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Effect of Irrigation Regimes and Soil Texture on the Potassium Utilization Efficiency of Rice

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Abstract: Understanding the effects of irrigation regime and soil texture on potassium-use efficiency (KUE) of rice (*Oryza sativa*. L) is essential for improving rice productivity. In this regard, experiments were conducted from July to October in 2016 and 2017 by using a randomized complete block design in a factorial arrangement with four replications. The rice plants were grown in three soils, with clay contents of 40%, 50%, and 60%, which were marked as $S_{(40\%)}$, $S_{(50\%)}$, and $S_{(60\%)}$, respectively. For each soil type, irrigation regimes, namely, $R_{(F,\,S100\%)}$, $R_{(F,\,S90\%)}$, and $R_{(F,\,S70\%)}$, were established by setting the lower limit of irrigation to 100%, 90%, and 70% of saturated soil water content, respectively, and the upper limit of irrigation with 30 mm of flooding water above the soil surface for all irrigation regimes. Results showed that the responses of the roots and shoots and the potassium accumulation (KA) and KUE of rice were significantly affected by the water regime and soil texture. In the same irrigation regime, increasing the soil clay content improved the K utilization of rice. Under the same soil type, $R_{(F,\,S100\%)}$ was the optimal water management practice for growing rice. The $R_{(F,\,S100\%)}$ $S_{(60\%)}$ treatment presented the highest KUE, which was 56.4% in 2016 and 68.1% in 2017. The $R_{(F,\,S70\%)}$ $S_{(40\%)}$ treatment showed the lowest KUE, which was 13.8% in 2016 and 14.9% in 2017. These results enrich knowledge regarding the relationship among soil, water, and rice, and provide valuable insights on the effect of irrigation regime and soil texture on the KA and KUE of rice.

Keywords: water regime; soil clay content; yield; potassium use efficiency; rice

1. Introduction

Agriculture is now facing the challenge of providing sufficient food for the rapidly growing population. Rice is one of the most important cereal crops, feeding more than 60% of the Chinese population [1] and 40% of the global population [2]. China has scarce water resources, and rice farming uses nearly 65% of Chinese freshwater resources [3]. As a result of the changing climate, increasing population, and water shortage, Alternate Wetting and Drying (AWD) irrigation has been implemented widely in China [4]. In AWD, alternating flood and non-flood conditions are practiced in the field [5,6].

Soil texture affects plant growth and nutrient uptake because it alters the availability of water in the soil. When the soil has high clay contents, often with a large proportion of 2:1 clay, it is classified as Vertisol [7]. The development of cracks in vertic clay soil is a physical phenomenon with important agricultural repercussions [8] and is mainly governed by the water and clay contents in the soil [9]. In flooded rice soil, soil swelling is dominant because clay absorbs water. In addition, Continuous Flooding (CF) irrigation adjusts soil properties in advantageous ways, such as creation of soft tilth for easier root penetration. This technique also leads to lower nutrient losses than AWD irrigation [10]. In AWD, the soil is allowed to dry out before irrigation is applied again [11]; as such, cracks are dominant in paddy soils [12] due to the removal of water from within and between clay microstructures. Thus, AWD irrigation tends to result in a rather dramatic change in the soil physical environment. This environment controls water and nutrient availability and plant growth. Solutes can be quickly transported to the groundwater by preferential flow through cracks [13]. The increase in the presence of cracks can increase the infiltration rate, thereby allowing for faster leakage of water [14] and nutrients into the subsoil [15] and making them unavailable to the roots [16]. The nutrient uptake of rice in AWD differs from that in CF due to the physiological responses of rice to water stress and the nutrient availability in the system of AWD [17]. Under water stress, plants absorb nutrients inadequately. The low mineral nutrition could affect the growth of the plant [18]. Therefore, soil cracking under AWD cycles influences the process of plant development in soils [19], as well as the nutrient uptake and nutrient use efficiency [20].

Rice plants absorb K in larger amounts compared with nitrogen (N) and phosphorus (P) [21]. High amounts of N or P fertilizers are often applied, whereas a low amount of potassium fertilizer is used in paddy soil. The former leads to lower N or P use efficiency, and the latter results in K deficiency. About 70% of paddy soil is considered to be K deficient in China [22] and is now widespread in lowland rice soils [23] and clay soils [24]. Much attention has been given to the shortage of water due to climate change, environmental contamination caused by over-fertilization, and the urgent demand for feeding the rapidly growing population with less water [25]. Therefore, water-saving and efficient fertilizer technologies must be developed for sustainable rice production. Hence, the effects of irrigation regimes and soil texture on the potassium-use efficiency (KUE) of rice grown in regions of Southern China must be evaluated.

Southern China accounts for 88% of national rice production [26]. CF irrigation is practiced by Chinese farmers in lowland rice, threatening rice production [27]. AWD irrigation is extensively recommended, although AWD cycles have implications for other aspects of the rice production system, including soil cracking and nutrient leaching losses. Given the increasing necessity for the introduction of rice agricultural water management, water-saving technologies are urgently required. In addition, the method of irrigation should guarantee optimal soil water conditions, thereby providing favorable absorption of water and nutrients and leading to preferred crop growth and marketable yield. Therefore, the main objective of the current study was to assess the effects of different irrigation regimes on the dry mass production and potassium utilization of rice.

In regions of Southern China, clay-textured soils offer the highest potassium-supplying potential [28]; most irrigated lowland paddy soils are classified as silt clay [6], clay loam [4], and clay [29]. The impact of irrigation regimes on the release and fixation of nutrients in the soil and the ability of soil to supply potassium are important factors for improving the yield and fertilizer use efficiency of rice. Therefore, this study also aimed to determine the impact of soil texture on the biomass yield and potassium use efficiency of rice under different irrigation regimes.

2. Materials and Methods

2.1. Experimental Site and Experimental Pot Setup

The experiment was conducted at the Agricultural Experimental Farm of the Soil and Water Engineering Department, Hohai University, Nanjing, China, from July to October in 2016 and 2017.

The park (longitude 118°83′ E and latitude 31°95′ N) has an elevation of 15 m above sea level. The climate of the region is humid subtropical and is under the influence of the East Asia Monsoon. The annual mean temperature is 16 °C, the absolute maximum and minimum temperatures of the area are 43 °C and −16.9 °C, respectively, and the annual precipitation is approximately 1062 mm.

