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Biofortification of finger millet with zinc and iron under biochar amendment: Effects of soil and foliar fertilization on yield and grain quality

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Abstract

Biofortification is an effective strategy to improve the micronutrient content of staple crops. However, biofortification of finger millet (*Eleusine coracana L.*) with zinc (Zn) and iron (Fe) has not been adequately investigated under biochar amendment. Pot experiments were conducted in Gulu, Uganda, during the years 2022 and 2023 to evaluate the effects of soil and foliar application of Zn and Fe fertilizers on grain yield and quality of finger millet grown in biochar-amended Alisol and Ferralsol. Treatments included Zn and Fe fertilizers applied individually and in combination through soil and foliar methods under biochar amendment. Biochar application significantly increased grain yield by 79% in Alisol and 185% in Ferralsol compared to the non-biochar control. Foliar applications of a combination of Zn and Fe fertilizers increased grain yield by 61% and 24% under Alisol and Ferralsol, respectively, compared to soil application. Zinc fertilization significantly enhanced grain Zn concentration relative to the untreated control in both soil types. In Ferralsol, foliar application improved grain Zn content by 11% compared to soil application, whereas no difference was observed in Alisol. Grain Fe concentration showed variable responses depending on soil type and treatment. Overall, while biochar improved grain yield, its effect on Zn and Fe enrichment was not consistent across treatments and soil types. These findings suggest that the effectiveness of Zn and Fe biofortification in finger millet under biochar amendment depends on soil type and fertilizer application method.

Abbreviations: SOC, soil organic carbon; WHC, water-holding capacity.

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Plain Language Summary

This study tested ways to increase yield and improve zinc (Zn) and iron (Fe) levels in finger millet using biochar and different fertilizer methods in Uganda. Adding biochar greatly increased grain yield, especially in Ferralsol soils. Spraying Zn and Fe on leaves (foliar application) often gave better yields than applying them to the soil. Zinc levels in the grain improved with fertilization, but iron levels varied depending on soil type and treatment. Overall, while biochar boosted yield, it did not consistently improve Zn and Fe content. The results show that the success of biofortification depends on soil type and how fertilizers are applied.

1 | INTRODUCTION

Finger millet (*Eleusine coracana L.*) is cultivated on approximately 4–4.5 million ha globally, producing about 5 million metric ton of grain annually (ICRISAT, 2024); of this total, Africa contributes ~2 million metric ton (with India ~2.2 million metric ton) (Gebreyohannes et al., 2024; Kasule et al., 2023). Despite its importance, the production of finger millet is constrained by various abiotic stresses, leading to decreased yield and quality over the years. Declining soil fertility is one of the abiotic stresses decreasing its productivity. Agronomic biofortification, the application of micronutrient fertilizers to increase nutrient concentrations in edible crop portions, has emerged as a promising strategy to address hidden hunger (Azeem et al., 2025; Bouis & Welch, 2010). Studies on other cereals have demonstrated that foliar application of zinc (Zn) and iron (Fe) can effectively increase grain micronutrient content. The effectiveness of micronutrient fertilization depends heavily on soil properties, crop species, and application method (Wang et al., 2018). Foliar application enables rapid nutrient uptake directly through leaves, while soil application builds long-term nutrient reserves but is influenced by soil chemical processes that may limit availability (Ebanyat et al., 2010; Ojok et al., 2019).

One of the approaches highly regarded as a measure of soil fertility restoration is the use of biochar (H. Singh et al., 2022), which is a heterogenous combination of pyrogenic compounds with varying physical and chemical properties that interact with soil (Omara et al., 2022). Biochar helps in soil fertility restoration through direct addition of nutrients, especially base cations, in addition to improved soil pH, soil water-holding capacity (WHC), and soil organic carbon (SOC), among other benefits (Obia et al., 2020). For these reasons, biochar has repeatedly been documented to increase crop yields (Kätterer et al., 2019).

Biochar helps in altering soil pH, which in turn influences nutrient solubility and availability (Obia et al., 2016). Ferralsol and Alisol, the two common soil types in Uganda used in this study, are highly acidic in nature, and biochar addition may help to neutralize the acidity. An increase in soil pH due to biochar addition is associated with increased availability of macronutrients such as potassium (K), phosphorus (P), calcium (Ca), and magnesium (Mg) (Major et al., 2010). Increasing soil pH also reduces aluminum (Al) toxicity in acidic soils. van Zwieten et al. (2010) observed that biochar application at 10 t ha^{-1} on acidic Ferralsol resulted in a reduction of ammonium acetate extractable Al from 1.93 cmol (+) per kg of soil to an undetectable level. As such, the liming effect of biochar helps in alleviating Al stress for better crop production. Thus, our study sought to determine if biochar amendment might differentially mitigate the acidity of Ferralsol and Alisol through direct addition of base cations to these highly weathered soils characterized by low base saturation, and subsequently enhance finger millet grain production.

