant density and spacing [50], which affected the decrease in ET in JL (lower tiller numbers per hill) compared to JM and TL. In the early phases of the rice growth, LAI rose gradually until it peaked during the crop development stages between (20-66 DAT) for JM and JL but peaked for TL at the reproductive stage due to the shading effect in TL during the crop development stage [18].

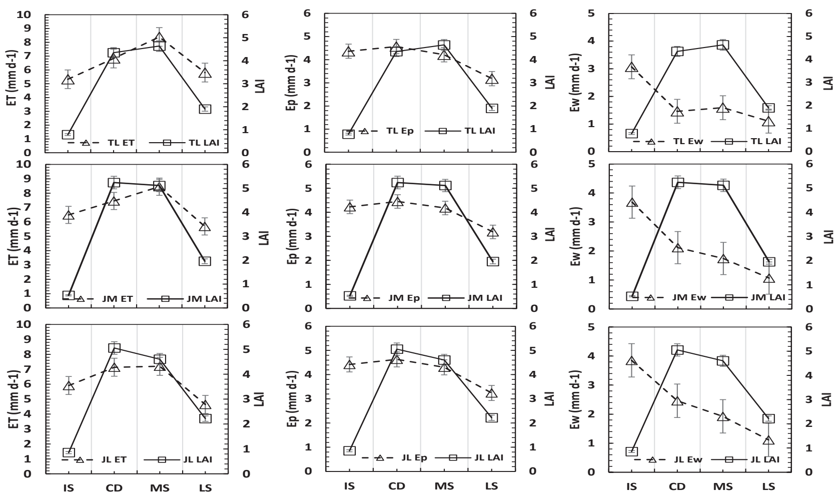


Fig 8. The average variations of crop evapotranspiration ET, potential evapotranspiration Ep, surface evaporation Ew in relationship to the crop's leaf area index LAI at the initial stage (IS), crop development stage (CD), mid-season (MS) and late season stages (LS).

LAI began to decline as the leaves reached senescence and maturity for all transplanting systems. LAI was higher in JL compared to JM and TL during the initial stages but became higher in JM compared to JL and TL in the crop development stage. At the initial stage, JL had more tiller numbers per hill compared to JM. This was responsible for JL having a higher LAI at initial stages. However, tillering decreased with increasing plant population and spacing in JL at the reproductive stage. The 30 cm spacing in JM compared to the 50 cm spacing between rows in JL improved tillering in JM at reproductive stages. ET was highest during the rice reproductive stage (Panicle initiation and flowering) in JM, JL, and TL. ET was estimated using a non-weighing lysimeter by measuring the changes in water level as a function of the crop's transpiration and soil evaporation within each lysimeter. It was suggested by [42] that the difference in ET may result from the development of canopy cover, leaf area index (LAI) and changes in the energy absorption mechanism. This agrees with [18, 55, 28], the estimated ET amongst the three transplanting system was affected by canopy cover, leaf area index (LAI) and changes in the energy absorption mechanism in JM, JL, and TL. ET was higher in the transplanting systems with the highest LAI and plant density. Figure 7 describes the relationship between ET, Ep, Ew and LAI. As plant density increases, so does LAI and yield, but as plant spacing increases, so does soil evaporation and a significant decrease in tillering. This agrees with [16, 18, 28, 50, 55]. The wider spacing in JL had a higher transmissivity of download solar radiation (TDSR) [18] which resulted in increased soil evaporation compared to JM and TL. Soil evaporation (Ew) increases as plant spacing increases. JL had the Ew, followed by JM and TL. The average Ew was 2.29 mm d-1 for JL, 2.10 mm d-1 for JM and 1.73 mm d-1 for TL. Ep is addressed in the next section.

