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Article

Impact of Water Management on Rice Varieties, Yield, and Water Productivity under the System of Rice Intensification in Southern Taiwan

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Abstract: The system of rice intensification (SRI) uses less water and enhances rice yield through synergy among several agronomic management practices. This claim was investigated to determine the effects of crop growth, yield and irrigation water use, using two thirds of the recommended SRI practices and two rice varieties, namely Tainan11 (TN11) and Tidung30 (TD30). Irrigation regimes were (a) intermittent irrigation with three-day intervals ($TD30_3$ and $TN11_3$); (b) intermittent irrigation with seven-day intervals ($TD30_7$ and $TN11_7$) and (c) continuous flooding ($TD30_F$ and $TN11_F$). Results showed that intermittent irrigation of three- and seven-day intervals produced water savings of 55% and 74% compared with continuous flooding. Total water productivity was greater with intermittent irrigation at seven-day intervals producing 0.35 kg·grain/m^3 ($TN11_7$) and 0.46 kg·grain/m^3 ($TD30_7$). Average daily headed panicle reduced by 166% and 196% for $TN11_3$ and $TN11_7$ compared with $TN11_F$, with similar reduction recorded for $TD30_3$ (150%) and $TD30_7$ (156%) compared with $TD30_F$. Grain yield of TD30 was comparable among irrigation regimes; however, it reduced by 30.29% in $TN11_7$ compared to $TN11_F$. Plant height and leaf area were greater in plants exposed to intermittent irrigation of three-day intervals.

Keywords: system of rice intensification; intermittent irrigation; total water productivity

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1. Introduction

Rice (*Oriza stiva* L.) is a major staple food for much of the world's population and the largest consumer of water in the agricultural sector [1]. World food security remains largely dependent on irrigated lowland rice, which is the main source of rice supply [2]. Fresh water for irrigation is becoming scarce because of population growth, increasing urban and industrial development, and the decreasing availability resulting from pollution and resource depletion [3–5]. Asia contributes more than 90% of the world's total rice production while using more than 90% of the total irrigation water [6]. It is estimated that by 2025, 15 million of Asia's 130 million hectares of irrigated rice area may experience "physical water scarcity" and approximately 22 million hectares of irrigated dry-season rice may suffer "economic water scarcity" [7].

Rice is a very important and valuable crop to Taiwan's economy. It yields more than 1.73 million tonnes from 271,077 hectares of land for a production value of NT$41.48 billion (about US$1.37 billion) in 2014 [8]. However, Taiwan is plagued with water scarcity problems as fresh water for irrigation is limiting rice production. Rapid urbanization and industrialization along with high irrigation water consumption from the agriculture sector (80%) have been major contributing factors [9]; furthermore, this situation is exacerbated by climate change. In 2014, rice production was compromised as a consequence of extended drought, forcing the Ministry of Economic Affairs (MOEA) to implement water rationing measures by fallowing approximately five percent of Taiwan's cultivated land [10]. Agricultural water productivity directly affects crop productivity; therefore, various water saving techniques and methods have been developed for rice producers to minimize water demand and maintain acceptable yield [11].

Pascual and Wang [11] and Kima et al. [12] evaluated several water depths for obtaining high water productivity in irrigated lowland rice using alternate wetting and drying technique (AWD). Results obtained showed that adequate yield and water savings could be achieved but at the expense of plant water stress at active tillering and panicle initiation growth stages. The challenge for sustainable rice production is to decrease the amount of water used while maintaining or increasing grain yields to meet the demands of an ever-growing population by increasing water use efficiency [2]. A common finding has been that irrigation can be reduced without lowering grain yield [13]. However, with conventional irrigated flooded rice production systems promoted by rice scientists at various research organizations, it has not been possible to obtain attractive increases in output that would provide farmers with the incentive to reduce their irrigation rates [1].

The system of rice intensification (SRI) could potentially become an approach for increasing rice production with reduced water demand, thus improving both water use efficiency and water productivity [14–16]. SRI was developed in Madagascar and is now spreading to most Asian countries, and more recently in several African and Latin American countries [1]. However, the serious labor constraints have made SRI appear less feasible in Taiwan than in some other countries [17]. The first SRI trials in Taiwan began in 2008, but there has not been much systematic study of SRI done since then [18]. While considerable evidence regarding the relevance of SRI to pro-poor development has become available, its scientific foundations have not yet been adequately pursued [19]. SRI offers the opportunity to improve food security through increased rice productivity by changing the management of plants, soil water and nutrients while reducing external inputs like fertilizes and herbicides [20,21]. The system proposes the use of a very young single seedling, wider planting space, intermittent wetting and drying, use of a mechanical weeder for soil aeration and enhanced soil organic matter [22]. However, not all these specific practices are always identified as essential [23]. For example, the use of compost is usually identified as a desirable but optional practice [24] even though, the importance of organic fertilizer for improving the chemical, physical and biological properties of the soil is heavily stressed [25]. Associated practices and refinements that are often mentioned include careful handling and quick transplanting of seedlings, in order to avoid causing trauma to the young plants, and the use of mechanical rotary weeder to control weeds while also aerating the soil [14].