Soil was sampled from the top layer of 0–20 cm. After the soil was well dried, ground, and passed through 5 mm screen, 50 kg of clay was separated from a subamount of original soil by sedimentation in water [30]. The clay was dried and ground. In 2016 and 2017, three types of soil were manufactured by the adjustment of clay content in the original soil. The original soil with clay content of 40% was named $S_{(40\%)}$. Soils containing 50% clay ($S_{(50\%)}$) and 60% clay ($S_{(60\%)}$) were prepared by blending 16 and 32 kg of pure clay with 80 and 64 kg of the original soil, respectively. Thirty-six PVC pots were installed as an experimental group under an open shelter. Each pot (length: 50 cm, diameter: 16 cm) with small holes at the base was filled with 8 kg of the dry soil. A layer of gravel-sand was placed in the cylinder's bottom as a filter to allow water to infiltrate through the soil. A removable pot was installed in the pipe base to collect water percolation (Figure 1).

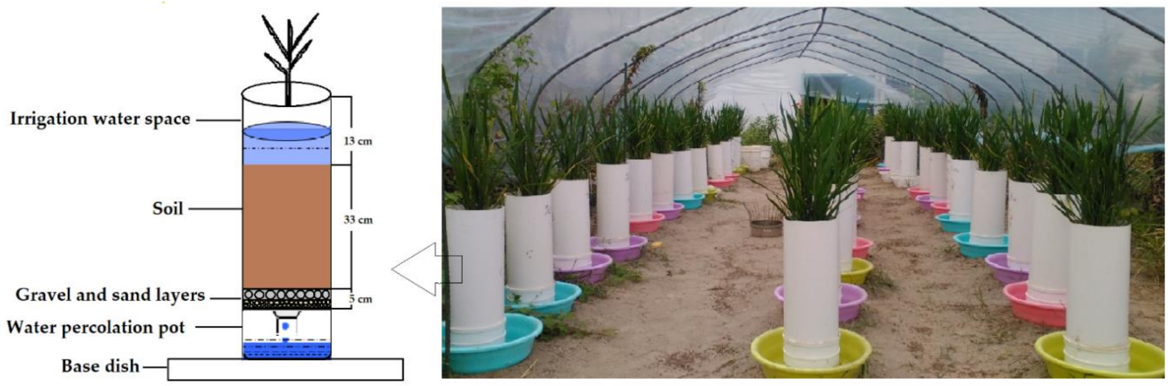

Figure 1. Experimental pot setup.

The soil properties are presented in Table 1. Soil texture was determined using a Bouyoucos hydrometer (TM-85, SHTG, Shanghai, China) [31]. Soil bulk density (BD) was determined by core sampler method [32]. Saturated soil water content (θ_s) was determined by total soil porosity, which was calculated from the soil bulk density, and the normal particle density of 2.65 g.cm^{-3} for mineral soil. Soil pH was determined in 1:5 soil and water extracted liquid by using a calibrated pH meter [33]. Soil organic matter (OM) was measured by oxidation method [34]. Two grams of the soil sample were digested within a mixture of selenium sulfate and salicylic acid by using a hotplate. The digestion temperature was conducted at 100 °C for 30 m and then increased to 380 °C for 3 h [35]. Total nitrogen (TN) in the respective digest was measured using a spectrophotometer (UV1901, Kejie, Nanjing, China) [36]. Available soil nitrogen (N) was measured using spectrophotometric method [37,38]. Available soil phosphorus (P) was measured according to spectrophotometric method [39]. Available soil potassium (K) was determined using a flame photometer (FB640N, Wincom, Hunan, China) [40].

Table 1. Physical and chemical properties of soil.

Soil Type	Sand %	Silt %	Clay %	BD g cm^{-3}	θ_s %	pH value	TN g kg^{-1}	N mg kg^{-1}	P mg kg^{-1}	K mg kg^{-1}	OM %
$S_{(40\%)}$	20.8	38.9	40.2	1.29	51.3	6.2	1.1	34.8	16.2	88.7	1.9
$S_{(50\%)}$	11.3	39.1	49.5	1.21	54.3	6.8	0.8	21.6	12.9	71.2	1.2
$S_{(60\%)}$	3.5	36.5	59.9	1.12	57.7	6.9	0.7	17.3	10.4	56.4	1.0

Note: Values are means of three replications for each measured propriety; $S_{(40\%)}$, $S_{(50\%)}$, and $S_{(60\%)}$ represent soils with clay contents of 40%, 50%, and 60%, respectively.

2.2. Experimental Dsign and Irrigation Regimes

The experiment was conducted in a randomized complete block design composed of two factors, the irrigation regime and soil texture, with four replications. The main treatment was irrigation regime, with three irrigation regimes expressed in Table 2. The sub-treatment was soil texture, with three soil types presented in Table 1. Accordingly, 36 (3 × 3 × 4) experimental pots were used, and each pot was transplanted with two seedlings of a local rice variety (*Oryza sativa* L. cv. Nanjing 44).

Table 2. Experimental design and controlled thresholds in different stages of different water regimes.

Irrigation Regime	Soil Texture	Water Limitation	Irrigation Quantity at Different Growth Stages					
			R	T	BH	F	MR	YR
$R_{(F, S100\%)}$	$S_{(40\%)}$, $S_{(50\%)}$, $S_{(60\%)}$	Upper (mm)	30	30	30	30	30	Natural drying
		Lower (S, %)	100	100	100	100	100	Natural drying
$R_{(F, S90\%)}$	$S_{(40\%)}$, $S_{(50\%)}$, $S_{(60\%)}$	Upper (mm)	30	30	30	30	30	Natural drying
		Lower (S, %)	90	90	90	100	90	Natural drying
$R_{(F, S70\%)}$	$S_{(40\%)}$, $S_{(50\%)}$, $S_{(60\%)}$	Upper (mm)	30	30	30	30	30	Natural drying
		Lower (S, %)	70	70	70	100	70	Natural drying

Note: R recovery, T tillering, BH booting and heading, MR milk ripening, and YR yellow ripening. The upper limit of irrigation means that the soil surface is flooded with 30 mm water depth after the soil is fully saturated. The lower limit of irrigation indicates the percentage of the volumetric soil water content (S, %) after the disappearance of ponded water. Irrigation water used in the experiment is fresh and devoid of nutrients.

The recommended amounts of urea (0.15 g N kg^{-1}), potassium phosphate (0.10 g P kg^{-1}), and potassium sulfate (0.13 g K kg^{-1}) were applied based on the soil test. The entire amounts of P and K were applied at pre-flooding as basal dose. The N amount was provided in four split doses during vegetative and reproductive growth stages.