3.2.3 Predicting potential evapotranspiration Ep

In Figure 8, Ep was estimated by taking the daily averages of hourly Ep divided into the rice growth stages. The original Penman 1948 empirical model combines the energy balance and aerodynamic approaches into a single equation that expresses the evapotranspiration rate (Ep) as a function of net radiation (Rn), soil heat flux (G), heat stored in water (ΔW), air temperature (Ta), vapor pressure deficit (VPD), wind speed (u), and aerodynamic resistance [20, 48, 67, 68, 69]. The values of Rn were obtained from meteorological station installed in JM, which was placed in the middle of the three planting systems. Soil heat flux and water temperature were estimated from sensors installed within each transplanting system. Ep estimated is dependent on the weather conditions of the region [20, 69, 70]. One of the important parameters for the estimating Ep is net solar radiation (Rn). Rn is the ratio of upward and downward solar radiation. Energy balance affects evapotranspiration in plants, hence estimating Rn is important to research agro-climatic relationships [70]. Daily Ep was predicted during the experiment when ($Rn \geq 0$) [69]. The soil heat flux (G) is another parameter considered in this research. It is the heat conduction in the soil caused by temperature changes, depending on the soil composition. Because G has the smallest contribution to energy balance, it is frequently overlooked, but this ignorance can lead to significant errors [70].

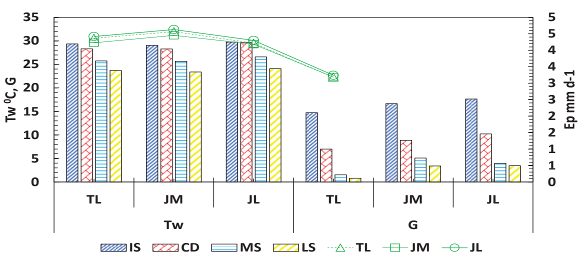


Figure 9. Average variations of potential evapotranspiration Ep, Surface water temperature Tw and soil heat flux G in the four growth stages. initial stage (7−21 DAT), crop development stage (22−61 DAT), mid-season stage (62-91 DAT), and late season stage (92-110 DAT).

Fig 9. Average variations of potential evapotranspiration Ep, Surface water temperature Tw and soil heat flux G in the four growth stages. initial stage (7−21 DAT), crop development stage (22−61 DAT), mid-season stage (62-91 DAT), and late season stage (92-110 DAT).

The heat energy stored in water ΔW was also estimated. It is a function of the depth of water surface beneath the canopy d_w, is the density of water $\rho_{w,}$ (kg m^{-3}), and the temperature of the water at the time *t*, (ºC) represented in (Equ. 2). Previous studies by [73], found that canopy cover influences the rate of soil evaporation and water temperature changes during the early stages of rice growth. The influence of canopy cover can be seen as water temperature and soil heat flux decreases with increase in canopy cover at the reproductive and ripening stages in JM, JL, and TL Figure 9. During the initial and crop development stages, water temperature and soil heat flux was higher which agrees with [73]. JM had the largest canopy cover, followed by TL and JL at reproductive stage. Which influenced the energy absorption mechanism in all transplanting systems. The total Ep for TL, JM and JL was 333.34 mm, 327.41 mm, and 338.55 mm respectively and average daily Ep per day during the experiment was 4.07 mm d^{-1} for TL, 3.99 mm d^{-1} for JM and 4.13 mm d^{-1} for JL. Statistically there was no significant differences amongst Ep in all transplanting systems. Ep was divided into the rice growth stages. The increase in Ep in JL was due to its wide row spacing, increasing surface evaporation between rows [35]. Figure 9 shows the factors influencing Ep.

3.2.4 The influence of plant spacing on soil and water temperature

The wider spacing between rows increased solar radiation on both canopy and soil surface [18, 35]. The influence of varied plant density on soil and water temperature was investigated by [72] and found that increased plant spacing exposes soil and water to higher solar radiation interception which increases the rate of soil and water evaporation. High soil and water temperature in rice field affects yield [74]. It was observed that the factors responsible for significant differences in ET, Ep and Kc was the difference in G, ΔW, and Tw. The increase solar radiation penetration within canopy and plant spacing affected the variation in heat energy stored in surface water ΔW, soil heat flux (G) within TL, JM, and JL. JM had the denser canopy and LAI at the crop vegetative stage followed by JL and TL but the wider rows in JL influenced the increase in surface water Temperature, soil heat flux and the heat stored in the water ΔW thereby leading to increased surface evaporation compared to JM and TL. The variation can be seen in Figure 10 amongst the three transplanting systems.