SRI practices deviate from the green revolution standards that intend to increase grain yields by improving genetic potentials of crops, making them more responsive to chemical inputs, and/or by increasing the use of external inputs [4,23]. Research conducted by [14,26,27] among others confirmed high yields under SRI, and in some cases even yield increase of 50%–100% while reducing irrigation water use by 25% and 50% or more [27]. However, criticism arose from [28,29] for the extraordinary high yields, effectiveness of SRI practices and the experimental procedures. Dobermann [28] explained that SRI is an example for the first approach, which may make it more suitable for niches such as the management of previously poor systems on mostly marginal land, provided that cheap labor is available. Likewise, Moser and Barrett [30] noted that studies in Madagascar showed slowed adoption and high disadoptaion rates, mainly because the method requires additional knowledge and labor input at times of labor shortage or greater other opportunities for investment. Chapagain et al. [4] conducted a crop budget analysis for SRI versus conventional rice farming using organic and inorganic management. They concluded that labor input required in SRI-organic plots was double (90 man day/hm^2) than in conventional-inorganic plots (45 man day/hm^2), and was primarily affected by the weed requirement of (50 man day/hm^2). Similar observations were made Rakotomalala [31] who reported that SRI required approximately 38%–54% more labor than conventional methods, with 62% of the extra labor needed for weed control, while 17% was required for transplanting. However in

Madagascar, a comparison over five years found that SRI was labor saving by year four compared to years one to three [32]. Nonetheless, SRI advocates argue that the system should be regarded as a suite of flexible principles rather than a fixed technological package [14,33]. Despite the challenges encountered in SRI, and even though failed trials exist, it is important to note that SRI is still a "work in progress "and should be adopted to local conditions and traditions". Thakur et al. [1] explained that little research has been done to quantify the impact of different degrees of AWD on grain yield and on water savings in rice, and even less research has considered the effects of making concurrent changes in crop management practices.

Farmers should be enabled to enhance their rice production while improving their soil and environmental quality, making fewer demands on their limited fresh water supplies. The limited SRI trials conducted in Taiwan confirms that high potential grain yield can be obtained during the first cropping season (January–February with harvest in May–June during the dry season). During this time there is high labor productivity, capital, and irrigation water productivity. On the contrary, crops grown during the second season (July–August to October during the rainy season), are exposed greater incidence of pest damages, diseases and weeds. Moreover, flooding creates more risk of yield losses, and narrows the range for exploiting the potential labor, capital, and irrigation water productivity gains of SRI [18]. Against this backdrop, the present study was conducted using two thirds of the aforementioned SRI practices during dry season as there is still limited knowledge about rice adaptation, growth and water saving at this time. Understanding the effects of different irrigation regimes on root growth and rice plant physiology is critical to raise both water and rice crop productivity especially when some SRI attributes for rice cultivation is used under continuous flooding. Therefore, the objective of this research was to assess water productivity, crop growth (above and below ground) and yield components of the two rice varieties using SRI management practices under different irrigation regimes.

2. Materials and Methods

2.1. Trial Design and Experimental Area

The research was conducted from January to June 2016 at the National Pingtung University of Science and Technology irrigation research and education field in the southern Taiwan. The experimental site is located at 34.95° (E) longitude and 22.39° (N) latitude at 71 m above sea level. The experiment was laid out in a complete randomized block design consisting of four replications and two rice varieties Tainan11 (TN11) and Tidung30 (TD30). Experimental plots were 6 m^2 and 0.3 m soil bed heights with spacing of 1 m between blocks and plots. The irrigation regimes evaluated were (a) continuous flooding (CF) represented as ($TN11_{CF}$ and $TD30_{CF}$); (b) intermittent irrigation at 3-day interval ($TN11_3$ and $TD30_3$) and (c) intermittent irrigation at 7-day interval ($TN11_7$ and $TD30_7$). Ponded water depths of 3–6 cm were applied for the first 5 days after transplanting in intermittent irrigation regimes thereafter successive irrigation of 3- and 7-day intervals followed until one week before harvest. Under CF regime, 4–7 cm ponded water depth was applied immediately after transplanting for the same duration. To minimize seepage from flooded plots, bunds were covered with plastic films which were installed at 50 cm depth below the soil surface. In order to reach 6 cm ponded water depth, the applied water volume was obtained using the following equation [34]:

$$IR = Axhx10^3 \tag{1}$$

where IR is the amount of irrigation water (L) at a specific depth above the soil surface, A is the surface area of the plot (m^2), and h is the specific water depth above the soil surface (m). The amount of irrigation water applied for CF was measured with a flow meter installed in the irrigation pipelines. The soil was characterized as loamy with a field capacity of 30.5% volume; wilting point of 15% volume; bulk density of 1.40 g/cm^3; saturation 42.9% volume; hydraulic conductivity at 55 mm/h; and matric potential 11.09 bar.