2.3. Data Collection

2.3.1. Soil Water Content and Crack Intensity

Given previous knowledge of the weight of the empty pot, the filter layers, and the dry soil, moisture values were directly measured during the season by weighing the pipes with their contents on precision scales. Moisture values (%) were calculated by the following equation:

$$\mathrm{SWC} = (\mathrm{WSM} - \mathrm{DSM}) / \mathrm{DSM} \times 100 \tag{1}$$

Within the soil surface area, the length (cm), depth (cm), and width (cm) of each crack were recorded as the soil moisture content reached the low limit and before irrigating water in each irrigation regime throughout the season [19]. The volume (V, cm^3) of each crack was computed using the following equation and assuming a triangular shape of the cracks [41]:

$$\mathrm{V} = \sum 0.5 \times \mathrm{dwl} \tag{2}$$

where w is the width of the crack (cm), d is the depth of the crack (cm), and l is the length of the crack (cm). Crack volume was correlated with soil clay content and soil water content at the low limit for $R_{(F, S100\%)}$, $R_{(F, S90\%)}$, and $R_{(F, S70\%)}$.

2.3.2. Irrigation and Water Percolation Quantities Determination

Irrigation water volume was calculated according to the soil type by using the equation:

$$\mathrm{I} = 30 + (\mathrm{SWC} - \mathrm{AWC}) \times \mathrm{DSM}/\mathrm{A} \times 1000 \tag{3}$$

where I is the irrigation water (mm), SWC is the saturated water content of the soil (%), AWC is the actual water of the soil when irrigating (%), DSM is the dry soil mass (kg), and A = 3.14 × $(D/2)^2$, where D is the inner diameter of the tube in millimeter. Irrigation and water percolation volumes were determined and quantified to $R_{(F, S100\%)}$, $R_{(F, S90\%)}$, and $R_{(F, S70\%)}$ at each irrigation.

2.3.3. Determination of Potassium Concentration in Plant Tissues

At maturation, the plants were harvested and partitioned into grain, stem, and leaves. Roots were collected individually by sampling soil columns and separated by carefully washing the soils. The plant parts were dried at 70 °C for 72 h, weighed, milled into a powder state, sieved with a 1 mm screen, and stored in paper bags. Four wet-washing digestion sets for the grains, leaves, stems, and roots were prepared. Each set included 36 digestion tubes, with 0.5 g of the powder for each plant part placed in each digestion tube of each set. The tube was added with 10 mL of concentrated sulfuric acid and 1 g of selenium reagent mixture [35]. Potassium concentration (K%) in the grains, leaves, stems, and roots was measured using flame photometry method [42]. Moisture content in the plant tissues was measured by taking 2 g of the subsample powder for each part of the plant, which was oven dried at 121 °C for 6 h. Moisture content (%) was determined by re-weighing the sample to calculate the amount of water lost.

2.3.4. Determination of the Amount of Potassium Removed with Harvest and KUE

The amount of potassium accumulated and removed with the crop were calculated by the following equations [43]:

$$\text{KA by plant tissue} = \%\,\text{K content in the tissue} \times \text{dry weight of the respective tissue}/100 \quad (4)$$

$$\text{K Crop Removal} = \text{Grain KA} + \text{Leaves KA} + \text{Stems KA} + \text{Root KA} \quad (5)$$

KUE was determined as the apparent recovery efficiency by the equation:

$$\text{KUE} = \text{KCR}/\text{KI} \times 100 \quad (6)$$

where KA is the potassium accumulation (mg plant^{-1}), KCR is the potassium crop removal (mg plant^{-1}), KUE is the potassium use efficiency as the apparent recovery efficiency (%), and KI is the potassium input (mg soil^{-1}).

2.4. Statistical Analysis

Data were analyzed using the IBM-SPSS statistical package (IBM-SPSS, 19, USA). A general linear model procedure was used to perform analysis of variance. When *P* values were significant, the mean values were compared by applying the least significant difference (LSD) test at 0.05 level of significance.

3. Results and Discussion

3.1. Water Regime and Soil Texture Combination Effects

The hydrological properties of soil are highly influenced by water regime in irrigated rice fields [44]. In paddy soil, 2:1 clay content and soil water content are the main factors governing the amount of cracking. Soil fractures are of interest because they affect the transport of gases, water, and nutrients to the plant roots [45]. In the current study, crack network intensity was significantly affected by soil water content at the low limit of the irrigation regime and soil clay content (Figure 2).

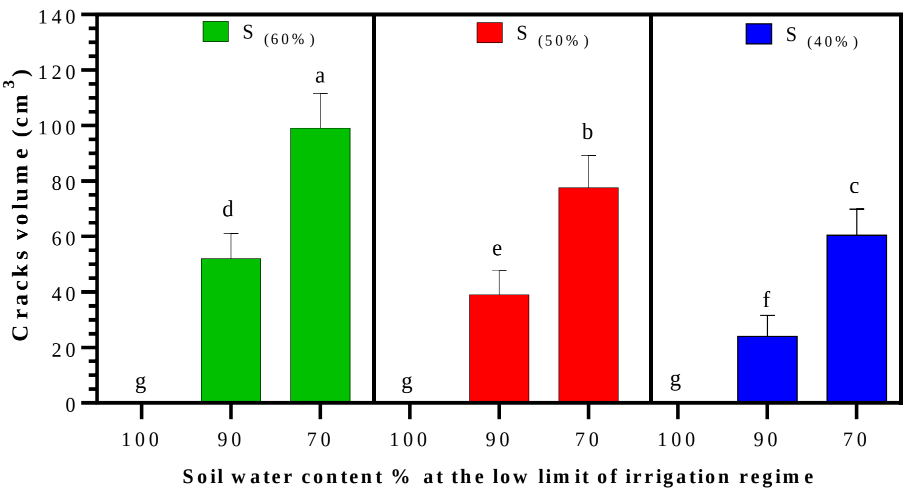

Figure 2. The crack volume due to soil water content and soil clay content in 2017. Values are means ± SD. S $_{(40\%)}$, S $_{(50\%)}$, S $_{(60\%)}$, representing soil clay contents of 40%, 50%, and 60%, respectively. The means are not significantly different when followed by the same letter.

The crack volume was strongly correlated with 2:1 clay content in the soil and the soil water content at the low limit of different irrigation regimes (Table 3).

Table 3. The relation between crack intensity, soil 2:1 clay content, and soil water content.

