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Impact of irrigation techniques on rice yield and dynamics of zinc in plants and soil

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Abstract: Zinc (Zn) insufficiency and water deficiency are primary challenges in intensive rice production systems. This study aims to examine the influence of two irrigation regimes, flood irrigation (FI) and water-saving irrigation (WSI), on rice grain yield and mobile Zn accumulation in soil and rice grains. Experiments were conducted in An Vien rice fields in the Tien Lu district, Hung Yen province, located in the middle of the Red River delta during four rice seasons from 2015 to 2016. The results showed that the WSI regime dramatically increased the grain yield and Zn concentrations in grain of rice. Grain yield was increased by 14.76% and grain Zn concentration by 17.93% when compared with the FI regime. The decrease in the mobile Zn concentration in soil was only 5.7% in the WSI technique, compared with 73.6% for FI techniques. Therefore, it can be concluded that WSI can be effective agricultural practice to elevate grain yield and increase Zn retention in soil and bioavailability in rice grains.

Keywords: water-saving irrigation; flooding irrigation; zinc uptake; rice yield; sustainable agricultural production

Zinc (Zn) is an essential micronutrient for healthy growth and optimum yield in rice production (Alloway 2008). Interest in Zn has risen in recent decades because Zn deficiency stress is extensive in many areas, causing decreased crop yields (Sadeghzadeh 2013). Zn deficiency can reduce rice yields by over 20% and leads to a lack of Zn nutrition in rice (Alloway 2008). Zn deficiency is the most widespread micronutrient deficiency in agricultural lands around the world, causing yield decreases and diminishing the nutritional quality of agricultural plants (Alloway 2008). Zn deficient soils have extractable Zn concentrations below 0.5 mg Zn/kg diethylenetriaminepentaacetic acid (DTPA) extractable Zn. Approximately half of the agricultural soil area in the world has low available Zn or Zn deficiency (Alloway 2008). For example, the total Zn concentration is only about 34 mg/kg in Australian soil (Bertrand et al. 2002), 56.5 mg/kg in US agricultural sites (Holmgren et al. 1993), 82 mg/kg in England and Wales and 17 mg/kg and 40 mg/kg in French sandy and silty soils, respectively (Baize 1997). It is estimated that nearly half the soils in the world on which cereals are grown have low levels of available Zn to cause its deficiency (Alloway 2008). Zn deficiency in Vietnam is also severe. According to a study of Vietnamese agricultural soils (Tau 1999), over 11% of agricultural areas lack Zn nutrition for crop production. Some studies on alluvial paddy soils in the Red River delta showed poor Zn nutrition, with total Zn contents of about 84 mg/kg and mobile Zn contents of 0.68 mg/kg in recent years (Tau 1999, Phuong and Nga 2017).

Flood irrigation (FI) is a traditional technique that has long been utilised in the Red River delta. In the FI, water is continuously kept at 5–7 cm during paddy growth, even it rises over 7 cm in the rainy season.

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The total volume of irrigation water consumed by paddy cultivation is about 52.5 billion m^3/crop for about 7 billion ha in Vietnam (Phuong 2016, Tran 2016), leading to a lack of water for agricultural production. Therefore, rice production consumes more than 80% of the total agricultural water in Vietnam (Tran 2016). Due to climate change, the water level of the Red River system has become insufficient to flow through the irrigation sewers. Furthermore, the FI regime results in methane greenhouse gas emissions and reduced oxygen contents in the soil, as well as changes to the soil's redox potential (E_h), pH, and concentration of micronutrients and minerals in recent years (Lin et al. 2011). Therefore, water-saving irrigation (WSI), which reduces the amount of water irrigated to rice, is necessary due to the increasing scarcity of irrigation water in Vietnam.