2.2. Crop Management

The SRI practices employed in this research comprised particularly of 2/3 of the aforementioned practices. All treatments in this research were planted using young seedlings (15 days old), using wide spacing (25 cm between rows and 25 cm between hills), and using one seedling per hill. Weed control was done manually using a hand rake cultivator with 20 cm spikes. It is widely known that SRI recommendation is for organic in preference to chemical fertilization however, in this research, fertilizer application was standard across all plots. Therefore, fertilization practices were not a variable in the evaluation. Fertilizer ($N{:}P_2O_5{:}K_2O$) with a ratio of 12:18:12, was applied at 270 kg/ha at basal, mid-tillering and panicle initiation. Pests were controlled by using pesticides only when and where needed with the necessary amount for control of the specific pest.

2.3. Soil Moisture

Soil moisture content was measured every 3 and 7 days before irrigation. This was done from six weeks after transplanting to one week before harvest using the gravimetric method, whilst it was measured every 7 days for CF regime for the same duration. Soil samples were collected at 20 cm depth from three different locations in each plot using an auger thereafter, it was weighed and the dry weight was obtained after oven drying at 105 °C for 24 h.

The soil moisture content per unit volume was calculated using the following equation [12]:

$$SW = \frac{100\ x\ (fresh\ weight - dry\ weight)\ x\ \gamma_s}{Dry\ weight} \tag{2}$$

where SW is the soil water content (cm) soil depth and γ_s is the soil bulk density (g/cm^3). The soil water trend was analyzed by defining the moisture content at saturation level, field capacity, wilting point, and stress threshold using Equations (3)–(6) derives from [35].

$$SW_{Sat} = 1000\ (Sat)\ x\ Z_r \tag{3}$$

$$SW_{FC} = 1000\ (FC)\ x\ Z_r \tag{4}$$

$$SW_{WP} = 1000\ (WP)\ x\ Z_r \tag{5}$$

$$SW_{ST} = 1000\ (1-P)Sat\ x\ Z_r \tag{6}$$

where SW_{Sat}, SW_{FC}, SW_{WP} and SW_{ST} are soil water content (mm) at saturation, field capacity, wilting point, and stress threshold level, respectively. Sat, FC, and WP are the soil water content at saturation, field capacity and wilting point, respectively in percentage of volume. P is the fraction of water that can be depleted before moisture stress occurs and represent 20% of the saturation for rice crop; Z_r is the sample collection depth (m).

2.4. Assessment of Agronomic Parameters

2.4.1. Plant Height, Tiller Numbers and Chlorophyll

Measurements for plant height, tiller numbers, and chlorophyll were recorded at panicle initiation and heading stage. Twenty (20) hills were randomly selected from throughout the diagonals and median for evaluation of plant height and tiller numbers. Plant height was measured from the base to the tip of the highest leaf and tillers were individually counted. The 20 uppermost fully expanded leaves were selected from the randomly selected hills with three observations made per leaf for chlorophyll content analysis among treatments. Analysis of leaves sampling patterns done by [36,37] showed that at least four leaves per plot are needed, with several observations per leaf. Then, the average of these observations was used to represent the leaf chlorophyll content. A chlorophyll meter (model SPAD-502, MINOLTA, Osaka, Japan) was used to determine leaf chlorophyll content.

2.4.2. Leaf Area

Data for leaf area and leaf area index (*LAI*) was collected from the 20 sampled hills at heading and calculated following the methods of [38,39].

$$Leaf\ area\ \left(cm^2\right) = L\ x\ W\ x\ K \tag{7}$$

where, L is leaf length; W is maximum width of the leaf and K is a correction factor of 0.75.

Leaf Area Index (*LAI*):

$$LAI = \frac{sum\ of\ the\ leaf\ area\ of\ all\ leaves}{ground\ area\ of\ field\ where\ the\ leaves\ have\ been\ collected} \tag{8}$$

2.4.3. Root Parameters

Five (5) hills from each replicate were randomly selected for root assessment at panicle initiation. This was done using an auger 10 cm diameter to remove soil of 20 cm depth from selected hills. A uniform soil volume of 1570 cm^3 was excavated to collect root samples for all treatment. Roots were washed and removed from uprooted plants. Root volume was measured by water displacement method by putting all the roots in a measuring cylinder and getting the displaced water volume [40]. Root depth was obtained by direct manual measurements of top root using a ruler against a millimeter paper. Roots dry biomass per hill was obtained after oven drying at 70 °C for 24 h.

2.4.4. Heading Rate and Yield Components

The heading rate was analyzed in each plot from the appearance of the first headed panicle until 25 days after emergence. At harvest (7 June) yield components (panicle length, panicle number per hill, panicle weight, grain number per panicle, grain weight per panicle and filed grain per panicle) were obtained from the 20 sampled hills. Panicle length and number of grains per panicle were determined according the methods of [12]. The grain weight per panicle was obtained at a constant weight after oven drying at 70 °C for 72 h. The filled spikelets were separated from the unfilled spikelets using a 2 mm seed blower, and the percentage of filled grain was calculated, mass basis as the ratio of filled grains weight to the total grains weight per panicle multiplied by 100. All remaining plants in the 6 m^2 area were harvested from each plot for grain yield determination per unit area (t/ha^{-1}). Three samples of harvested grains were randomly taken from each replicate and the dry weight was obtained after oven drying at 70 °C for 72 h; thereafter the grain yield was adjusted to 14% seed moisture content. Five samples of 1000 grains were randomly selected from the harvested grains in each replicate for 1000-grain weight determination.