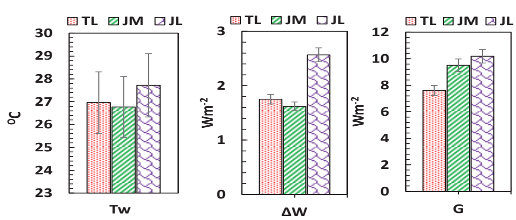


Figure 10. Total averages of (*left*) Surface water temperature Tw (*center*) Heat store in water ΔW and, (*right*) Soil heat flux G

Fig 10. Total averages of (*left*) Surface water temperature Tw (*center*) Heat store in water ΔW and, (*right*) Soil heat flux G

According to [60], wider row spacing in wheats increased solar radiation incident on the soil surface leading to higher soil evaporation Ew. Evidently, the wider the space between rows resulted in higher soil surface evaporation (Ew) as was observed in JL, JM, and TL. The average soil evaporation was 2.29 mm d^{-1} for JL, 2.10 mm d^{-1} for JM and 1.73 mm d^{-1} for TL. The increased solar radiation beneath wider row spacing also influence increased water temperature Tw, and heat stored in the water **Δ**W.

3.2.5 Determination of single Kc

Determining crop coefficient (Kc) is significant for various reasons in agricultural practices. Kc values are specific to different crops and growth which helps in determining crop water requirements [15]. Daily Kc was estimated in Figure 14 from 18 -110 DAT. According to the FAO estimation of single Kc, single Kc was divided into in four stages, initial stage (7−21 DAT), crop development stage (22‒61 DAT), mid-season stage (62-91 DAT), and late season stage (92-110 DAT) in Table 2. To determine Kc, we used the FAO equation for single Kc in equation (3). The Kc is influenced by how the crop's qualities change throughout the growing season [26]. The crop coefficients were lowest in the study's early crop growth period, progressively rose to a peak between (20-66 DAT), and then started to fall when the leaves senescence and matured.

Table 2. Crop coefficient for all growth stages in TL, JM, and JL.

Growth crop stages	No. of Days	Average Crop Coefficients		
		TL	JM	JL
Initial	20	0.71	0.86	0.79
Crop development	31	1.01	1.09	1.02
Mid-season	15	1.28	1.30	1.07
Late season	27	1.18	1.13	0.91

According to [26], the crop coefficient can be influenced by the crop's type, growth stage, canopy cover, and crop density. Due to the difference in canopy cover, and crop density. The Kc values was different for each transplanting system.

3.2.6 The influence of plant spacing on water use efficiency (WUE)

Plant spacing can influence water use efficiency and water productivity in rice cultivation [28, 61]. This is shown in the water use efficiency (WUE) estimated between TL, JM, and JL from 10 DAT and expressed in kg kg^{-1}. The water use efficiency (WUE) was 1.14 kg kg^{-1} for TL, 1.28 kg kg^{-1} for JM and 1.40 kg kg^{-1} for JL in Figure 11.