The WSI in Vietnam was established as part of the system of rice intensification (SRI) beginning in 2005 and was initially only applied to some paddy cultivation regions (about 395 000 ha equivalent to 6% total rice areas of the country) (in 2016). This is an irrigation management method in which the water level is controlled at 3–5 cm, and the field is dried for 3–5 days between irrigation periods and 7–10 days at the end of the tillering stage. Draining the fields for a few days increases the efficiency of oxygen use from the air to limit anaerobic conditions. It is known that in rice cultivation, the aerobic irrigation (AI) reduces the irrigation water amount by 10–17% (Ma et al. 2017), increases grain yields by 10.6% (Jain et al. 2000) and reduces greenhouse gas emissions by up to 80% (Tyagi et al. 2010). In addition, the WSI method has demonstrated many advantages, such as decreased concentrations of toxic Fe^{2+} and Mn^{2+} in soils (Hafeez et al. 2013, Nguyet 2013), significantly increased soil redox potential and increased sulfate and available Zn in Vietnamese paddy soils (Phuong 2016). Under intermittent water application, as recommended in the SRI system, grain yield increased by 10.5–11.3% compared to the FI method. The factor that contributed most to higher yield was the increased number of grains per panicle. It was seen that of the organic fertilisation treatments evaluated, intermittent irrigation promoted better dry matter production and a higher leaf area index during the main growth stages compared with FI (Prasad et al. 2017, Uçgun et al. 2018). This affects soil properties, such as reducing the available Mn and Fe and preventing the subsequent inhibition and toxicity to rice growth (Hafeez et al. 2013, Nguyet 2013).

Recently, Vietnam has applied both irrigation techniques to its rice production system, including FI, with water levels from 5–7 cm and WSI with more controlled water levels. However, WSI has not been applied widely in agricultural areas (about 6%) (in 2016), whereas nearly all agriculture soil areas receive the FI. Decreased crop yields due to water loss and soil nutrient depletion have recently become problematic in Vietnam. The present study, focusing on Zn dynamics in the alluvial soil of the Red River delta under the influence of FI and WSI, was conducted with the aim to propose management solutions for soil nutrition toward sustainable agriculture in Vietnam. The present study focused on (1) examining the effects of two irrigation methods on the dynamics of Zn, yield, and Zn uptake by rice grains and (2) providing a technical suggestion for increasing the Zn utilisation efficiency toward sustainable agricultural production.

MATERIAL AND METHODS

Reagents. Diethylenetriamine pentaacetic acid (DTPA) 0.025 mol/L; triethanolamine (TEA) 0.5 mol/L and calcium chloride ($CaCl_2$) 0.05 mol/L were purchased from Merck (Germany). HNO_3 68% (Xichlong, China), H_2O_2 40% (Duc Giang, Vietnam), and HCl 37% (Xichlong, China) were also used.

Experimental areas and soil sampling. The experiments were conducted in two fields (A and B) in the Tien Lu district (Hung Yen province) at 20°40'57.47''N and 106°6'8.67''E with areas of 0.25 ha and 0.30 ha, respectively, in the north of Vietnam from 2015 to 2016. The fertiliser NPK was added with a ratio of 16-16-8, without Zn.

Soil samples were taken in the topsoil at depths of 0–20 cm and air-dried and sieved to < 1 mm. These were analysed for physical and chemical characteristics, such as cation exchange capacity (CEC), pH value, organic, following standard methods (Page et al. 1982), including the ammonium acetate method, Walkley-Black method. The characterisation of the soils is presented in Table 1.

Experimental treatments in the fields. The FI is a conventional irrigation method where the water level is kept at 5–7 cm long-term and can increase to 7–10 cm in the rainy season. In addition to being applied at the experimental location, FI is also commonly used in the Red River delta.

The WSI is an irrigation type where the water level is controlled from 3–5 cm above the soil surface,

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Table 1. Properties of the soil in the study area

Property	Values
CEC ($mmol_+$/100 g)	14
Organic content (%)	1.11
Clay (%)	18–20
pH	6.71–6.92
pH_{KCl}	5.82–5.94
Total Zn (mg/kg)	8.43 ± 0.26
Mobile Zn (mg/kg)	0.68 ± 0.02

CEC – cation-exchange capacity

with drying periods of 3–5 days between irrigation periods and 7–10 days during the end of the tillering stage (3rd stage). A popular local rice cultivar, Khang Dan, was chosen for these experiments. The experimental fields were dried for 15 days before harvesting. The irrigation water was sourced from the irrigation systems of Hung Yen province and had a Zn concentration of 0.001–0.003 mg/kg.