2.5. Water Productivity Assessment

The total water productivity (TWP) and irrigation water productivity (IWP) are the total water (rain + irrigation), and irrigation water respectively. It was calculated as grain yield divided by total water supplied in the plot, and was expressed in kg/m^3 [41]. Water saving was obtained with reference to the irrigation water and calculated as the difference in irrigation under the two irrigation regimes divided by the irrigation water applied under the CF regime.

2.6. Statistical Analysis

The data was subjected to statistical analysis of variance using SPSS 22 software (IBM, Armonk, NY, USA). The significance of treatment effect was determined using F-test while means were separated through Tukey's test at 0.05.

3. Results

3.1. Agro-Hydrological Conditions and Production Environment

The summary for the climatic data presented in Table 1 was recorded at the National Pingtung University of Science and Technology agro-meteorological station during the crop cycle. The lowest mean minimum temperature was recorded in February (14.1 °C), whereas the highest mean maximum temperature was in the month of May (33.0 °C). Maximum solar radiation (h) was recorded in the month of May while April produced the highest total monthly rainfall.

Table 1. Temperature, rainfall and sunshine hours during the crop cycle.

Months	**Temperature (°C)**		**Rainfall (mm)**	**Solar Rad (h)**
	Mean Maximum	**Mean Minimum**	**Total Monthly**	
January	23.5	14.8	141	125.7
February	24.2	14.1	4.50	158.3
March	26.0	16.3	58.5	160.4
April	31.4	21.3	271	216.6
May	33.0	23.3	97	218.2
June	31.2	21.7	0	55.6

The soil moisture analysis was done according to the soil stress threshold which is defined as the critical line Figure 1. At 20 cm depths the values for SW_{Sat}, SW_{FC}, SW_{WP} and SW_{ST} were 85.8, 61, 30, and 68.6 respectively. Soil moisture during the crop cycle was always above the soil stress threshold level. As a result, crops were able to avoid soil moisture stress during the critical stages such as anthesis and grain filling. Thakur et al. [1] explained that the frequency of alternate wet and dry periods may cause variation in grain yield; however, practicing safe alternate wet and dry irrigation should reduce farmer's water demand by a small to considerable amount without imposing any yield penalty.

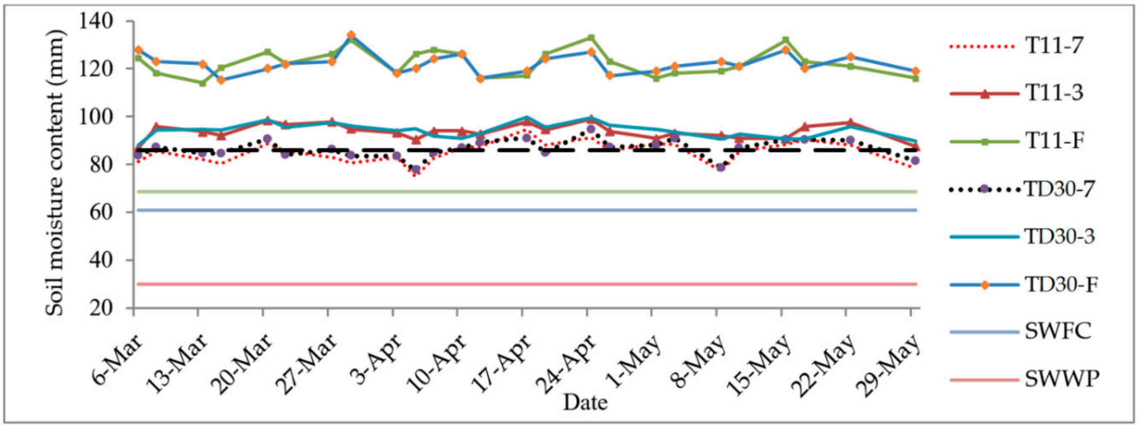

Figure 1. Soil moisture content in different irrigation regimes during the crop production cycle.

Low soil moisture was recorded for intermittent irrigation of seven-day interval in early April and May, prior to the heavy rainfalls. The low values for April were 74.9 ($TN11_7$), and 77.6 ($TD30_7$) whereas in May it was 77.1 ($TN11_7$), and 78.6 ($TD30_7$).

3.2. Interaction of Crop Variety under Irrigation Regimes

3.2.1. Rice Growth

Irrigation regime significantly affected average plant height, tiller numbers per hill and LAI (Table 2). Plants were taller at panicle initiation and heading under intermittent irrigation of three-day intervals. Inter-varietal comparison at panicle initiation showed that plant height decreased by 20.04% and 12.12% in TN11$_7$ and TN11$_F$ when compared with TN11$_3$. It decreased by 19.20% and 9.27% in TD30$_7$ and TD30$_F$ compared with TD30$_3$. At heading, plant height decreased by 10.93% (TN11$_7$) and 13.63% (TN11$_F$) compared with TN11$_3$, and 12.55% (TD30$_7$) and 14.79% (TD30$_F$) when compared with TD30$_3$. Inter-varietal comparison showed that TN11$_F$ produced the least number of tillers at panicle initiation and heading stage; however, no significant differences were observed for the TD30 variety. LAI was highest under intermittent irrigation of three-day intervals 2.69 (TD30$_3$) and lowest under CF irrigation 2.16 (TN11$_F$) with no significant difference observed for irrigation intervals of three and seven days.