Zn and Fe are micronutrients vital in physiological and structural roles in humans. Low Zn and Fe content of finger millet compromises the quality of finger millet grains. It is reported that finger millet contains 2.9 and 3.0 mg 100 g^{-1} mean values of Zn and Fe, respectively, which are inadequate to meet the daily dietary allowance. According to Han et al. (2023), the daily dietary allowance for Zn in children over 6 months ranges from 2 to 5 mg day^{-1}; meanwhile, the recommended daily dietary allowance for Fe is over 8 mg day^{-1} for adults (D. Zhao et al., 2023). Fe and Zn deficiencies are two of the most widespread micronutrient deficiencies worldwide, and these, together with vitamin A, iodine, and selenium deficiencies, constitute significant "silent" public health challenges (Monika et al., 2023). These micronutrient deficiencies are particularly significant among young children, pregnant and lactating women, athletes, and manual laborers because of their higher physiological requirements. Considering the risk to health due to deficiencies of these two micronutrients, developing and testing strategies to improve Fe and Zn availability in diets, such as biofortification and better agronomic practices, remains an important priority for nutrition-sensitive agriculture (Zulfiqar et al., 2024). Therefore, strategies to enhance the micronutrient density of finger millet grains could have significant public health impacts in

regions where it is a dietary staple. One such novel strategy, which has received growing attention, is biofortification, which is aimed at improving the nutritional value of edible crops (Garg et al., 2018).

Studies on micronutrient biofortification have focused on other crops with little attention on finger millet (Ebanyat et al., 2010; Ojok et al., 2019). Further, the behavior of micronutrients applications on the weathered tropical soils typical of Uganda in the presence of biochar remains unclear (Apori & Byalebeka, 2021). Among micronutrient-based fertilizer management approaches, Foliar application is often effective for rapidly correcting plant Zn and Fe deficiencies, whereas soil application helps build soil reserves and support sustained uptake (Pal et al., 2026). Generally, foliar applications of fertilizers require less material than soil applications. According to a study by Ojok et al. (2019) on agronomic biofortification of cowpea and cabbage using iodine, results showed that foliar applications significantly increased iodine content in both crops compared to soil applications. Ebanyat et al. (2010) noted that soil application of Zn had very little effect on the Zn concentration of brown rice compared to foliar Zn application. Soil application of Zn fertilizer has been shown to increase grain Zn concentration in finger millet, demonstrating the potential of agronomic biofortification; for example, grain Zn concentration increased by about 18%–20% following Zn fertilization (Teklu et al., 2023). An increase was observed under foliar application, and a distinct increase was observed when Zn was applied at the flowering stage. Dhaliwal et al. (2010) reported that applying 0.5% foliar Zn and Fe significantly increased rice grain Zn and Fe concentrations by 37% and 30%, respectively, compared with the control, which received no micronutrient application.

Micronutrient fertilization works best in a specific condition or in combination with other strategies such as the use of organic manures, synthetic fertilizers, and biofertilizers. According to a study on pearl millet, nitrogen fertilization combined with Zn increased the yield as well as Zn content in pearl millet grains (R. Singh et al., 2014). Zn content in grain significantly varied with nitrogen and Zn rates. Therefore, this research utilized the concept of additive amendment by incorporating biochar into the biofortification of finger millet with Zn and Fe fertilizers, which, to the best of our knowledge, has not been previously reported. The objectives of this study were to (i) evaluate the effects of biochar and micronutrient-based fertilizers on the growth and yield performance of finger millet, (ii) assess the influence of foliar versus soil application of Zn and Fe fertilizers on Zn and Fe accumulation in finger millet grain, and (iii) compare the effects of biochar amendment and foliar application of Zn and Fe fertilizers on the micronutrient enrichment of finger millet grain. We hypothesized that (i) the application of biochar in combination with foliar Zn and Fe fertilizers significantly enhances the growth and yield of finger millet compared to the control treatment, (ii) foliar application of Zn and Fe fertilizers results in greater accumulation of Zn and Fe in finger millet grain compared to soil application, and (iii) biochar amendment improves the micronutrient content of finger millet grain at comparable level to foliar Zn and Fe fertilization.