Soil Type	S $_{(40\%)}$	S $_{(50\%)}$	S $_{(60\%)}$
SWC%	100 90 70	100 90 70	100 90 70
Equation	V = −2.0 × SWC + 205	V = −2.6 × SWC + 263	V = −3.2 × SWC + 332
R^2	0.98	0.95	0.93

Notes: S $_{(40\%)}$, S $_{(50\%)}$, and S $_{(60\%)}$ indicate that soil contains a clay percentage of 40, 50 and 60%, respectively. SWC indicates the soil water content at the low limit for R $_{(F, S100\%)}$, R $_{(F, S90\%)}$, and R $_{(F, S70\%)}$, respectively. V indicates crack volume.

In the R $_{(F, S100\%)}$ regime, cracks were not observed in all soils. In the R $_{(F, S90\%)}$ regime, cracks developed, and the volumes of cracks increased significantly from S $_{(40\%)}$ to S $_{(60\%)}$. In the R $_{(F, S70\%)}$ regime, cracks further increased from S $_{(40\%)}$ to S $_{(60\%)}$, resulting in larger crack volumes than those in the R $_{(F, S90\%)}$ regime (Figure 2). In the R $_{(F, S100\%)}$ regime, cracks were not formed in soils due to clay swelling under the anaerobic-flooded conditions. Soil cracking under R $_{(F, S90\%)}$ was attributed to the removal of water from within and from between 2:1 clay microstructures; meanwhile, evapotranspiration and deep drainage are the major reasons for water removal. The increase in the volume of fractures from S $_{(40\%)}$ to S $_{(60\%)}$ was due to the increase in the swell-shrinkage potential. Soil cracking intensity and soil clay content showed a similar pattern of increase with decreasing soil moisture [46]. Additionally, growing rice in clayed soil increased the volume of cracks as the soil water content decreased [19,47]. The volume of the largest cracks under R $_{(F, S70\%)}$ was attributed to large water evaporation on the soil surface and the high water percolation rate because cracks increased the soil surface and helped water to penetrate to in-depth layers. As a result, growing rice in swell-shrink clay soil, with implementing long cycles of AWD irrigation causes the soil to undergo a great amount of cracking. Our result confirms the result of previous studies, i.e., a decrease in the soil water moisture content increases the volume of the cracks [48,49]. Soil cracking intensity is correlated with irrigation regime and soil clay content [46,47,50].

3.2. Frequency and Quantity of Irrigation Input

The volumes of water applied to soils under different irrigation regimes are presented in Figure 3. Increasing the clay content reduced the quantity of water applied to the soil for the R $_{(F, S100\%)}$. The highest amount of water was applied to S $_{(40\%)}$, whereas the lowest amount of water was applied to S $_{(60\%)}$. For the other irrigation regimes, the highest amount of irrigation water was recorded with S $_{(60\%)}$, whereas the lowest amount was recorded with S $_{(40\%)}$. Irrigation was applied 75, 36, and 24 times under R $_{(F, S100\%)}$, R $_{(F, S90\%)}$, and R $_{(F, S70\%)}$, respectively.

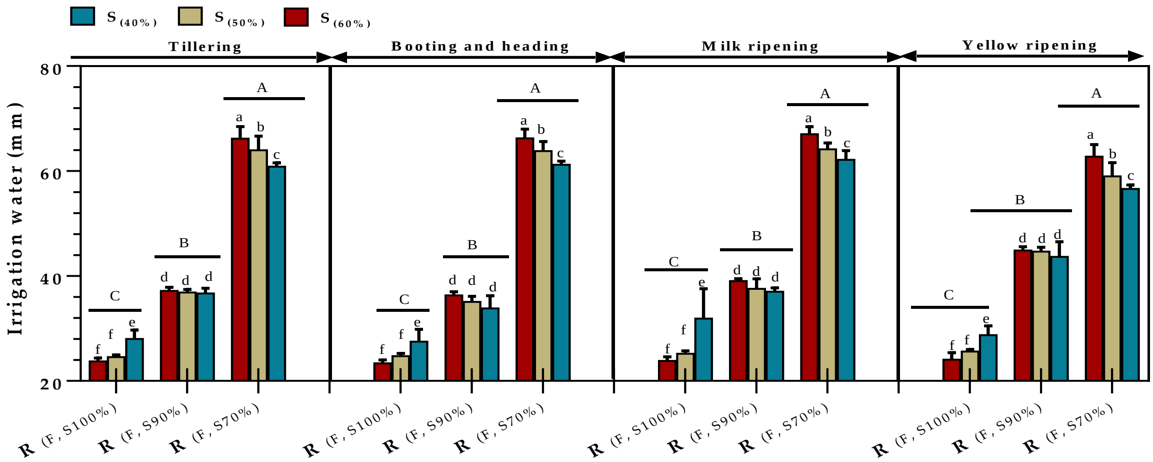

Figure 3. Volumes of water at each irrigation according to the irrigation regime and soil texture in 2017. Error bars represent the mean standard error. During the same growth stage, means are not significantly different between different treatments ($P \leq 0.05$), when followed by the same lowercase letter. During the same growth stage, the means are not significantly different between different irrigation regimes ($P \leq 0.05$), according to the two-way ANOVA analysis, when followed by the same uppercase letter.

The timing of irrigation was dependent on the low limit of the irrigation regime. Soils under the R $_{(F, S100\%)}$ regime reached the low limit 1 day after irrigation due to evapotranspiration and water percolation. The irrigation was applied to the soil every day to reach the upper limit of the R $_{(F, S100\%)}$ regime. Therefore, 75 irrigations were performed in R $_{(F, S100\%)}$. For the R $_{(F, S90\%)}$ regime, soils required 2 days to reduce the soil moisture content to 10% below the saturation. Thus, the irrigation was performed once every 2 days to reach the upper limit, resulting in 36 irrigations during the growing season. In R $_{(F, S70\%)}$, decreasing the soil water content to 30% below saturation was achieved after 3 days, although the water loss was enhanced because of soil cracking. Therefore, 24 irrigations were applied during the growing season. The difference in water use at each irrigation event should be mainly attributed from the difference among the low limit of irrigation regimes, soil cracking, and the percolation rate. The percolation of water was increased by the large depth of standing water, and soil cracks were the motivation for a substantial increase in the water inputs at the time of irrigation.