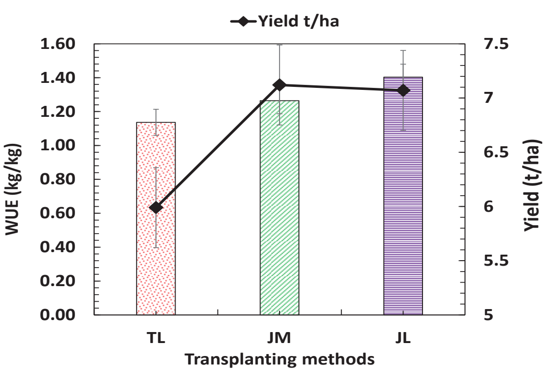


Fig. 11. (a) Water use efficiency and yield performance of TL, JM, and JL

As spacing increases, the number of tillers per unit hill decreases [50] resulting in lower LAI and ET especially for JL at the reproductive stage but TL could have a higher ET compared to JL (with the highest plant density per unit area) due to the increase in tillering in TL compared to JM and JL. JM had the highest LAI and ET, followed by JL and then TL at the crop development stages. However, TL later had the highest LAI and ET compared to JL at the reproductive stages. At the reproductive stage, [18] found out that per unit of leaf,

TL had the highest solar radiation interception and photosynthesis, but JL and JM could achieve the highest solar radiation interception and photosynthesis at the crop development stage. This is evident as to the increase in LAI for TL at the reproductive stage and slightly lower in JL at the same stage. This is caused by the shading effect at the JL's reproductive stage [18]. Transpiration was higher in JM and TL than JL hence, the higher water user efficiency in JL compared to the rest. The results of experiments presented in Table 3, gives an insight into factors that influences and affects rice productivity with respect to plant spacing, density and canopy covers.

Table 3. Water use efficience and yield performance of TL, JM, and JL

Transplanting methods	Mean variables								
	Yield	WUE	ET	Ep	Ew	Tw	G	ΔW	Ew/ET
	t/ha	kg/kg	mmd^{-1}	mmd^{-1}	mmd^{-1}	^{o}C	Wm^{-2}	Wm^{-2}	
TL	5.99b	1.14b	6.43a	4.07a	1.73b	26.96a	7.60b	1.75a	0.303
JM	7.21a	1.28b	6.87a	3.99b	2.10a	26.77a	9.51a	1.62a	0.326
JL	7.08a	1.40a	6.15b	4.13a	2.29a	27.72b	10.19a	2.57b	0.382

Level of significance 0.05** a means not significant, b means significant.

The performance of the three different planting systems, TL, JM, and JL were evaluated based on key parameters, such as the crop coefficient (Kc), evapotranspiration (ET), plant density, water use efficiency (WUE), and crop yield. Our findings shed light on the complex interplay of these factors and provide insights into the overall performance of these systems. Our analysis revealed that the JL planting system demonstrated the highest water use efficiency (WUE) within its specified Kc range, suggesting that it uses water resources more sparingly, which is crucial for regions facing water scarcity. From previous studies [16, 17, 18, 28, 61], JM have consistently outperformed JL and TL in terms of crop production per unit area. It is essential to consider the local conditions, soil type, crop type and water availability before selecting the transplanting system suitable to specific regions.

3.2.7 Limitations

We used the same dimensions of lysimeter boxes for all transplanting system even though the planting density was different. This might have led to under or overestimation of ET and Kc in JL and JM. We planned to continue the experiment by modifying the dimension of the boxes to suit the soil to plant population ratio of individual planting system.

4 Conclusion

The influence of different plant spacings on actual evapotranspiration (ET) to estimate the crop coefficient (kc) of Japonica rice was examined. Factors such as plant spacing, canopy cover and plant density influenced the differences in ET, Ep and Kc amongst the three transplanting systems: The interplay between soil heat flux, water temperature, heat energy stored in water, and soil moisture is critical in understanding and predicting evapotranspiration processes within the transplanting systems. TL was used as the control, while JM and JL were used as treatments. The lysimeters used were able to measure ET. The accuracy of the estimation was said to be underestimated because the same size of lysimeter was used irrespective of the transplanting system. Neverther less, JM and JL planting density improved the rice yield, canopy structure, border effects and increased LAI. The crop coefficient (Kc) estimated can be used to determine the water requirements of Japonica rice for effective irrigation management. Decreased ET was observed with increased plant spacing in JL compared to JM and TL, but Ep increased with spacing in JL. The yield difference between JM and JL was insignificant compared to TL. In conclusion, selecting a preferred transplanting system will depend on the farmers preference. In terms of water efficiency and conservation, JL had a higher WUE. JM might be chosen if maximising yield is the main objective. When selecting the most appropriate planting scheme, it is crucial to take local conditions, water availability, and the specific goals of the farming operation into account.