Experimental analysis and observation were conducted at five rice growth stages, including the seeding (stage 1), transplanting (stage 2), the end of tillering (stage 3), flowering (stage 4), and ripening stage (stage 5).

Analysis. The E_h redox potential and pH were measured by oxidation-reduction potential (ORP) and pH meters (Horiba, Japan) at a depth of 0–20 cm.

Mobile Zn in the soil was analysed by a wet DTPA method, as described by (Johnson-Beebout et al. 2009). The DTPA method was used to extract mobile Zn. A 5 L volume of DTPA extracting solution was mixed from 1 L of 0.05 mol/L DTPA, 1 L of 0.1 mol/L TEA, 1 L of 0.01 mol/L $CaCl_2$, and distilled water. After settling at room temperature for 12 h, the solution was adjusted to pH 7.3 with concentrated HCl. A 10 g sample of dry soil was mixed with 20 mL of DTPA extracting solution in a 125-mL Erlenmeyer flask and agitated with a shaker (KS 3000i, IKA, Germany) at 250 rpm at a constant temperature of 25°C for 2 h. The suspended solution was then filtered through a filter paper (Whatman No. 42, UK).

The total Zn in the soil was extracted by an *aqua regia* solution with a 3:1 volume ratio of HCl/HNO_3 and heated in Teflon containers in a microwave.

Rice grains (0.10 g) from each irrigation treatment were digested with 5.0 mL of HNO_3/H_2O_2 (4:1, *v*/*v*) using a hot block heater. After cooling, the digested grains were transferred to a 20-mL volumetric flask and then filtered.

Zn concentrations were measured by inductively coupled plasma mass spectrometry (ICP-MS; Agilent Modell 7500a, Agilent Technologies, USA).

Statistical analysis. All statistical analyses of the data were performed using Microsoft Excel (version 5.5, Microsoft, USA). Each value represented the average of three replicates. The data were subjected to an analysis of variance (ANOVA), and significant differences in mean values were determined using Duncan's multiple range test ($P < 0.05$).

RESULTS AND DISCUSSION

Comparison of two irrigation techniques on the water level and the E_h. The water levels in the FI treatment was maintained above 6 cm during the crop season (Figure 1).

Figure 1 shows that the water levels fluctuated from 6.6–8.5 cm in overalls crop. As the previous research, the concentration of oxygen, be decreased in flooded rice soils, and E_h of soils have affected primarily by water level (Reddy and Patrick 1986). Figure 2 illustrated that E_h of paddy soils had reduced considerably by the flood irrigation system. One of the most important physicochemical properties of the soil that are impacted significantly by continuous flooding is E_h redox potential (Patrick et al. 1985). Since the floodwater had been in place for a long time, roots and respiration of bacterias, as well as oxidation reactions, have led to the concentration of oxygen, be contented in the soil solution, immediately declination in several hours to a few days (Mitsch and Gosselink 2000). The oxygen consumption depends on the temperature changes, the biology oxygen demand for microbial respiration, and the chemical oxygen demands for reductants sustains as Fe^{2+}, and Mn^{2+} ions (Mitsch and Gosselink 2000). As a result, the soil environment became anaerobic due to reduced E_h; this may increase the concentration of reduction subtains in soils (Mitsch and Gosselink 2000). The experimental results indicated the dropped E_h under the flooding situation (Figure 2). Thus, there is a negative correlation between water level and E_h in FI treatment.

