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## Zinc fractions in soil and their bioavailability to rice under different water management regimes

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### Abstract

What determines how much zinc actually reaches rice roots in paddy soils? A field experiment at Ahmadu Bello University, Zaria, Nigeria during the 2023 wet season examined zinc fractions and their bioavailability to lowland rice under four water regimes: continuous flooding (CF), alternate wetting and drying (AWD), saturated soil culture (SSC), and aerobic rice (AR). Sequential extraction separated zinc into water-soluble, exchangeable, organically-bound, Fe-Mn oxide-bound, and residual fractions. AR and AWD treatments showed higher water-soluble and exchangeable Zn than CF, likely because periodic aeration encouraged oxidative release from oxide phases. Grain Zn was highest in AR (28.7 mg kg<sup>-1</sup>) and lowest in CF (19.4 mg kg<sup>-1</sup>). Exchangeable and water-soluble Zn together explained 78.3% of the variation in grain Zn uptake. These findings suggest that water-saving irrigation may improve Zn nutrition in rice grown on marginally Zn-deficient soils.

**Keywords:** Zinc fractions, bioavailability, rice, water management, alternate wetting and drying, sequential extraction, DTPA-extractable zinc, paddy soil, aerobic rice, micronutrient nutrition

### Introduction

How much zinc in paddy soils is actually plant-available, and does irrigation management change that picture? Roughly two billion people depend on rice as a staple, and zinc deficiency in both soils and human diets is widespread across tropical Asia and sub-Saharan Africa <sup>[1]</sup>. Total soil zinc is a poor predictor of plant uptake; the distribution among chemical fractions differing in solubility matters far more <sup>[2]</sup>.

Sequential extraction protocols partition soil zinc into water-soluble, exchangeable, organically-bound, oxide-bound, and residual pools <sup>[3]</sup>. The first two are generally plant-available, while oxide-bound and organic fractions serve as slower-release reserves <sup>[4]</sup>. These pools shift in response to redox conditions and microbial activity, both influenced by water management <sup>[5]</sup>. Continuous flooding creates reducing conditions that can lower Zn availability through co-precipitation with iron sulfides <sup>[6]</sup>, whereas water-saving methods like AWD allow periodic aeration, potentially releasing zinc from oxide-bound pools <sup>[7]</sup>.

Nigeria's Savanna zone, where rice cultivation is expanding, often has marginally Zn-deficient soils <sup>[10]</sup>. This research assessed how four water management regimes affect zinc fractionation and bioavailability to lowland rice under field conditions at Zaria, Nigeria.

### Research Area Description

The experiment was sited at the Teaching and Research Farm of Ahmadu Bello University, Samaru, Zaria (11°11'N, 7°38'E; 686 m a.s.l.) in the Northern Guinea Savanna zone. Mean annual rainfall is 1,050 mm (May-October), with a dry season from November to April. The soil is a Typic Haplustalf with sandy loam texture. Previous land use was mixed cereal-legume rotation with no rice for at least five years.

### Materials and Methods

#### Materials

Rice variety FARO 44 was transplanted at 21-day-old seedlings. Basal fertilisers were 60 kg N ha<sup>-1</sup> (urea, split-applied), 30 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>, and 30 kg K<sub>2</sub>O ha<sup>-1</sup>. No zinc fertiliser was applied.

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Soil samples (0-20 cm) were collected at transplanting, mid-tillering, panicle initiation, flowering, and harvest. Grain and straw were oven-dried at 65 °C and digested in HNO<sub>3</sub>:HClO<sub>4</sub> (9:4) for AAS determination <sup>[11]</sup>.

Methods

The trial used a randomised complete block design with four treatments and three replications (July-November 2023). Plot size was 5 m × 4 m with 1 m bunds. Treatments: (i) CF—maintaining 5-7 cm standing water; (ii) AWD—allowing water table to drop 15 cm below surface before re-flooding; (iii) SSC—saturation without standing water; (iv) AR—irrigating to field capacity at 70% saturation. Sequential extraction followed Tessier *et al.* <sup>[3]</sup> modified by Mandal and Mandal <sup>[13]</sup>. DTPA-extractable Zn was measured using Lindsay and Norvell <sup>[14]</sup>. Treatment means were compared by LSD at 5%.

Soil Quality Analysis

The plough layer had 64.2% sand, 21.7% silt, 14.1% clay, pH 6.7, organic carbon 0.83%, total Zn 37.8 mg kg<sup>-1</sup>, and DTPA-Zn

1.94 mg kg<sup>-1</sup>—below the 2.0 mg kg<sup>-1</sup> critical level for rice <sup>[14]</sup>.