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References

1. P. Reuben, F. C. Kahimba, Z. Katambara, H. F. Mahoo, W. Mbungu, F. Mhenga, A. Nyarubamba, M. Maugo, *Agric. Sci*, ***07*****(04)**, 270–278 (2016b).
2. B. Dunn, W., T. S. Dunn, J. H. Mitchell, J. Brinkhoff, J. Crop and Pasture Sci**, 71(3**), 219–228 (2020).
3. H. F. Yan, C. Zhang, H. Oue, G. J. Peng, R. O. Darko, ***10*****(4)**, 130–139 (2017).
4. S. Chatterjee, P. C. Stoy, M. Debnath, A. K. Nayak, C. K. Swain, R. Tripathi, D. Chatterjee, S. S. Mahapatra, A. Talib, H. Pathak, *Theo. and App. Cli.*, ***146*****(1–2)**, 155–171 (2021)
5. P. Reuben, F. C. Kahimba, Z. Katambara, H. F. Mahoo, W. Mbungu, F. Mhenga, A. Nyarubamba, M. Maugo, *Agric. Sci.*, ***07*****(04)**, 270–278 (2016a).
6. V. Davis, IJCS, 1(2), **28-39** (2023).
7. L. Suranny, E. Gravitiani, M. Rahardjo, IOP Conf. Ser.: Earth Environ. Sci., **1**(1016), 012038 (2022).
8. A. Mirzabaev, **477-495** (2017).
9. J. Bellvert, K. Adeline, S. Baram, L. Pierce, B. Sanden, D. Smart, Remote *Sens.*, ***10***, 2001 (2018).
10. N. Rajan, S. Maas, ARS, **03(03)**, 197-207.
11. D. Jensen, D. Ramirez. Biom. J., **5(35)**, 615-625 (2014).
12. D. Aprialdi, M. Haiban, B. Pradhan **10(11)**, 1972 (2019).
13. S. Martins, M. Santos, J. Souza, G. Lyra, I. Teodoro, F. Ferreira, R. Souza, Water Resource Manage, **12(36)**, 4557-4574 (2022).
14. V. Silva, C. Borges, C. Farias, V. Singh, W. Albuquerque, B. Silva, AS, **02(03),** 274-286 (2012).
15. W. Silva, J. Santana, C. Silva, A. Nunes, Eng. Agríc., **5(37)**, 953-960 (2017).
16. R. Asnawi, R. W. Arief, Slameto, R. D. Tambunan, M. J. Martias, Mejaya, and Fitriani, *Annu. Res. & Rev. in Bio*. **42–52** (2021).
17. D. Susilastuti, A. Aditiameri, and U. Buchori, JAS. *1*(1), **1–8** (2018).
18. Y. Taufig, H. Oue, N Ichwan, and U. Augustine. IOP Conf. Series: Earth and Env. Sci. **1182** (2023)
19. M. Sakai, M. Okamoto, K. Tamura, R. Kaji, R. Mizobuchi, H. Hirabayashi, T. Yagi, M. Nishimura and Fukaura. Bull. NARO Kyushu Okinawa Agric. Res. Cent. **54** 43–61 (2010).
20. International symposium on water management in rice fields Japan, August **26-31**, 1975
21. H. L. Penman, M. Ryle, D. D. Vonberg, and L. B. H. Penman. Soc. A, 190, 357. Nyquist, H. I928 Phys. Rev. 32, 110. Pawsey. In *J. Franklin Inst* (Vol. 193, Issue 1032) (1948).
22. Y. Cui, S. Jiang, P. Feng, J. Jin, H. Yuan, water, **9(10)**, 1208 (2018).
23. M. Abedinpour, Soil & Water Res., **2(10)**, 99-104 (2015).