Under the flooded condition, the soil formed an anaerobic environment due to increasing of electron donors, such as Fe^{2+}, Mn^{2+}, CH_4, H_2S, NH_4^+, and H_2 (Reddy and Patrick 1986). In there, the reduction of CH_4 required a very low redox potential, with E_h under –200 mV. Other terminal electron acceptors were the redox potential from –200 to –100 mV (Reddy and

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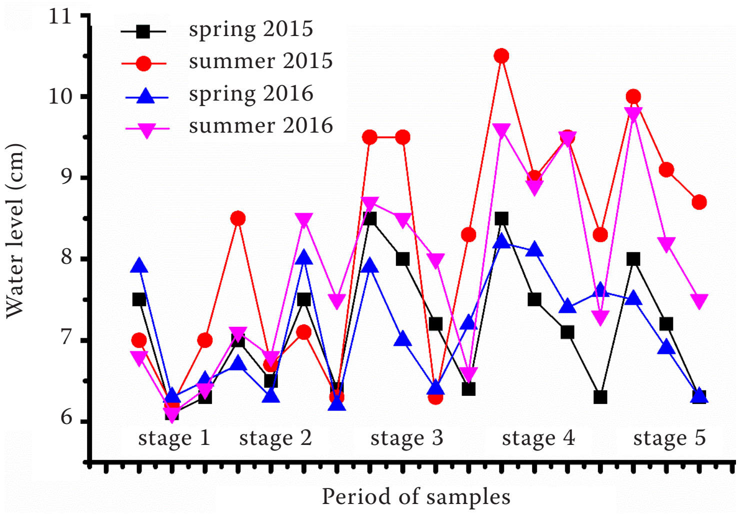

Figure 1. Water levels over the course of four different harvests grown with flood irrigationtreatment. stage 1 – seeding; stage 2 – transplanting; stage 3 – end of tillering; stage 4 – flowering; stage 5 – ripening stage

Patrick 1986). In this treatment, nearly all redox potential values of paddy soil fell under –200 mV, except for stage 2 (–165 mV).

When the E_h is below –100 mV, the reduction of SO_4^{2-}-S to H_2S can occur (Mitsch and Gosselink 2000). When E_h decreases to lower than –200 mV, this reduction is more favourable (Mitsch and Gosselink 2000, Sarafraz et al. 2009). Thus, the SO_4^{2-}-S reduced to H_2S in the paddy soils happens under flood conditions. In soils with low E_h, sulfate is reduced to sulfide through the participation of anaerobic bacteria:

$$4H_2 + SO_4^{2-} \rightarrow H_2S + 2H_2O + 2OH^- \quad (1)$$

Whether sulfide appears in the form of H_2S, HS^- or S^{2-} strongly depends on the pH value. H_2S occurs at a low pH, while S^{2-} is present at a higher pH. All sulfide forms are dangerous for rice growth because they prevent nutrient uptake by the roots (Yoshida and Chaudhry 1979).

There was a different trend of the redox potential in stage 2 of FI treatment with the E_h –165 mV. This result could be explained by two reasons. The first, the redox potential changed due to the water level in the field. This phenomenon could be described that high the water level limited the dosage of dissolved oxygen as well as lower E_h values in the soil. In contrast, a low water level increases diffuse oxygen into soil systems to improve the E_h. The water level in stage 2 was the lowest at 6.9 cm. On the other hand, the addition of nitrogenous fertiliser (KNO_3) led to increasing the E_h value. The NO_3^--N ion is oxidised and accepts electrons causing E_h to increase from –220 to –165 mV.

$$NO_3^- + 2H^+ + 2e \rightarrow NO_2^- + H_2O \quad (2)$$

In the flooded soils, anaerobic micro-organisms also facilitated the reduction of $Fe^{(III)}$ and $Mn^{(III)}$ to $Fe^{(II)}$ and $Mn^{(II)}$, respectively, causing harmful effects to plants, particularly by breaking enzymatic

