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Zinc nanoparticles mediated biofortification and nutrient interactions in cowpea (*Vigna unguiculata* L.)

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Zinc deficiency remains a major constraint to crop nutritional quality and human health, particularly in grain legumes consumed as protein-rich staples. The present study evaluated the effectiveness of zinc oxide nanoparticles (ZnO-NPs) as a foliar biofortification strategy in cowpea (*Vigna unguiculata* L.), with emphasis on nutrient interactions, nutrient quality indices, and micronutrient partitioning. A pot experiment was conducted at Chaudhary Charan Singh Hayana Agricultural University, Hisar during the Kharif season of 2023-24 using the variety Kashi Kanchan under Completely Randomized Design with thirteen treatments and three replications. Zinc was applied as foliar spray at three zinc concentrations (400, 500 and 600 ppm) in both ZnO-NPs and bulk form, along with an untreated control. Foliar sprays were imposed at 25 and 50 DAS. Seed nutritional parameters, including protein, nitrogen, total soluble sugars, total phenolics, potassium, zinc, iron, copper, manganese, and zinc nutrient harvest index (Zn-NHI), were determined. Zinc application significantly improved seed nutritional quality, with ZnO-NPs treatments consistently outperforming bulk zinc. The highest protein (27.81%), nitrogen (4.45%), soluble sugars (39.57 mg g^{-1}), phenolics (931.10 mg GAE 100 g^{-1}), micronutrient concentrations, and Zn-NHI (61.72%) were recorded under 600 ppm ZnO-NPs applied twice which remained statistically at par with 500 ppm ZnO -NPs applied twice. Nutrient responses were further integrated using Z-score transformation and a Z-based Nutrient Quality Index (Z-NQI), supported by regression analysis where Z-score and NQI analyses clearly differentiated treatments, with 500 & 600 ppm ZnO-NPs (two sprays) achieving the significantly highest NQI, indicating superior nutrient balance and biofortification efficiency. Regression analysis revealed strong associations between NQI and protein, zinc, and Zn-NHI (R^2 up to 0.90), confirming zinc as a key driver of overall nutritional enhancement. The study demonstrates that ZnO-NPs, particularly at 500 ppm with two foliar applications, offer an efficient and integrative strategy for zinc biofortification and nutritional quality improvement in cowpea.

Keywords: Zinc Nutrient Harvest Index, Z-score Analysis, Regression analysis, Nutritional Quality Index, Foliar Application, ZnO-NPs and nutrient interaction