Considering water consumption for each irrigation event (Figure 4) and the total number of irrigation events for different irrigation treatments, our results confirm that the total water use in CF irrigation is higher than that in AWD irrigation due to the increase in the irrigation interval [51]. This finding could explain the higher total water input under the R $_{(F, S100\%)}$ regime than that under R $_{(F, S90\%)}$ and R $_{(F, S70\%)}$. Growing rice in the AWD system reduced the total water use compared with that in the CF system [5,52]. R $_{(F, S70\%)}$ resulted in a higher amount of water loss than hypothesized owing to the great amount of cracking on the soil surface. A great amount of soil cracking resulted in immediate water percolation, thereby increasing the total water use, despite the reduction in the irrigation intervals in the experiment.

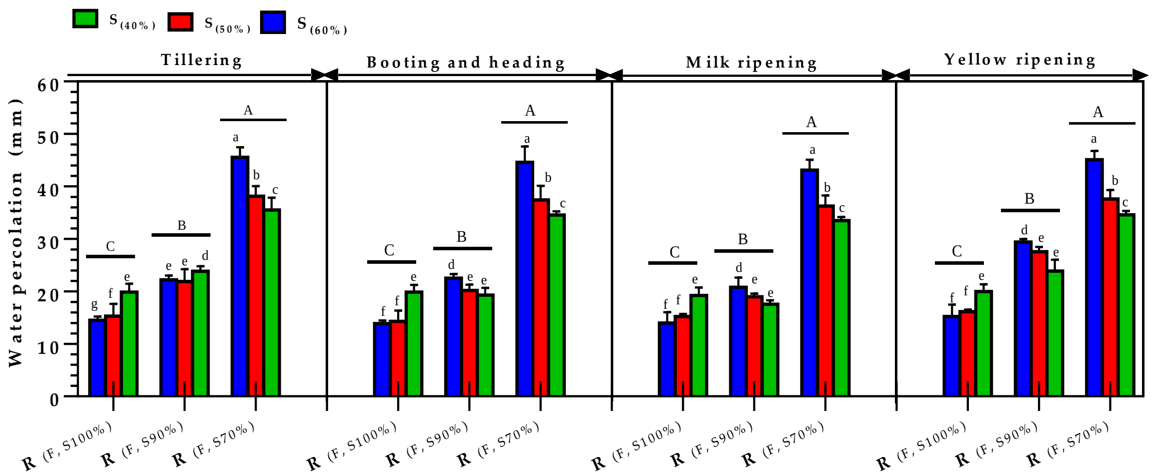

Figure 4. Water percolation as affected by the irrigation regime and soil texture in 2017. Error bars represent the mean standard error. During the same growth stage, means are not significantly different between different treatments ($P \leq 0.05$), when followed by the same lowercase letter. During the same growth stage, the means are not significantly different between different irrigation regimes ($P \leq 0.05$), according to the two-way ANOVA analysis, when followed by the same uppercase letter.

3.3. Water Percolation After Each Irrigation

Volumes of water percolation after each irrigation event during the growing season are shown in Figure 4. The increase in the clay content only reduced the water percolation for the R $_{(F, S100\%)}$; the highest amount of water percolation was obtained with S $_{(40\%)}$, and the lowest amount of leakage water was recorded with S $_{(60\%)}$. For the other irrigation regimes, increasing the clay content enhanced the water percolation. The highest amount of water percolation was recorded with S $_{(60\%)}$, and the lowest amount was recorded with S $_{(40\%)}$.

The increase in the clay content strengthened the soil capability of holding a great amount of water upon swelling, causing a reduction in water percolation under the R $_{(F, S100\%)}$ regime. The amount of water percolated after each irrigation event under R $_{(F\text{-}S90\%)}$ outweighed the amount of water percolated under R $_{(F\text{-}S100\%)}$ in the order of S $_{(60\%)}$, S $_{(50\%)}$, and S $_{(40\%)}$. When the soil water content reached the low limit, the volume of cracks enlarged, increasing the rate of water percolation. Percolation losses are highly dependent on the hydrological properties of a given soil. For example, in sandy loam soil, half of the total water input in the rice field is lost by percolation [53]; in swelling clayey rice soils, approximately 15% of applied water is lost via percolation [5]. Given that the upper limit of R $_{(F, S70\%)}$ was reached by irrigating soil with 30% of soil saturation plus 30 mm, much water was lost through the soil cracks. Therefore, the highest quantity of water percolated after each irrigation was under R $_{(F, S70\%)}$ in the order of S $_{(60\%)}$, S $_{(50\%)}$, and S $_{(40\%)}$, compared with the other regimes. Soil cracks caused higher percolation rates, and similar to our results, the daily consumption of water in AWD irrigated clay soil was higher than in CF irrigated soil [54]. Moreover, soil cracks enhanced water percolation because the percolation rate was affected by the extent of soil cracking and the depth of standing water in the rewetting phase [55].

3.4. Dry Weight of Plant Partitionings and Total Biomass

The dry weight of the grains, leave, stem, and roots and the total biomass under different treatments are presented elsewhere. In this study, we averaged the values of 2 years and described it briefly. As shown in Figure 5, across irrigation regimes, the highest and the lowest mean values of the grain, leaves, stems, and roots, and the total dry weight were detected in R $_{(F, S100\%)}$ and R $_{(F, S70\%)}$, respectively. Across soil types, the highest and lowest mean values of the dry weight of the grain, leaves, stems, and roots, and the total dry weight were obtained with S $_{(60\%)}$ and S $_{(40\%)}$, respectively.

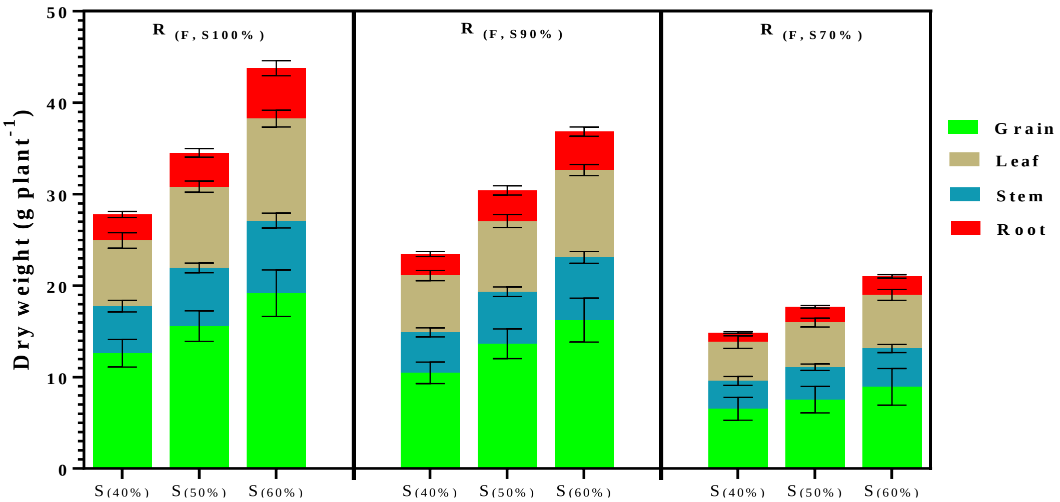

Figure 5. Plant biomass parameters for different irrigation regimes and soil types. The full-length column represents the total biomass.