Table 2. Effect of irrigation regimes on plant height, tiller numbers and leaf area.

	Panicle Initiation		**Heading**		**Heading**
Treatments	**Plant Height (cm)**	**Tiller Numbers (Hill)**	**Plant Height (cm)**	**Tillers Number (Hill)**	**Leaf Area Index**
TN11$_3$	78.15^{ab}	14.40^{ab}	107.27^{a}	18.45^{ab}	2.55^{a}
TN11$_7$	65.10^{d}	15.35^{a}	96.70^{b}	20.75^{a}	2.41^{ab}
TN11$_F$	69.70^{cd}	11.10^{b}	94.40^{b}	16.02^{b}	2.16^{c}
TD30$_3$	78.75^{a}	13.55^{ab}	110.55^{a}	19.20^{ab}	2.69^{a}
TD30$_7$	66.05^{d}	13.20^{ab}	98.22^{b}	20.05^{a}	2.38^{ab}
TD30$_F$	72.15^{bc}	12.65^{ab}	96.30^{b}	17.21^{ab}	2.23^{bc}
p	**	**	**	**	**

Notes: ** Means with columns not followed by the same letter are significantly different at $p < 0.05$ level by Tukey's test.

3.2.2. Chlorophyll

Leaf chlorophyll content varied according to irrigation regimes and growth stages (Figure 2). At panicle initiation, the SPAD values for chlorophyll content was similar among irrigation regimes; however, inter-varietal comparison showed that TD30$_F$ were significantly lower compared with TD30$_3$ and TD30$_7$ (see Figure 2a). At heading the SPAD values for leaf chlorophyll content was lowest under CF irrigation for both varieties whereas statistically comparable results were observed for intermittent irrigation of three- and seven-day intervals (TN11 variety) (see Figure 2b). Inter-varietal comparison showed that chlorophyll decreased by 10.98% in TN11$_F$ compared with TN11$_3$, while similar results were produced for the TD30 variety.

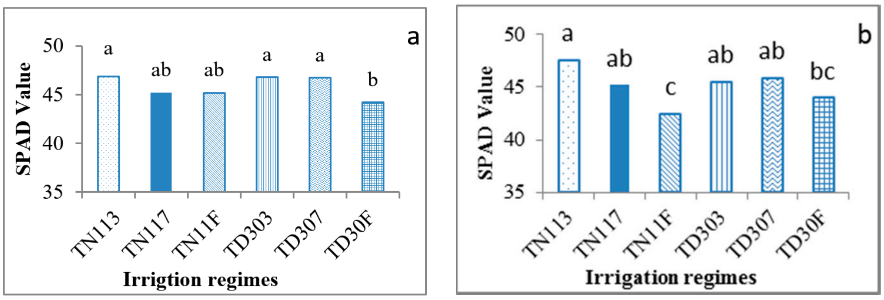

Figure 2. Effects of irrigation regime on chlorophyll content: (**a**) panicle initiation (**b**) heading.

3.2.3. Roots Parameters

Plants grown under intermittent irrigation of three-day intervals produced the longest roots and highest root volume Table 3. Root lengths were statistically shorter and reduced by 9.70% (TD30$_7$) and 23.84% (TD30$_F$) compared with TD30$_3$, similarly TN11$_7$ and TN11$_F$ was 12.26% and 28.16% shorter than TN11$_3$. Lowest root volume was produced under CF irrigation; however, comparable results were observed for TN11 variety. No significant difference was observed among irrigation regimes for root dry biomass per hill; nonetheless, roots were heavier under intermittent irrigation of three-day intervals.

Table 3. Effect on irrigation regimes on root parameters.

Treatments	Length (cm)	Volume (cm^3)	Root Dry Biomass (g/Hill)
TN11$_3$	23.25 ^{ab}	52.50 ^{ab}	23.03
TN11$_7$	20.71 ^{b}	42.01 ^{ab}	22.71
TN11$_F$	18.14 ^{b}	38.37 ^{b}	18.31
TD30$_3$	24.31 ^{a}	56.51 ^{a}	24.31
TD30$_7$	22.16 ^{b}	47.01 ^{ab}	23.51
TD30$_F$	19.63 ^{b}	40.83 ^{b}	20.65
p	**	**	*ns*

Notes: ** Mean with columns not followed by the same letter are significantly different at $p < 0.05$ level by Tukey's test; *ns* not significantly different at $p < 0.05$ level by Tukey's test.

3.2.4. Yield and Yield Components

Panicle emergence appeared first under CF regime Figure 3. Emergence occurred six days later for intermittent irrigation of three-day interval and 10 days later in crop under intermittent irrigation of seven-day intervals. Under CF regimes, significantly higher numbers of panicle per meter square were observed for both varieties at this particular stage. No significant difference was observed for plants subjected to irrigation intervals of three and seven days. Average daily headed panicle was reduced by 165.64% and 195.58% for TN11$_3$ and TN11$_7$ compared with TN11$_F$, likewise a reduction of 149.50% and 155.63% was recorded for TD30$_3$ and TD30$_7$ when compared to TD30$_F$.

