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Application of zinc improves the productivity and biofortification of fine grain aromatic rice grown in dry seeded and puddled transplanted production systems

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ABSTRACT

Zinc (Zn) deficiency is a major constraint for rice (*Oryza sativa* L.) production and a global concern for human nutrition. Water scarcity and increasing labour costs are dictating the shift in rice culture from puddling, transplanting and flooding to dry seeding and the use of alternate wetting and drying water management. These changes may affect Zn availability to rice plants. This study was conducted to evaluate the effect of four different Zn application methods on the productivity, profitability, and grain Zn concentration of rice at two different sites (Faisalabad and Sialkot) in Punjab, Pakistan in 2013 and 2014. Zinc was applied as $ZnSO_4{\cdot}7H_2O$ either as a (1) basal application to the soil (10 kg Zn ha^{-1}), (2) foliar spray (0.5% Zn solution), (3) seed primer (0.5 *M* Zn), or (4) seed coating (2 g Zn kg^{-1} seed). The rice cultivar, Super Basmati, was grown in conventional puddled transplanted flooded (TR) and dry-seeded non-flooded rice (DSR) systems. All Zn application methods increased grain yield of both DSR and TR by around 30% compared with the control (no added Zn). While there were significant differences between the effects of the application methods on grain yield at both sites, the differences were small ($\leq$0.2 t ha^{-1}) and there were no consistent trends, apart from much lower yield with seed coating of TR at Sialkot. All Zn treatments significantly increased grain Zn concentration in both production systems at both sites, apart from seed coating in DSR at Faisalabad. Seed coating consistently gave the smallest increase in grain Zn concentration. Foliar Zn application consistently gave the highest or equal highest grain Zn concentration at Faisalabad, while soil application consistently gave the highest or equal highest concentration at Sialkot. Profitability was greatly increased by all Zn application methods, with net benefit increasing by factors of 1.4–3.1. Foliar application was the most profitable method for TR at both sites, while seed coating was the most profitable method for DSR. At both sites, seed coating produced by far the highest agronomic efficiency and apparent recovery, mainly due to the low amount of Zn applied. In conclusion, all four Zn application methods increased rice paddy yield and profitability at both sites in both TR and DSR. Given the low effectiveness of seed coating in increasing grain Zn concentration, it is recommended that farmers apply Zn to rice by soil application, seed priming or foliar application.

1. Introduction

Rice (*Oryza sativa* L.) fulfils about 21% of the global energy and protein requirements of the human population and feeds more than half of the world population (McLean et al., 2002). About 60–70% of people in Asia and sub-Saharan Africa are at risk of Zn deficiency (Gibson, 2006), which is equivalent to 2 billion people in Asia and 400 million in sub-Saharan Africa (IRRI, 2006). More than 4% of the worldwide mortality and morbidity in children under five years and 16 million of the global disability-adjusted life years are caused by Zn deficiency (Black et al., 2008; Walker et al., 2009).

Zinc has multiple roles in the core biochemical processes in plants including enzyme activation, protein synthesis, starch, auxin and nucleic acid metabolism, and pollen development (Marschner, 1995;

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Cakmak, 2000; Chang et al., 2005). More than 50% of field crops are sensitive to Zn deficiency, but Zn deficiency in rice is more common than that observed in other field crops (Dobermann and Fairhurst, 2000; Fageria et al., 2002; Quijano-Guerta et al., 2002).

Zinc deficiency occurs in both conventional flooded (Dobermann and Fairhust, 2000) and direct-seeded aerobic (Fageria, 2000; Gao et al., 2006) rice production systems. Various soil factors such as pH, redox potential and the concentrations of Zn, P, Fe and Mn in the soil solution affect plant availability of Zn in paddy fields (Mandal et al., 2000; Alloway, 2009; Fageria et al., 2011). For instance, Zn precipitates as ZnS at low redox potential, as $Zn(OH)_2$ with increases in soil pH, and as $ZnCO_3$ in calcareous soils (Bostick et al., 2001), which decreases plant Zn availability (Quijano-Guerta et al., 2002; Johnson-Beebout et al., 2009).

Physical or economic water scarcity, increasing labour costs, and labour shortages are driving change from conventional puddling, transplanting and flooding (TR) of rice to labour-saving and irrigation water-saving systems such as dry seeding with alternate wetting and drying water management (Farooq et al., 2011). This shift alters soil water content and redox potential, and thus other soil properties including Mg:Ca ratio, bicarbonate concentration and soil organic matter status (Rehman et al., 2012), which influence plant Zn availability (Gao et al., 2006, 2012; Rehman et al., 2012; Guo et al., 2016). Plant uptake of Zn is mainly controlled by diffusion (Marschner, 1995). Thus, the lower soil water content in dry-seeded aerobic rice (DSR) compared with flooded rice may reduce the transport of Zn to roots (Yoshida, 1981). Likewise, the increased soil redox potential (Gao et al., 2002) under aerobic conditions may cause iron (Fe) and manganese (Mn) oxides to form, onto which Zn might be adsorbed (Guo et al., 2016).

Grain biofortification is an economical and viable option for improving Zn levels in grain and reducing the wide-scale nutritional disorders induced by Zn deficiency in rice, the staple food crop in much of Asia. The two main approaches for grain biofortification are breeding (Cakmak, 2008; Phattarakul et al., 2012; Johnson-Beebout et al., 2016) and micronutrient fertilisation. Micronutrient fertilisation is a cost-effective approach for increasing Zn concentration in grains (Cakmak, 2008; Phattarakul et al., 2012).