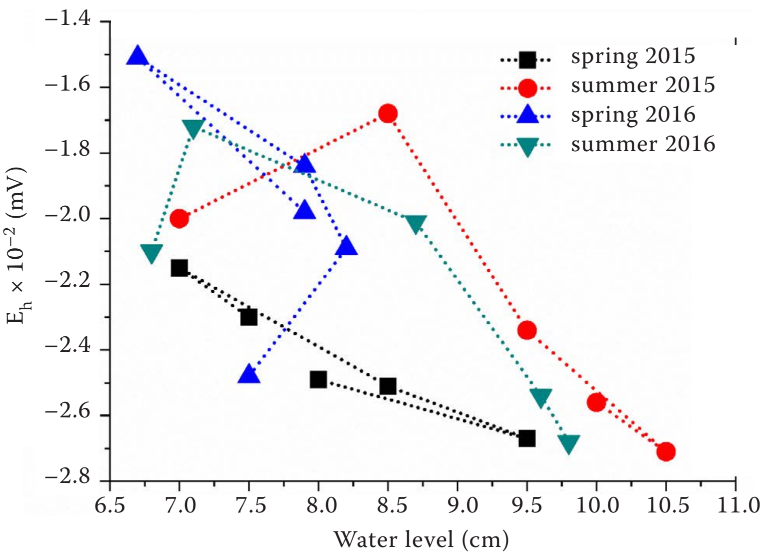

Figure 2. The relationship between water level and redox potential (E_h) in the flood irrigation treatment

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structures (Hafeez et al. 2013). Precipitants formed in the root zone by compounds of sulfide with heavy metal ions, such as Zn^{2+}, Mn^{2+}, or Fe^{2+}, as presented in Eqs. 3–6, not only reduced hypoxia near the rice roots but also served as an explanation for decreasing Zn nutrients in the soil (Hafeez et al. 2013).

$$HS^- + Zn^{2+} \rightarrow H^+ + ZnS\downarrow \quad (3)$$

$$S^{2-} + Zn^{2+} \rightarrow ZnS\downarrow \quad (4)$$

$$Mn^{2+} + S^{2-} \rightarrow MnS\downarrow \quad (5)$$

$$Fe^{2+} + S^{2-} \rightarrow FeS\downarrow \quad (6)$$

In contrast, the WSI management regime of flooding fields to 3–5 cm and drying fields between irrigation periods for 3–7 days. The water level of the WSI field was presented in Figure 3.

The water level fluctuated from 0–2.5 cm during irrigation and was 0 cm during the drying stage. Drying the field increased oxygen gas penetration into the soil (Hafeez et al. 2013). Although the soil was once an anaerobic environment, the appearance of oxygen increased the oxidation reaction of electron acceptors (for example, NO_3^--N, SO_4^{2-}-S, MnO_2 and HCO_3^-), thus increasing E_h (Reddy and Patrick 1986). Results showed higher the E_h value under the WSI cultivation system compared with FI water management treatments. Water control contributes to the aerobic soil environment and limits reduction processes (Hafeez et al 2013). The reduction environment could be limited when the redox potential increases above –100 mV and the E_h relatives positively to the oxygen concentration (Reddy and Patrick 1986, Mitsch and Gosselink 2000). Oxygen provided during drying periods resulted in increases of E_h from –200 to –50 mV, as shown in Figure 3.

The increase E_h sharply in the drying period corresponded to the water level at 0 cm. The effect of drying field from 3–7 days of the WSI cultivation system created slightly cracked soils on the surface. Oxygen diffusion rates and oxygen concentration became better in this soil system (Mitsch and Gosselink 2000b). At this time, the E_h values of the WSI soil system increased from –85 to –50 mV. The E_h potential is above the level of –100 mV limits the production of sulfide in soils (Reddy and Patrick 1986, Mitsch and Gosselink 2000).

The change of mobile Zn in paddy soils under the FI and WSI technique. Figure 4A showed a significant decrease in the mobile Zn concentration over the course of the FI regime. These results show a clear trend of low mobile Zn concentration in soils exposed to flood irrigation. Mobilisation of Zn was lower under the reducing conditions present in anaerobic flood soils (from 0.65–0.17 mg/kg, Figure 4A). The average mobile Zn decreased sharply from 0.52 to 0.39 mg/kg (R^2 = 0.71–0.80) during the growth stages. There was a significant difference (P < 0.05) in the mean values of mobile Zn between consecutive sampling stages, showing that long-term flooding affects Zn dynamics.