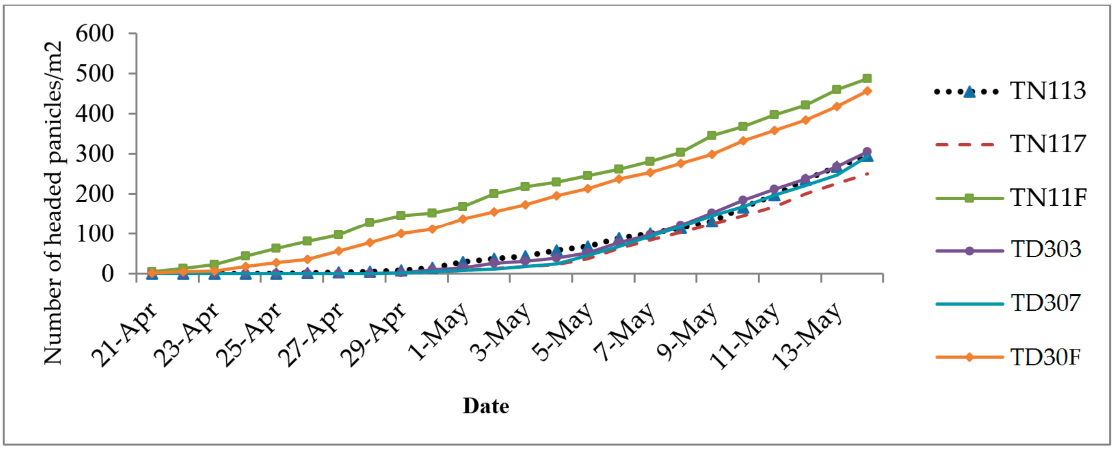

Figure 3. Daily headed panicle number produced by different irrigation regimes.

Yield components such as average panicle weight, grain number per panicle, 1000 grains weight and fill grains percentage were usually higher for both varieties grown under CF regimes Table 4. Average panicle weight decreased by 72% and 86% in TN11$_3$ and TN11$_7$ when compared with TN11$_F$, similarly it decreased by 50% and 56% in TD30$_3$ and TD30$_7$ compared with TD30$_F$. Inter-varietal comparison showed that average panicle weight was similar for irrigation intervals of three and seven days; however, TN11 variety produced significantly lower panicle weight compared to TD30 variety under similar irrigation regime. Grain numbers per panicle yielded similar for TN11 variety, with significant differences observed between TD30$_F$ and TD30$_7$. One thousand grain weight and fill grain percentage were greater under CF regimes. No significant difference observed for 1000 grain weight in inter-varietal comparison for intermittent irrigation of three- and seven-day intervals. Grain yield reduced by 30.29% in TN11$_7$ compared to TN11$_F$; however, grain yield was comparable in TD30 variety.

Table 4. Effects on irrigation regimes on yield and yield components.

Treatments	**Average Panicle Number per Hill**	**Average Panicle Length (cm)**	**Average Panicle Weight (g)**	**Grain Number per Panicle**	**1000 Grain Weight (g)**	**Grain Filling Rate (%)**	**Grain Yield (ton/ha)**
TN11$_3$	16.72	20.78	1.96 ^{c}	120.25 ^{b}	22.04 ^{cb}	81.14 ^{b}	8.04 ^{bc}
TN11$_7$	15.87	20.65	1.81 ^{c}	117.55 ^{b}	21.08 ^{c}	70.48 ^{c}	7.46 ^{c}
TN11$_F$	14.29	21.87	3.37 ^{a}	130.90 ^{ab}	26.67 ^{a}	84.71 ^{a}	9.72 ^{ab}
TD30$_3$	18.42	20.53	2.46 ^{b}	121.13 ^{ab}	24.29 ^{b}	82.89 ^{ab}	10.26 ^{a}
TD30$_7$	18.30	21.25	2.30 ^{b}	116.88 ^{b}	23.29 ^{b}	77.20 ^{bc}	9.83 ^{ab}
TD30$_F$	14.55	21.67	3.59 ^{a}	138.25 ^{a}	26.61 ^{a}	86.42 ^{a}	10.46 ^{a}
p	*ns*	*ns*	**	**	**	**	**

Notes: ** Mean with columns not followed by the same letter are significantly different at $p < 0.05$ level by Tukey's test. *ns* not significantly different at $p < 0.05$ level by Tukey's test.

3.2.5. Water Productivity

The percentage of rainfall contribution towards the total irrigation water was 22% for intermittent irrigation of three-day intervals, 36% for intermittent irrigation of seven-day intervals and 10% for CF. Crops were almost exclusively grown under irrigation throughout the early growth stages; however, rainfall was more frequent towards the end of April and coincided with the heading stage. Continuous flooded irrigation consumed the largest quantity of water during the crop cycle Table 5. Intermittent irrigation of three-day intervals produced water saving of 55% whereas intermittent irrigation of seven-day interval produced water saving of 74% compared with CF. Irrigation water productivity (IWP) and total water productivity (TWP) were greater under intermittent irrigations. At seven days intermittent irrigation, IWP was 0.48 (TN11$_7$) and 0.63 (TD30$_7$) likewise, TWP was 0.35 kg·grain/m^3 (TN11$_7$) and 0.46 kg·grain/m^3 (TD30$_7$). Overall, varietal differences showed consistency when comparing the same irrigation regimes with TD30 producing a higher IWP and TWP than TN11.