The high dry mass of the grains, leaves, and stems in the anaerobic-flooded regime was attributed to the sufficient amount of water and nutrients in the root zone for rice. By contrast, the low dry mass of the grains, leaves, and stems in the aerobic-flooded regime might be ascribed to soil cracks, providing an easy passage for water and nutrients to leak to the groundwater, and reducing the water and nutrients available to rice [56]. Previous research demonstrated that irrigation regimes could influence the growth and grain yield of rice [11,57]. In clay soil, the grain yield of rice decreased under AWD irrigation [57]. Our result confirms that AWD irrigation reduces the rice yield if not implemented correctly (Figure 5). In addition to irrigation regimes, soil type could be another important factor that affects the biomass of rice. Increasing the clay content could improve the soil fertility [58]. A high biomass was recorded in rice grown in high clay soil than in rice grown in low clay soil [58–60]. In the present study, S $_{(60\%)}$ showed a higher value for the dry weight of the leaves, stem, and spikelet, leading to the higher dry weight of the shoots than those in S $_{(50\%)}$ and S $_{(40\%)}$ (Figure 5).

High root biomass indicates the strong ability of nutrient uptake. Studies have reported a close correlation between shoot and root weights [61] and between nutrient uptake and root biomass [62]. Therefore, the high root mass under the saturated-flooded conditions referred to the vigorous root and shoot growth. By contrast, soil cracks under the aerobic-flooded conditions could reduce the development of roots and the overall plant growth. Our result demonstrated that AWD irrigation decreased the rice root biomass with decreasing soil water content (Figure 5). In addition to irrigation regimes, soil type could be another important factor that affects root growth during the aerobic period of AWD irrigation [63]. In the present study, root biomass was severely restricted under R $_{(F, S70\%)}$ S $_{(40\%)}$.

3.5. Potassium Concentration in Plant Partitionings

The K concentrations in the grains, leaves, stems, and roots of the rice plant significantly differed across irrigation regimes ($P < 0.05$). The rice plants were more responsive to K under anaerobic conditions than under aerobic conditions during the seasons of 2016 and 2017. The highest K concentrations in the grains, leaves, stems, and roots were obtained under the R $_{(F, S100\%)}$ regime. The lowest K concentrations in the grains, leaves, stems, and roots were achieved under the R $_{(F, S70\%)}$ regime. Soils with different clay contents significantly affected the concentration of K in all rice plant parts ($P < 0.05$). The highest concentrations of K in the grains, leaves, stems, and roots were achieved by S $_{(60\%)}$, whereas the lowest concentrations were found in S $_{(40\%)}$ (Table 4).

Table 4. Mean values of K concentrations in rice tissues (% dry weight) with different irrigation regimes and soil types as well as a summary of ANOVA on the main effects of the water regime and soil texture on the K content in the tissues.

Factor	**K Concentration (% Dry Weight)**							
Water Regime (R)	**Grains**		**Leaves**		**Stems**		**Roots**	
	2016	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**
R $_{(F, S100\%)}$	0.38 ^{A}	0.38 ^{A}	0.89 ^{A}	0.89 ^{A}	0.73 ^{A}	0.71 ^{A}	1.00 ^{A}	1.00 ^{A}
R $_{(F, S90\%)}$	0.31 ^{B}	0.33 ^{B}	0.79 ^{B}	0.76 ^{B}	0.66 ^{B}	0.65 ^{B}	0.91 ^{B}	0.90 ^{B}
R $_{(F, S70\%)}$	0.25 ^{C}	0.26 ^{C}	0.51 ^{C}	0.50 ^{C}	0.41 ^{C}	0.41 ^{C}	0.57 ^{C}	0.55 ^{C}
Soil texture (S)								
S $_{(40\%)}$	0.24 ^{c}	0.25 ^{c}	0.58 ^{c}	0.57 ^{c}	0.47 ^{c}	0.47 ^{c}	0.65 ^{c}	0.64 ^{c}
S $_{(50\%)}$	0.32 ^{b}	0.32 ^{b}	0.73 ^{b}	0.73 ^{b}	0.59 ^{b}	0.59 ^{b}	0.82 ^{b}	0.80 ^{b}
S $_{(60\%)}$	0.38 ^{a}	0.39 ^{a}	0.89 ^{a}	0.88 ^{a}	0.75 ^{a}	0.74 ^{a}	1.00 ^{a}	1.00 ^{a}
ANOVA								
R	***		***		***		***	
S	***		***		***		***	
Y	ns		ns		ns		ns	
R × S	ns		ns		ns		ns	
R × Y	ns		ns		ns		ns	
S × Y	ns		ns		ns		ns	
R × S × Y	ns		ns		ns		ns	

Notes: Means of different uppercase and lowercase letters indicate a significant difference between different irrigation regimes (R) and soil types (S). Means are not significantly different between the irrigation regimes (uppercase) or between soil types (lowercase) when followed by the same letter; ANOVA, analysis of variance tests; ns, not significant; ***, denote significant differences at $P \leq 0.001$, respectively, among treatments; and Y indicates the year.

The high K concentration under the R $_{(F, S100\%)}$ regime was due to high amount of water, including soluble forms of K, available to plants grown under the anaerobic-flooded conditions rather than under the aerobic-flooded conditions. Flooding a soil increased the K concentration in the soil solution as a result of the exchange reaction [64]. Additionally, CF irrigation maintained the highest values of accessible NPK, whereas water stress reduced their availability. Moreover, the K content was higher in plants under CF conditions than under AWD conditions [64]. In the present study, under the anaerobic-flooded conditions, big rooting systems were developed, transporting high amounts of K into the shoot parts. K application promoted the growth of the rice roots and the overall plant growth because of increasing contact between the ions and roots with increasing K availability in the soil [65], contributing to a high K uptake [56,66]. In plants, fundamental physiological processes, including photosynthesis and growth, are dramatically affected by K availability [67]. The K response under the aerobic-flooded regime was reduced due to the decrease in the soil moisture content, resulting in soil cracking, which may cause greater leachates of soluble nutrients, water percolation, and disturbance in the root growth and overall plant growth. Our results are in agreement with previous findings that AWD irrigation reduced the nutrient availability [64], where rice plants developed poorly [65]. Big cracks preferentially bypass water and solutes [15], making them unavailable to plant roots and potentially leading to groundwater pollution [16]. Therefore, the nutrient leaching loss considerably increased under AWD irrigation compared with that under CF irrigation due to soil cracks [68].