24. O. Raphael, K. Ogedengbe, J. Fasinmirin, D. Okunade, I. Akande, A. Gbadamosi, Agri. Wat. Mgt, (**203**), 179-185 (2018).
25. M. Tahashildar, P. Bora, L. Ray, D. Thakuria, Ind. Jour. of Dryl. Agri. Rese. and Deve., 1(**30**), 15 (2015).
26. R. G. Allen, & L. S. Pereira, Jou. of Hydro. (1998).
27. Abhijit Sarma and Krishna Bharadwaj. Jou. of Agro. **22** (2): 172-178 (June 2020)
28. B.D.A Nugroho, C. Arif, F. Suryandika, U. Hapsari, B. Nihayah, and Muslihin. IOP Conference Series: Eth. and Env. Sci., **1038(1)** (2022).
29. D. Qi, Q. Wu, J. Zhu, Sci Rep, **1(10)** (2020).
30. Oo, A., Sudo, S., Inubushi, K., Chellappan, U., Yamamoto, A., Ono, K and R. Venkatachalam, Agro.**10(8)**, 202 (2018).
31. A. Darzi-Naftchali, H. Ritzema, Sus., **6(10)**, 1775 (2018).
32. J. L. Hatfield, and C. Dold. *Fro. in plt. Sci.*, **10**, 103 (2019).
33. L. J. Briggs and H. L. Shantz. **282–285** (1913).
34. B. Basso and J. T. Ritchie. Agri. & Envi. Ltr., **3(1)**, 170039 (2018).
35. S. R. Hardwick, R. Toumi, M. Pfeifer, E. C. Turner, R. Nilus, R. M. Ewers. Agric. and Fors. Met. (**201**), 187-195 (2015).
36. C. Wahren, M. Walker, M. S. Bret-Harte. Global Change Biol, **4(11)**, 537-552 (2005).
37. A. B. Abdullah, S. Ito. & Adhana, K. (2006)
38. S. Marju Ben Sayed, M. Senge, Volume 8, Pages 199-215 (2020).
39. A. Chapagain. Re-Thinking Water and Food Security, 219-250 (2010).
40. B. Bouman, RiceToday. *How much water does rice use*? (2009)
41. OECD. "Oecd-fao agricultural outlook", OECD Agriculture Statistics, 2012.
42. N. Tyagi, D. K. Sharma and S. K. Luthra. Agri. Wat. Mgt., **45**(1), 41-54 (2000).
43. M. Kadiyala, R. Mylavarapu, Y. Li, G. Reddy, & M. Reddy, Agro. Jou, vol. **104**, no**. 6**, p. 1757-1765, (2012).
44. H. Ahmadpari, S. E. Hashemi Garmdareh and K. Ghalehkohneh. Nivar, **41**(98-99), 13-22 (2017).
45. C. C. and A. Quiñones. vol. **25**, no. 9, p. 583-590, 2021.
46. M. Lage, A. Bamouh, M. Karrou, & M. Mourid, vol. **23**, no. 7, p. 625-631, 2003.
47. J. Doorenbos and W. O. Pruitt. Crp. Wat. Req. FAO Irri. and Dr. Paper 24, FAO, Rome, 144 p (1977)
48. P. Lafleur and W. Rouse, Agri. and For. Met., vol. **49**, no. 2, p. 135-153, 1990.
49. S. Yoshida. (IRRI) 1981
50. C. Arif, S. Saptomo, B. Setiawan, M. Taufik, W. Suwarno, & M. Mizoguchi, Water, vol. **14**, no. 2, p. 170, 2022.
51. T. Horie, Proceedings of the Japan Academy, Series B, vol. **95**, no. 6, p. 211-245, 2019.
52. R. Caruso, I. Petrarca, & R. Ricciuti, Jou. of Peace Res., vol. **53**, no. 1, p. 66-83, 2016.
53. I. Ghiat, H. Mackey, & T. Al-Ansari, Water, vol. **13**, no. 18, p. 2523, 2021.
54. L. Pereira, R. Allen, M. Smith, & D. Raes, Agri. Wat. Mgt, vol. **147**, p. 4-20, 2015.
55. S. Kumar and N. Thavaprakaash, Jour. of App. and Nat. Sci., vol. **13**, no. SI, p. 9-17, 2021.