Table 5. Effects of irrigation regimes on water productivity.

Treatments	**Irrigation Water (m^3/ha)**	**Rain Water (m^3/ha)**	**Irrigation Water Productivity (kg/m^3)**	**Total Water Productivity (kg/m^3)**
TN11$_3$	26,400	5720	0.30	0.25
TN11$_7$	15,600	5720	0.48	0.35
TN11$_F$	59,300	5720	0.16	0.15
TD30$_3$	26,400	5720	0.39	0.32
TD30$_7$	15,600	5720	0.63	0.46
TD30$_F$	59,300	5720	0.18	0.16

4. Discussion

The system of rice intensification aims to make irrigated rice cultivation more sustainable and profitable, as it not only enhances grain yield and net income, but also saves considerable amounts of capital, seed, and most importantly water [21]. For generations, rice has been regarded as an aquatic plant; however, this belief has been repeatedly challenged, as rice is known to be capable of growing under both flooded and non-flooded conditions. Plants grown under intermittent irrigation of three-day intervals were significantly taller compared to the others at both panicle initiation and heading stages, whereas comparable results were observed between CF and intermittent irrigation intervals of seven days at heading. This continues to support the findings of [12,42,43] among others, who detailed that rice does not need to be continuously submerged to produce high yields if adequate water is provided at critical growth stages. The SRI practices employed enhanced plant growth and tillering ability to improve plant/culm height and strengthen tillers. The wet and dry cycles experienced under SRI enhances air exchange between soil and the atmosphere and may have contributed to more tiller numbers per hill at panicle initiation and heading under both three- and seven-days irrigation intervals. Singh et al. [44] explained that higher number of tillers recorded in SRI may be attributed to practices such as water management undertaken to maintain paddy soils mostly under aerobic conditions, active soil aeration through mechanical weeding and organic fertilization. During the wet and dry cycle enough oxygen is supplied to the root system to accelerate soil organic matter mineralization and inhibit soil N immobilization, all of which should increase soil fertility and produce more essential plant-available nutrients to favor rice growth [3,45,46]. Thakur et al. [5] also explained that tillering is directly linked to continuous root development (through adventitious roots), which remains active under AWD regime, while the roots under CF degenerate significantly.

Plants grown under intermittent irrigation of three-day intervals produced the highest leaf area. As it is casually known, leaf area index is caused by two main factors, namely, the increase in tiller numbers and leaf size. The total number of leaves and leaf size were greater in plants grown under intermittent irrigation compared with CF and may have contributed to the lower leaf area in plants grown under CF. SRI plants enhance water and nutrient uptake, resulting in greater leaf elongation rates which may have further contributed to larger leaf size. Such observations continue to reinforce the findings of [5], who noted that leaf number and size were significantly increased in SRI plants and produced higher LAI compared with those of CF. Similarly, Lin et al. [47] stated that intermittent irrigation promoted higher LAI compared with CF while [38] highlighted that continuous and prolonged flooding resulted in the lower leaf area index, crop growth rate, net assimilation rate and productive tillers.

Chlorophyll content in leaves was usually higher at panicle initiation and produced similar results under the same irrigation regime. At heading, it was lower and significantly different among irrigation regimes of TN11 variety. Chlorophyll content were lowest under CF regimes, indicating that leaf senescence occurred faster compared to plants grown under intermittent irrigation. Such observations were also documented by [42], who confirmed that higher levels of chlorophyll are maintained in the leaves while fluorescence efficiency and photosynthetic rate can be increased under AWD-SRI compared with CF. Thakur et al. [5] highlighted that SRI leaves had higher light utilization capacity and a greater photosynthetic rate which ensures sufficient supply of assimilates to the roots for their development and longevity. Bigger roots and greater root activity under AWD-SRI translates to increased root oxidation activity and root-sourced cytokinins [48], which are believe to play a major role in promoting cell division and thereby delaying leaf senescence [49,50].

Plants grown under CF and intermittent irrigation of seven-day intervals produced shorter roots with decreased root lengths of 9% to 29% compared with those of intermittent irrigation of three-day intervals. In addition, root volume was heaviest in plants grown under three-day intermittent irrigation intervals. Greater root volume and longer roots is regarded as an adoption measure for plants to maximize water capture and access water at grater depths [36,51]. Even though root dry biomass produced similar results, it was highest under intermittent irrigation of three-day interval, which could indicate a strong water and nutrient absorption capacity translating into high grain production. Roots of plants grown under CF regimes also showed higher proportion of decayed or nonfunctional parts compared with those under intermittent irrigation. Such observations were also highlighted by [52] and [5], who explained that continuous flooding caused the soil to become increasingly anaerobic with low redox potential causing adverse effects on root development and activity; moreover, plants grown under continually saturated or flooded soil produced a higher percentage of decayed root [4,5].