Continual flooding of the soil in an anaerobic state led to a decrease in the mobile Zn content of 3.6–5.7 times/crop. High Zn demanded at the ripening stage and long-term flooding during growth stages 4 and 5 reduced mobile Zn by 0.11 and 0.18 mg/kg, respectively (Figure 4A).

Maintaining deep floods on paddy fields limits dissolved oxygen in the soil, leading to precipitated ZnS. Therefore, the rice roots not only lack oxygen but also have less Zn and sulfate nutrition for growth (Hafeez et al. 2013).

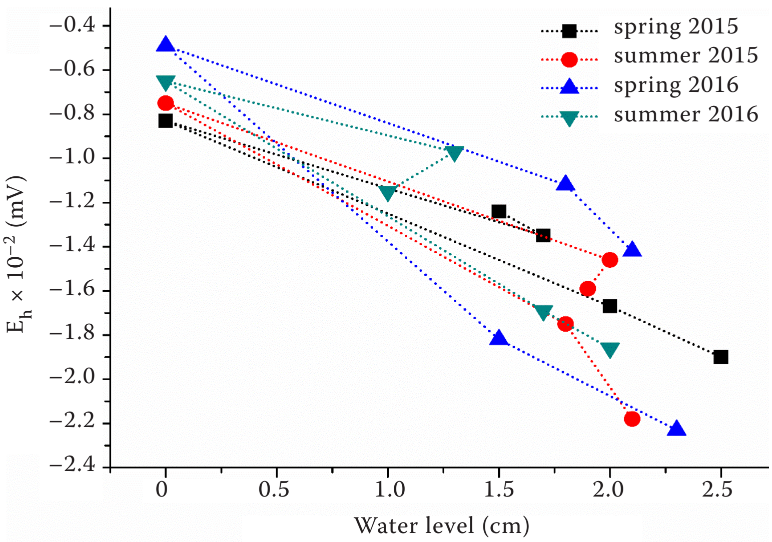

Figure 3. The relationship between water level and redox potential (E_h) in the water-saving irrigation regime

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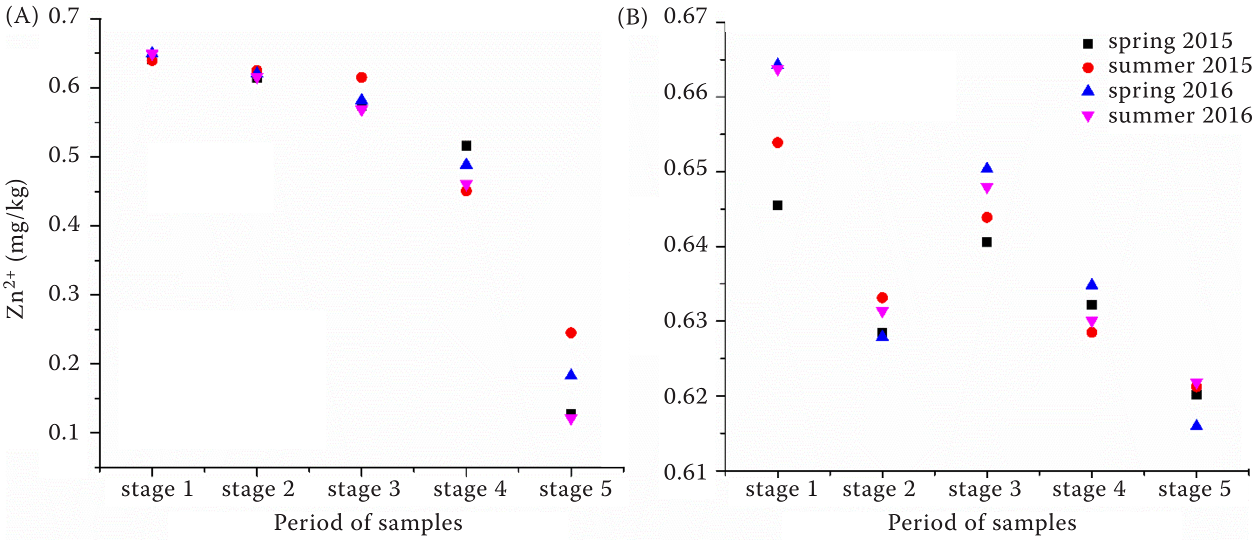