Results

Table 1: Zinc fractions (mg kg<sup>-1</sup>) at flowering under four water management regimes

| Zinc Fraction     | CF    | AWD   | SSC   | AR    | LSD (0.05) |
|-------------------|-------|-------|-------|-------|------------|
| Water-soluble     | 2.34  | 3.18  | 2.87  | 3.52  | 0.41       |
| Exchangeable      | 4.67  | 5.93  | 5.21  | 6.38  | 0.73       |
| Organically-bound | 8.92  | 7.45  | 8.13  | 6.71  | 0.89       |
| Fe-Mn oxide-bound | 12.38 | 10.67 | 11.24 | 9.83  | 1.12       |
| Residual          | 21.46 | 22.13 | 21.89 | 22.67 | NS         |

CF = Continuous Flooding; AWD = Alternate Wetting-Drying; SSC = Saturated Soil Culture; AR = Aerobic Rice; NS = Not Significant.

AR recorded the highest water-soluble Zn (3.52 mg kg<sup>-1</sup>) and exchangeable Zn (6.38 mg kg<sup>-1</sup>), while CF had the lowest values (Table 1). Fe-Mn oxide-bound Zn was higher under CF (12.38) than AR (9.83). The residual fraction didn't differ among treatments.

Table 2: Grain and straw zinc concentration and total uptake

| Treatment  | Grain Zn (mg kg <sup>-1</sup> ) | Straw Zn (mg kg <sup>-1</sup> ) | Total uptake (g ha <sup>-1</sup> ) | LSD (0.05) |
|------------|---------------------------------|---------------------------------|------------------------------------|------------|
| CF         | 19.4                            | 11.2                            | 187.3                              | -          |
| AWD        | 25.8                            | 14.7                            | 234.6                              | -          |
| SSC        | 22.3                            | 13.1                            | 211.8                              | -          |
| AR         | 28.7                            | 16.3                            | 258.9                              | -          |
| LSD (0.05) | 3.2                             | 1.9                             | 28.4                               | -          |

Grain zinc followed AR > AWD > SSC > CF, with AR at 28.7 and CF at 19.4 mg kg<sup>-1</sup> (Table 2). AWD and SSC didn't differ statistically for grain Zn but both exceeded CF.

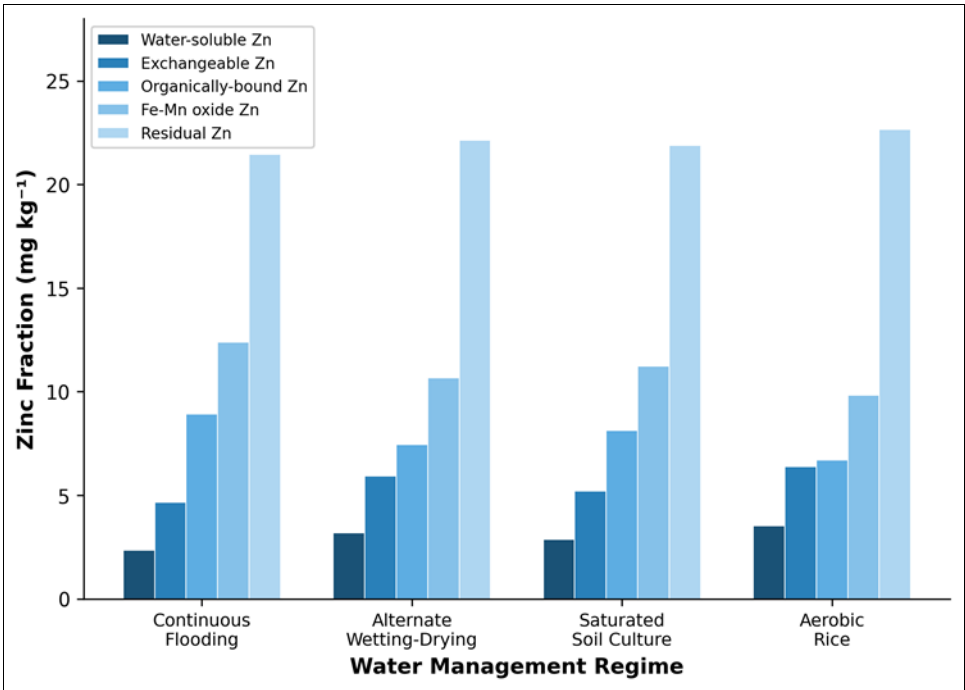


Fig 1: Zinc fractions at flowering under four water regimes.

The residual fraction dominated total Zn under all treatments (43-46%). Under CF, Fe-Mn oxide Zn was the second largest pool; under AR, the exchangeable fraction was proportionally larger (Figure 1).