56. C. Song, M. Yin, X. Zheng, S. Liu, G. Chu, C. Xuet al., Agro. Jou, vol. **111**, no. 3, p. 1229-1238, 2019.
57. G. Tian, L. Gao, Y. Kong, X. Hu, K. Xie, R. Zhanget al., Plos One, vol. **12**, no. 8, p. e0182310, 2017.
58. A. Thakur, S. Rath, S. Roychowdhury, & N. Uphoff, Jou. of Agro. and Crop Sci., vol. **196**, no. 2, p. 146-159, 2010.
59. Li, X. P., Wang, S., Huang, Y. C., Jia, B. Y., Wang, Y., & Zeng, Q. Y. The jou. of app. Eco., **26**(11), 3329–3336. 2015
60. P. Eberbach and M. Pala, Plant and Soil, vol. 268, no. 1, p. 195-208, 2005.
61. O. Purwanto, Y. Pujiharti, and Ramadhan, Planta Tropika, vol. **11**, no. 1, p. 50-60, 2023.
62. Hayashi, Satoshi & Kamoshita, Akihiko & Yamagishi, Junko. Plt. Pro. Sci. - PLANT PROD SCI. **9**. 298-311. 10.1626/pps.9.298. 2006
63. Y. San-oh, R. Oclarit, T. Ookawa, T. Motobayashi, & T. Hirasawa, Plt. Pro. Sci., vol. **9**, no. 3, p. 334-342, 2006.
64. G. Zhang, B. Ming, D. Shen, J. Xue, K. Wang, & S. Li, Agr., vol. **11**, no. 4, p. 313, 2021.
65. LI Hongqiao, LAI Ying, MU Na, YAN Hongmei, TANG Weiqun, JIANG Xiaoling, GAO Wen, WU Yongcheng, 34(3): 419-427 (2022).
66. O. Purwanto, F. Palobo, & S. Tirajoh, SVU-Intl. Jou. of Agri. Sci., vol**. 2**, no. 2, p. 242-255, 2020.
67. C. Rim, KSCE Jou. of Civ. Eng., vol. **4**, no. 1, p. 47-52, 2000.
68. N. Nova, J. Miranda, A. Pereira, & K. Silva, vol. **26**, no. 3, p. 713-721, 2006.
69. A. Pereira, N. Nova, L. Pires, L. Angelocci, & G. Beruski, Met. App., vol. **21**, no. 2, p. 369-375, 2012.
70. M. Saifullah, B. Islam, S. Rehman, M. Shoaib, E. Haq, S. Gillaniet al., Int.l Journal of Agri. and Amp; Sust. Dev., vol. **01**, no. 01, 2019.
71. K. Kumar and P. Rakhecha, Theo. and App. Cli., vol. **38**, no. 3, p. 140-146, 1987.
72. S. Ohta and A. Kimura, Jou. of Agri.l Met., vol. **65**, no. 2, p. 167-178, 2009.
73. T. Suzuki, T. Ohta, Y. Izumi, L. Kanyomeka, O. Mwandemele, J. Sakagamiet al., Plt. Prod. Sci., vol. **16,** no. 1, p. 12-23, 2013.
74. M. Seizo, I. Hisashi, M. Akio, H. Susumu and N. Hikarugr.) J.Agr.Met. 26(3):149-156 1982.
75. W. Zheng, Y. Liu, D. Xu, & J. Cai, App. Mech. and Mat., vol. **539**, p. 832-837, 2014.