Figure 4. Comparison of the mobile zinc (Zn) concentrations in paddy soil for (A) the flood irrigation and (B) water-saving irrigation treatments. stage 1 – seeding; stage 2 – transplanting; stage 3 – end of tillering; stage 4 – flowering; stage 5 – ripening stage

Controlling water results in an insignificant improvement in the mobile Zn concentration in the paddy soil. The drying time of 5–7 days increased mobile Zn in paddy soils from 0.63 to 0.65 mg/kg during the growth stage 3, as shown in Figure 4B. Mobile Zn concentrations during stage 5 were lower than the ones in stage 4, although the water level was the same. This indicated the consumption of Zn by rice in this flourishing stage.

When water levels averaged from 1–2.5 cm during all growth stages, the mobile Zn concentrations were around 0.63–0.64 mg/kg (Figure 4B). It could be seen that mobile Zn was not fixed in sulfide precipitants, and there was a slight change of mobile Zn in soils subjected to WSI. The low water levels and drying periods accelerated the diffusion of oxygen gas into the soil, increasing the redox potential. In aerobic conditions, Zn and sulfate ions released from sulfide were precipitated by an oxidation reaction (Yoshida et al. 1979, Hafeez 2013) in which aerobic microorganisms participated.

$$2ZnS + 3O_2 + 2H_2O \rightarrow 2Zn^{2+} + 2SO_4^{2-} + 4H^+ \quad (7)$$

Mobile Zn increases during field drying periods between irrigation periods. Therefore, WSI can maintain mobile Zn content in the paddy soils.

A comparison of the mobile Zn dynamics at soil depths 0–20 cm of the experiment between the FI and WSI treatments shows that FI reduces mobile Zn significantly, and is maintained by WSI (Figures 4A, B).

The concentration of mobile Zn in the WSI field decreased slightly by 1.04–1.08 times (from 0.66–0.62 mg/kg, 5.7% respectively), while in the FI, it dramatically reduced by 3.6–5.7 times (73.6% respectively). Results showed greater availability of nutrient Zn content under drying soil treatment compared with flooding water management.

Independent *t*-test analysis of mobile Zn between FI and WSI shows that except in stage 1 at seeding ($P = 0.07$), all differences of mobile Zn between other stages are significant ($P < 0.05$). This indicates the impacts dramatically of irrigation water levels on Zn dynamics in paddy soil. This is in agreement with many other studies on rice (Alloway 2008, Lin et al. 2011, Johnson-Beebout et al. 2016) and indicates that effects of water management on the paddy soil can keep mobile Zn level in the soil.

Effects of water management on rice yield. High water levels affected rice yields (Alloway 2008) due to sulfide toxins in root zones (Yoshida and Chaudhry 1979) and decreased mobile Zn levels in the soil (Alloway 2008). The sulfide toxins prevent the nutrient absorption of roots (Yoshida and Chaudhry 1979). Therefore, Zn deficiency in paddy soil has affected the growth and yield of rice (Alloway 2008). The results showed that the rice yield from the WSI field was 0.83 t/ha more than the FI field, equating to an increased yield of 15.56% (Table 2). This difference was significant.

The Zn deficiency in paddy soil might cause a loss of yield of FI treatment because rice can absorb mobile Zn as Zn^{2+} cations and its organic complexes by roots systems (Suzuki et al. 2008, Yoneyama et al. 2015). In

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these mechanisms, an amount of mobile Zn in the soil solution is transported toward the rice roots (Yoneyama et al. 2015). However, sulfide substances can reduce mobile Zn in soil solution, which can precipitate available Zn as ZnS in anaerobic paddy soils (Yoshida and Chaudhry 1979). Therefore, forming insoluble sulfide compounds creates lower mobile Zn concentrations in flooding soil. This may reduce Zn absorption, and grain yield decreases sharply. Thus, it is essential to maintain Zn nutrition in paddy soils. The results for these yields confirm that Zn deficiency has its impact firmly already in rice growth stages (Alloway 2008). All of the differences are significant ($P < 0.05$); this indicates the effects of Zn deficiency in paddy soil on grain yield.