Better response to K was observed in S $_{(60\%)}$ than in S $_{(40\%)}$, possibly because increasing the clay content enlarged the surface area, in which a great amount of K ions were adsorbed by the clay particles and moved gradually from the soil to the plant roots. The capability of a plant to absorb nutrients from the soil depends on soil type [69]. In addition, the rates of the root growth and overall plant growth in S $_{(40\%)}$ were lower than those in S $_{(60\%)}$. Therefore, the higher the clay content is, the higher the yield and the KA of the rice plants will be. Limited studies have revealed the mechanisms of K transformation in the rice systems under CF or AWD irrigation. However, the physiological response of rice to nutrients in CF irrigation differs from that in AWD irrigation due to the decrease in nutrient availability in the latter [17,64]. In a previous study [56], in contrast to the control treatment, the greater response of the rice roots to K was attributed to the application of K, thereby promoting the availability of K in the soil. This phenomenon increased the K diffusion rate in the soil, and consequently, the contact between K and the rice roots. Additionally, plants with big rooting systems can exploit great soil volumes and increase the contact between the roots and nutrients [56].

3.6. Potassium Accumulation of Plant Parts and Total Biomass

The analysis of variance shows the significant difference ($P < 0.05$) in KA for all plant parts of rice in the seasons of 2016 and 2017 among all treatments. Rice grown in the anaerobic-flooded regime had higher KA in the grains, leaves, stems, and roots and larger total biomass than rice grown in the aerobic-flooded regime. Rice cultivated in $S_{(60\%)}$ had higher KA in all plant parts and larger total biomass than rice cultivated in $S_{(40\%)}$. The combination, $R_{(F, S100\%)}$ $S_{(60\%)}$, had the highest KA in the grains, leaves, stems, and roots and largest total biomass, whereas the combination, $R_{(F, 70\%)}$ $S_{(40\%)}$, presented the lowest KA values (Table 5). The greater value of KA was due to the higher K content and biomass in the anaerobic-flooded regime than in the aerobic-flooded regime. The high K concentration in the root zone could improve the crop yield [70] by increasing the K acquisition and the biomass production of rice [56,66]. The sharp decrease in KA in the aerobic-flooded regime was due to the disturbance in the overall plant growth and the low response to K was because reduction in the soil moisture content declines the K uptake in rice [71,72]. In addition, K is an essential element for plants; even slight deficiencies in the available K content can adversely affect the crop yield [73]. Moreover, K deficiency resulted in stunted roots and shoots, further limiting the K uptake in rice [74].

Table 5. Mean values of rice plant K accumulation for different irrigation regimes and soil types, as well as a summary of ANOVA on the main effects of the water regime and soil texture on the K accumulation of rice.

Factor		Potassium Accumulation (mg plant^{-1})									
Water Regime (R)	Soil Type (S)	Grains		Leaves		Stems		Roots		Total Biomass	
		2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
$R_{(F,S100\%)}$	$S_{(40\%)}$	32.7	38.4	49.4	51.5	28.1	29.4	20.5	23.9	130.6	143.2
	$S_{(50\%)}$	51.8	62.1	74.8	79.9	42.7	46.6	32.9	39.8	202.2	228.4
	$S_{(60\%)}$	72.5	102	116	126	67.7	78.5	61.4	76.1	317.4	383
$R_{(F, S90\%)}$	$S_{(40\%)}$	21.4	25.4	37.7	39.5	21.5	23.6	15.4	17.9	96.0	106.4
	$S_{(50\%)}$	36.3	46.8	59.9	63.5	35.2	38.1	27.3	32.3	158.7	180.6
	$S_{(60\%)}$	50.4	71.4	86.7	93.2	51.9	58.2	40.6	49.5	229.5	272.3
$R_{(F, S70\%)}$	$S_{(40\%)}$	10.8	13.5	17.2	17.2	10.0	10.6	4.7	4.9	42.6	45.9
	$S_{(50\%)}$	14.9	21.0	24.6	24.7	14.7	15.1	9.3	10.1	63.4	70.8
	$S_{(60\%)}$	21.1	32.6	36.1	36.5	20.9	21.4	13.2	14.7	91.3	105.2
ANOVA											
R		***		***		***		***		***	
S		***		***		***		***		***	
Y		ns		ns		ns		ns		ns	
R × S		**		***		***		***		**	
R × Y		ns		ns		ns		ns		ns	
S × Y		ns		ns		ns		ns		ns	
R ×S ×Y		ns		ns		ns		ns		ns	

Notes: (R) and (S) indicate the irrigation regime and soil type. ANOVA, analysis of variance tests; ns, not significant; **, ***, denote significant differences at $P \leq 0.01$, and 0.001, respectively, among treatments, and Y indicates the year.

The superior KA in the plant grown with $S_{(60\%)}$ was due to the better response to K and the larger biomass compared with those in $S_{(40\%)}$. The availability of K in the soil improves the yield and K uptake rate by plants [56]. Plant-available K showed a positive and significant correlation with clay content for soils [75]. Thus, the higher availability of K in the soil is, the greater the K uptake by the rice plant will be [56].

The combination R $_{(F, S100\%)}$ S $_{(60\%)}$ showed larger plant biomass and greater KA in the plant compared with the combination R $_{(F, S70\%)}$ S $_{(40\%)}$. The efficient absorption of K enhances the production and translocation of the dry matter of rice [76] because biological indicators, such as the root and shoot biomass of the rice plant, increase with increasing K application rates compared with lower K application rates [56]. Thus, the greater the availability of K in the soil is, the larger the KA rate of the rice plants will be [66]. By contrast, soil cracking observed in the R $_{(F, S70\%)}$ S $_{(40\%)}$ treatment could reduce the overall plant biomass and the KA of the plant. Changing from soil flooded to greater soil aeration can significantly affect nutrient supply to crops, root growth, and rice productivity [77]. Our results are in line with previous study reporting that the rice growth rate can be increased by increasing the K availability in soil; the difference in the rice growth rates is attributed to varietal differences in K uptake. Therefore, the higher the growth rate is, the higher the potassium uptake will be [56].