In rice, Zn fertiliser may be delivered through soil application, as a foliar spray or as seed treatments (Johnson et al., 2005). Soil application is the principal method for Zn supply in conventional flooded production systems (Dobermann and Fairhurst, 2000; Khan et al., 2003; Naik and Das, 2007). However, the high cost of chelated-Zn fertilisers, high application rates required, and Zn binding in the soil make soil application uneconomical in some situations (Jiang et al., 2008; Stomph et al., 2011). Foliar sprays may be a cost-effective alternative (Stomph et al., 2011). Different methods of Zn application may have different outcomes in different rice production systems (Rehman et al., 2012). For example, in conventional flooded systems, rice yields increased more with soil application of Zn than with a foliar spray (Ram et al., 2015; Ghoneim, 2016). In contrast, in dry-seeded aerobic rice, foliar spray improved zinc levels more than soil application, improved grain yield (Abilay and De Datta, 1978) and increased kernel Zn concentrations (Ram et al., 2015; Ghoneim, 2016). In another study on rice, soil application of Zn (10 kg ha^{-1}) improved grain yield and grain Zn concentration compared to foliar application (Rana and Kashif, 2014).

Micronutrient delivery of Zn as a seed treatment is another viable option (Farooq et al., 2012). For seed priming, seeds are soaked in aerated micronutrient solution followed by redrying to the original seed weight (Farooq et al., 2012; Rehman et al., 2016). For seed coating, the target material adheres to the seed surface as an outer covering (Farooq et al., 2012; Rehman et al., 2016).

Several published studies have compared soil, foliage and seed treatments of Zn application in rice (e.g., Slaton et al., 2001; Khan et al., 2003; Phattarakul et al., 2012; Imran et al., 2015). However, no study has been carried out to compare the influence of various Zn application methods on the productivity, profitability and grain Zn concentrations of rice grown in DSR and TR production systems. For this study, we hypothesised that Zn application would improve paddy yield and grain Zn concentration in rice grown in different production systems and that DSR would be more responsive to Zn than TR because of the drier soil conditions. The specific objective of this study was to determine the most effective and economical way of applying Zn to improve paddy yield and grain Zn concentration of fine grain rice grown in DSR and TR production systems.

2. Materials and methods

2.1. Site, soil and climatic conditions

This study was conducted at two locations—the Agronomic Research Farm, University of Agriculture Faisalabad (31°N, 73°E, 184.4 m asl), Pakistan, and in a farmer's field in the district of Sialkot (32.51°N, 74.53°E, 256 m asl)—in 2013 and 2014. At both sites, there were two production systems: puddled transplanted flooded rice (TR) and dry-seeded rice with alternate wetting and drying water management (DSR).

The soil at Faisalabad was a sandy loam from the Lyallpur series with pH 7.6, 0.38% soil organic matter, 0.35 dS m^{-1} electrical conductivity, 0.05% total N, 6.88 mg extractable P kg^{-1}, 163 mg extractable K kg^{-1}, and 0.63 mg DTPA extractable Zn kg^{-1}. The experimental soil at Sialkot was a silt loam from the Sialkot series with pH 7.5, 0.52% organic matter, 0.31 dS m^{-1} electrical conductivity, 0.23% total N, 11.61 mg extractable P kg^{-1}, 170 mg extractable K kg^{-1}, and 0.67 mg DTPA extractable Zn kg^{-1}. Total N, extractable P, soil organic matter, and DTPA extractable Zn were estimated using the methods of Bremner and Mulvaney (1982), Olsen et al. (1954), Lindsay and Norvell (1978), and Walkley and Black (1934), respectively, as detailed in the USDA Handbook No. 60. Exchangeable K was estimated using the protocol of Cox et al. (1999). A Thermo Scientific Orion 4-star meter (Thermo Fisher Scientific Inc., Beverly, MA) was used to measure the pH and electrical conductivity in both soils.

The climate of Faisalabad is subtropical with frequent periods of high temperature during summer. The mean minimum and maximum temperatures during winter and summer vary from 6 to 21 °C and 27–39 °C, respectively. The climate of Sialkot is humid subtropical, and temperatures in winter may drop to −2 °C, and in summer may reach 49 °C. Cumulative water input (irrigation + rainfall) for the rice-growing period at Faisalabad and Sialkot in 2013 and 2014 are given in Fig. 1. Cumulative pan evaporation at Faisalabad site is given in Fig. 2.

2.2. Experimental design and treatments

The seed of rice cultivar Super Basmati was obtained from the Rice Research Institute, Kala Sha Kaku, Pakistan. At both sites in both years, the experiment was laid out in a randomised complete block design with a split-plot arrangement, where rice production systems were randomised in the main plots and Zn application methods were randomised in subplots (8 m × 2.2 m) with three replicates. The experiment was conducted in the same fields for two successive years. The experiment had two rice production systems, *viz.* DSR and TR, and four Zn application methods, *viz.* soil application, foliar application, seed priming and seed coating.

For soil application, Zn was applied as a basal dose at 10 kg ha^{-1}. For foliar application, Zn solution (0.5%) was applied as a foliar spray solution using a manual sprayer at the peak tillering stage (BBHC 23) (Lancashire et al., 1991). For seed priming, rice seeds were soaked in 0.5 *M* aerated solution of Zn for 24 h, with a seed to solution ratio of 1:5 (w/v). During soaking, aeration was provided with an aquarium pump. After removal from the solution, the seeds were thoroughly rinsed with water and re-dried to their original weight with forced air in the shade. For seed coating, a sticky slurry was prepared with Arabic gum. The rice