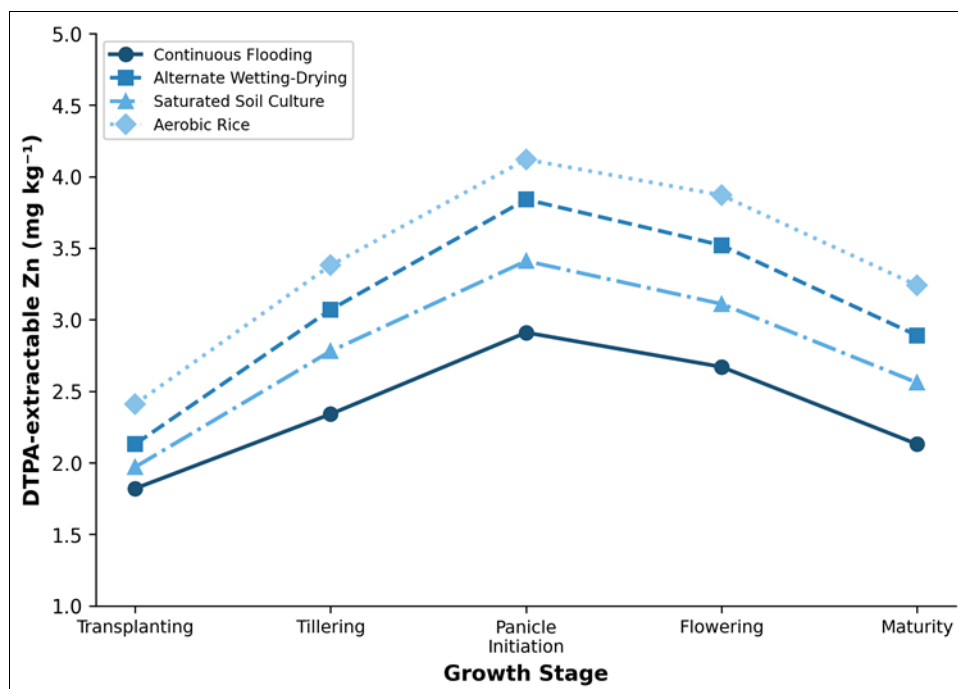


Fig 2: DTPA-extractable Zn across growth stages under four water regimes.

DTPA-Zn peaked at panicle initiation in all treatments (Figure 2). AR reached  $4.12 \text{ mg kg}^{-1}$  while CF peaked at only  $2.91 \text{ mg kg}^{-1}$ . This peak coincides with the period of greatest Zn demand.

### Comprehensive Interpretation

Stepwise regression showed exchangeable Zn explained 64.7% of grain Zn variation ( $p < 0.01$ ). Adding water-soluble Zn raised  $R^2$  to 0.783. No other fraction entered at the 5% level, confirming labile pools as the dominant supply pathway.

### Discussion

The redistribution of zinc among fractions is consistent with redox-driven mechanisms. Under continuous flooding, strongly reducing conditions favour zinc co-precipitation with iron oxyhydroxides, locking it in oxide-bound phases [6, 15]. Periodic aeration in AWD and AR re-oxidises these compounds, releasing co-precipitated zinc onto exchange sites [7].

The exchangeable Zn pool under AR was 37% higher than CF, and grain Zn increased by nearly 48%. These results agree with Gao *et al.* [8], who reported 30-40% rises in brown rice Zn under intermittent irrigation in Chinese paddy soils. The absolute values here were lower, reflecting the lower CEC and total Zn of this sandy loam.

An important finding is that AR maintained DTPA-Zn above the  $2.0 \text{ mg kg}^{-1}$  critical level throughout the season, while CF fell below it at transplanting and maturity. That said, grain yield under AR was about 11% lower than CF due to brief drought stress. AWD appears to offer the best compromise—maintaining 87% of CF yield while boosting grain Zn by 33%.

### Conclusion

This research showed that water management significantly altered zinc distribution among soil fractions and affected bioavailability to rice. Periodic aeration under AWD and AR shifted zinc from Fe-Mn oxide-bound forms into labile pools. Grain zinc was highest under AR ( $28.7 \text{ mg kg}^{-1}$ ) compared with CF ( $19.4 \text{ mg kg}^{-1}$ ). The exchangeable and water-soluble fractions jointly explained 78.3% of variation in grain zinc uptake. AWD appears to balance water saving, acceptable yield,

and improved grain zinc nutrition. Future work should test whether combining AWD with targeted zinc fertiliser can raise grain zinc to nutritionally meaningful levels.

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