Zn uptake by rice. Rice is one of the most important food crops in Asia (Alloway 2008) and is the leading food for about half the world's people (Prasad et al. 2017). The Zn decrease in rice grain has affected the nutritional quality and causes health problems of humans (Alloway 2008), and its effects are more profound in children (Boonchuay et al. 2013). Grain Zn is derived either from the root uptake process, which is dependent on mobile Zn in soil solution and root activity during the grain stage (Arnold et al. 2010, Impa and Johnson-Beebout 2012). Zn content in rice grains is impacted by related factors of plant and environmental and crop management techniques (Nakandalage et al. 2016). Grains' quality of many kinds of cereal, including rice, were affected by Zn deficiency on flood soil types in most agricultural areas of the world (Alloway 2008). To evaluate the effect of zinc deficiency on rice seeds, we analysed the Zn content in grains. The results showed that the uptake of Zn by rice was affected by

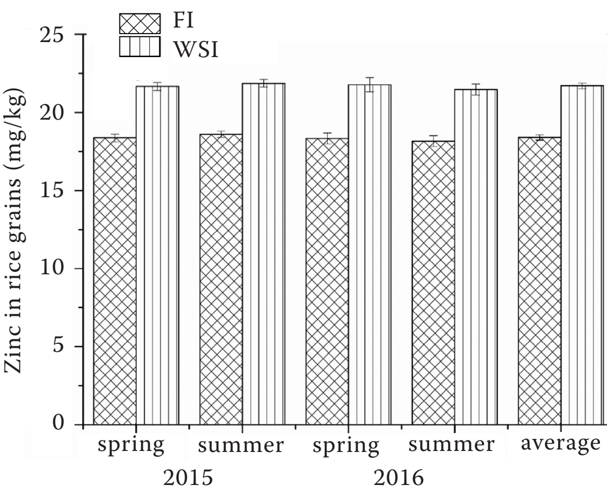

Figure 5. The concentration of zinc in rice grains with the flood irrigation (FI) and water-saving irrigation (WSI) regimes

the irrigation techniques (Alloway 2008, Nakandalage et al. 2016). As seen in Figure 5, the average Zn content in rice grown in the WSI field was 21.7 ± 0.18 mg/kg, while 18.4 ± 0.17 mg/kg for the FI rice. The impact of the different irrigation strategies was significant ($P < 0.05$). The application of WSI is practical at increasing Zn content in grain of rice, and the time spent drying the fields plays an essential role in this process.

Due to the control of irrigation water, the Zn content in grain of rice grown by WSI is higher than FI rice by 3.35 mg/kg. The WSI regime had a significant effect on the Zn concentration in the rice seeds, increasing grain Zn by 17.93%. This result is suitable for other studies of (Uçgun et al. 2018) about the effects of the FI on Zn uptakes of the plant. The greatest Zn (53.05 mg/kg) mineral content was obtained on the leaf from 4–7 days interval of drip irrigation while the lowest values were obtained from the FI (43.05 mg/kg). These results suggest that in paddy soils under flooded conditions, there is decreased Zn content in the rice, and increases in grain Zn in paddy soils treated by WSI.

In conclusion, the present study demonstrated that the FI application creates an anaerobic soil environment that quickly increases sulfide toxins and reduces mobile Zn due to ZnS precipitation, causing Zn deficiency in paddy soils in Vietnam. This study shows the advantages of the WSI method. The decrease in mobile Zn concentration was lower for the WSI method at 1.06 times/crop compared with 4.06 times/crop for the FI method. The rice yield from the WSI field was significantly higher than the FI field by 15.56%. The WSI treatment had a grain Zn increasing by 17.93% than the FI treatment. These results demonstrate that the application of FI rice systems on soils may increase Zn deficiency problems. Thus, the WSI irrigation method contributes to maintaining Zn nutrients in the soil as well as improving the yield of rice production.

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