3.7. KUE

In both seasons, KUE varied depending on water regimes. R $_{(F, S100\%)}$ presented the highest value of KUE, whereas R $_{(F, S70\%)}$ showed the lowest value of KUE (Figure 6).

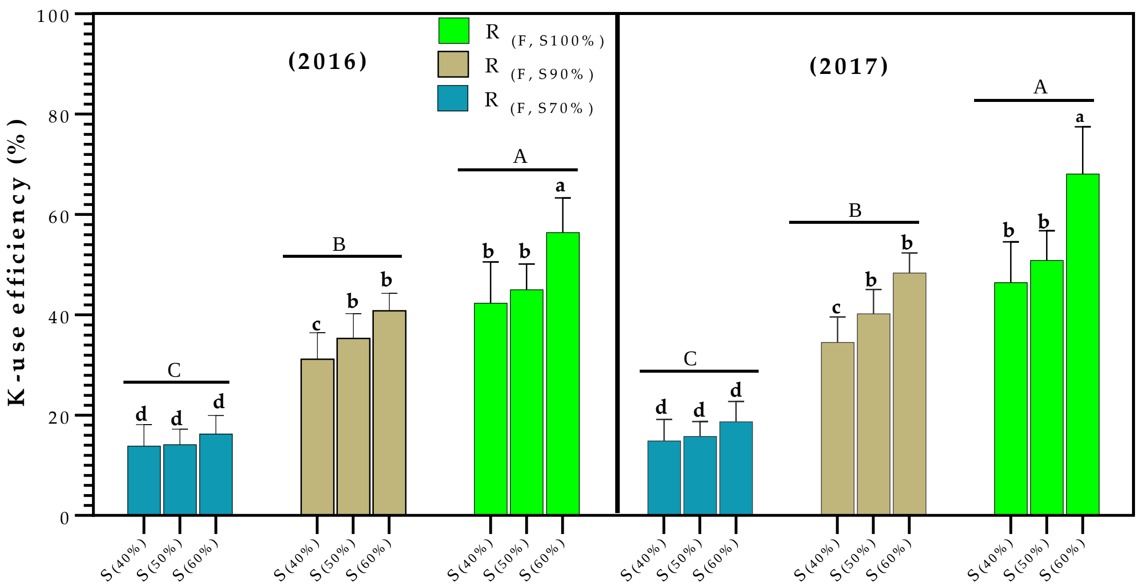

Figure 6. Potassium use efficiency, as affected by the irrigation regime and soil texture. During the same year, the means are not significantly different between different treatments ($P \leq 0.05$) when followed by the same lowercase letter. During the same year, the means are not significantly different between different irrigation regimes ($P \leq 0.05$) when followed by the same uppercase letter, according to the two-way ANOVA analysis.

The saturated-flooded regime resulted in abundant available K to the roots, increased the plant biomass and KA in the plants, and led to the highest KUE value. By contrast, the aerobic-flooded regime decreased the K availability within water stress and soil cracking, resulting in lower K supply. A lower supply of K and water reduced the root and shoot growth of the plant, and therefore the access to K, leading to the lowest KUE value. Correspondingly, the KUE in irrigated rice was high under high growth and K acquisition rates and efficient biomass allocation [22,56,66]. In addition, the K supply under CF conditions was better than the K supply under AWD conditions. Therefore, the latter reduced the nutrient utilization efficiency and uptake of applied nutrients [64].

Soils with different textures significantly affected the KUE of rice. The average of the highest KUE was found in S $_{(60\%)}$, whereas the lowest was detected in S $_{(40\%)}$ (Figure 6). Hence, increasing the clay content enhanced the K fixation, leading to efficient utilization of applied K. In addition, S $_{(60\%)}$ resulted in larger total biomass associated with higher KA in the plant compared with S $_{(40\%)}$. The increase in the clay content increased the K availability in the soil [75] and subsequently increased the K uptake [56] and the KUE of rice.

The ANOVA results showed a significant interaction between the irrigation regime and the soil texture. The R $_{(F, S70\%)}$ S $_{(40\%)}$ treatment showed the lowest value of KUE, at 13.8–14.9%, whereas the R $_{(F, S100\%)}$ S $_{(60\%)}$ treatment presented the highest value of KUE, at 56.4–68.1%, during both seasons (Figure 6). The results could be attributed to the large amount of available K in the soil being available to plants in the R $_{(F, S100\%)}$ regime, leading to higher K absorption in the greater total biomass, and therefore, better K utilization, compared with that in the R $_{(F, S70\%)}$ regime. In addition, the soil's ability to provide K to the rice plant increased with increasing clay content. The higher availability of K in the soil is, the greater the KUE of the rice plant will be [56]. The aerobic-flooded regime sharply reduced the KUE through water stress, affecting the rice growth and yield, along with 40% clay content, which might contribute to lower K supply. Thus, less water, including K, was available to the plant, resulting in the lowest plant biomass and KA. The lowest KUE was observed in the combination R $_{(F, S70\%)}$ S $_{(40\%)}$. Correspondingly, the KUE in the rice plant decreased due to the reduction in the plant growth, accumulation, and fixation of K in dry matter [22,64].

4. Conclusions

The saturated-flooded irrigation regime is preferred over the aerobic-flooded irrigation regime for obtaining high biomass production and potassium utilization of rice. The increase in the soil clay content improves the biomass production and potassium utilization of rice.

Maintaining the soil water content at saturation followed by re-flooding could be the optimal water management practice for rice cultivation in swell–shrink clay soil. The optimal water management could enhance plant growth by supplying a sufficient amount of water and nutrients to the large shoots via the root. The vigorous rice root promotes the high production of plant biomass and the large absorption of potassium, thus achieving high utilization of applied potassium. Clay swelling, together with the role of the colloidal complex in the nutrient adsorption in soils with high clay content, helps in making potassium ions available to the rice plant during the growing season.

Reducing the soil water content to 30% below saturation and re-flooding is improper for the water management of rice cultivated in the expansive clay soil because it sharply declines the biomass production and potassium utilization of rice due to soil cracking. Soil cracks provide a pathway for water and nutrients to be easily percolated and adversely affect the root development. Therefore, the overall plant growth considerably declines and a lower amount of applied potassium is transported, leading to low utilization of potassium. This study demonstrates that the adoption of an efficient irrigation regime is crucial for increasing the rice productivity in the swell–shrink clay soil. The efficient irrigation regime should guarantee optimal root and overall plant growth, with optimal biomass return and sufficient potassium supply for potential yield increases.

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