Irrigation regimes affected the daily headed panicles and showed that heading occurred at a faster rate in plants grown under CF irrigation. Heading rate for irrigation interval of three days and seven days were delayed by six days and 10 days respectively when compared with CF. Thus, phenological development appears to be very sensitive to water management. Similar observations were also made by [12,53,54], who elucidated that water management affects phenological development and may cause delays in anthesis, panicle initiation and heading; however, plants may recover if favorable conditions are restored. Despite the faster heading rate experienced in CF, at harvest panicle number per hill showed no significant difference among irrigation regimes. Recovery may be attributable to the adoption of osmotic adjustments made by plants grown under SRI as explained by [25,42], likewise, rainfall during the month of May was probably sufficient to full fill crop water requirement.

Yield components of panicle weight, grain number per panicle and 1000 grain weight were usually higher under CF regime even though not significantly different at times when making inter-varietal comparison. Nonetheless, lower yield components contributed to lower grain yield. The grain yield of TD30 showed no significant difference among irrigation regimes; however $TN11_F$ produced significantly higher grain yield than $TN11_7$, while comparable results were observed for $TN11_3$ and $TN11_F$. Therefore, it is safe to say that crop variety is a major contributing factor for SRI enhancement, thus additional research is required for farmers to obtain maximum benefits from this practice. Several authors cited higher yield under SRI and AWD indicating that difference in results compared with CF conditions may also be attributable to effects of crop management practices rather than water regime alone. Furthermore, SRI was only partially implemented in this research thereby creating uncertainties about the influence of adding soil organic matter for enhancement, or providing active soil aeration (to mobilize the effects of beneficial aerobic soil organisms), which may contribute to an increased yield over CF in absolute terms. Zhang et al. [43] also explained that reduced yields were also obtained under SRI management. Therefore, more rigorous and systematic research is needed to identify the potential advantages of SRI practices over those currently recommended [4]. Belder et al. [55] noted that under AWD, discrepancies for variation among research may be attributed to differences in soil hydrological conditions and timing of irrigation methods applied; moreover, [56] cited varietal difference may also be a contributing factor.

Plants cultivated under CF were exposed to SRI attributes, which may have boosted physiological performance leading to enhancement in yield components and high grain yield. For instance, under CF conditions [57], found that rice yield was higher when single seedlings per hill were transplanted compared with three seedlings per hill. The explanation in support was that single plants per hill had higher cytokinin concentration in their roots during the late reproductive stage compared with plants grown using three seedlings per hill. Therefore, high cytokinin concentration in the roots was associated with delayed senescence of the plant, which in turn may positively affect grain yield. In addition, wider spacing in a CF environment reduces plant completion for nutrients, air and light, which may lead to higher light utilization capacity and a greater photosynthetic rate. Results presented by [42] explained that even under CF conditions, transplanting single seedlings per hill could produce significantly better results than the current usual management practices, i.e., transplanting three to four seedlings per hill. However, Jones [58] highlighted that the yield of any crop is dependent on a combination of genetic makeup, physiological processes and agronomic attributes and any degrees of imbalance of the said parameters may reduce the crop yield.

The highest irrigation water productivity and total water productivity were obtained under intermittent irrigation and seven days; however, the six-centimeter ponded water depth at three- and seven-days intervals provided adequate soil moisture and proved to support plant growth while maintaining acceptable yield without bearing soil moisture stress. Even though all the practices attributed to SRI were not implemented in this research, it is worthwhile to mention that even two thirds of the recommended elements produces positive results in terms of water productivity. A similar observation was made by [59], who concluded that intermittent irrigation of three or seven-day intervals under SRI management can yield water savings of 50% and 72%, respectively. Furthermore, Senthilkumar et al. [60] and Ceesay et al. [61] also reported water saving of up to 60% under SRI compared with CF management.

5. Conclusions

The study has shown that not all the specific attributes of SRI management are required in order to have a positive effect on plant growth, increased yields, and enhanced water productivity. The challenges to sustain or maintain rice production are drastically increasing as fresh water for agriculture is sought of by other sectors. SRI offers the opportunity to reduce world hunger and sustainably manage world water resources; however, it merits a thorough comprehensive research program to unlock its full potential. Considerably high yield can be obtained under SRI using half or even one quarter of the amount of irrigation water consumed by CF. Irrigation water saved in one location may be used for irrigation in another, however soil type, agro-climatic conditions among other variables must be considered. Under intermittent irrigation of three-day intervals, yield was similar with to that of CF and may be credited to changes caused by SRI practices in all components of a rice plant, below and above the ground surface. Similar findings have also been reported in various published literatures, and therefore it can be expected that such results may also be obtained in Taiwan. Amidst labor constraints, which have made SRI appear less feasible in Taiwan, adopting SRI can contribute to a reduction in synthetic fertilizer, which has been a major cause of water contamination. Finally, with the impacts of climate change, and the growing competition for water in this region, SRI offers an opportunity worth exploring in Taiwan; however, further study on various components of rice water requirements is needed.

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