2 | METHODS AND MATERIALS

2.1 | Study site and design

The biochar-based micronutrients experiment (Fe, Zn, and Fe + Zn) was conducted at Gulu University, Gulu, Uganda (02˚78.712′ N 32˚31.322′ W). The climate is tropical, wet and dry, with an average annual rainfall of 1500 mm. An open pot experiment placed within a screen house was established in a completely randomized design using eight treatments (T1–T8) and four replicates (total 32 experimental pots). Treatments comprised one control (T1; no biochar or micronutrients), a biochar-only treatment (T2), three soil-applied biochar-based micronutrient treatments (T3, T5, and T7), and three foliar biochar-based micronutrient treatments (T4, T6, and T8). The full treatment descriptions are provided in Table 1. Biochar was applied at 10% (v/v), and Zn and Fe sulfates were each applied at 1.1% as per treatment. Pots were spaced 1 m apart. Pots were positioned with 1-m spacing between rows and columns. The first-year experiment was conducted from September to December, and the second-year experiment from January to May.

2.2 | Soil management

The experimental pots measured 25 cm width × 25 cm height. Two soil types, classified under the World Reference Base for Soil Resource system as Ferralsol and Alisol (Mantel et al., 2023), were collected from a depth of 0–20 cm from common soil groups in northern Uganda. The collected soil was air-dried, crushed, and passed through a 5-mm sieve before filling in the pots. For each soil type, Ferralsol and Alisol, 10 L were filled in a pot for each treatment and replication. Biochar (pH 9.7) made from pigeon pea stems using the flame curtain technique (Baronti et al., 2010) was crushed to a ≤5-mm size before mixing with soil. Crushing increases the surface-to-volume ratio and enhances the desirable effects on soils. A volume-to-volume biochar application rate was used, where 1 L of biochar was applied to 9 L of soil (10% biochar v/v) (Obia et al., 2020). The soil and soil–biochar mixtures were left for a week to stabilize prior to planting finger millet. The soils (Table 2) were acidic (pH 5.6–5.7), with Alisol a sandy loam, low OC (0.6%), and Ferralsol a clay loam, higher OC (1.0%). The biochar was high-carbon (OC ≈ 50.9%) and contained macro- and micronutrients as presented in Table 2.

TABLE 1 Treatment structure for pot experiments conducted at the Gulu University, Gulu, Uganda.

Treatment number	Treatment acronym	Treatment descriptions
T1	Control	Finger millet grown in soils without Zn/Fe and biochar application.
T2	BC	Finger millet grown in biochar-amended soils without Zn/Fe.
T3	BC + Zn	Finger millet grown in biochar-amended soils with soil application of Zn.
T4	BC + Zn foliar	Finger millet grown in biochar-amended soils with foliar Zn application.
T5	BC + Fe	Finger millet grown in biochar-amended soils with soil application of Fe.
T6	BC + Fe foliar	Finger millet grown in biochar-amended soils with foliar application of Fe.
T7	BC + Fe +Zn	Finger millet grown in biochar-amended soils with soil application of both Zn and Fe.
T8	BC + Fe + Zn foliar	Finger millet grown in biochar-amended soils with foliar application of both Zn and Fe.

Note: BC, biochar.

TABLE 2 Chemical properties (macro- and micronutrients) of pigeon pea biochar and physical properties of Alisol and Ferralsol soil collected from two different locations in Gulu, Uganda.

Macronutrients	K (%)	Ca (%)	Mg (%)	TP (%)	TN (%)	OC (%)
	1.06	0.18	0.06	0.05	0.3	50.9
Micronutrients	**Zn (mg kg^{-1})**	**Fe (mg kg^{-1})**	**Cu (mg kg^{-1})**	**B (mg kg^{-1})**	**Mn (mg kg^{-1})**	**S (mg kg^{-1})**
	8.93	508	10.3	1.59	66.2	1.19
Soil type	**pH**	**OC (%)**	**Sand (%)**	**Clay (%)**	**Silt (%)**	**Texture**
Alisol	5.7	0.6	63.2	14	22.8	sandy loam
Ferralsol	5.6	1	38	38	24	clay loam

Note: Initial soil properties were determined prior to biochar application.
Abbreviations: OC, organic carbon; TP, total phosphorus; TN, total nitrogen.

2.3 | Crop planting and management

Ugandan Naromil 2 (FMS 376) finger millet variety was used for this experiment. This variety is widely grown in eastern and northern Uganda. It was released by the National Agricultural Research Organization in 2017 and has since gained popularity for its ability to withstand the prevailing erratic rainfall conditions. The finger millet seeds were planted at a depth of about 5 cm. Excess millet seedlings were thinned in each pot to maintain a uniform spacing of 3–5 cm between plants. Watering of the finger millets was done as needed to supplement rainfall. Weeding was carried out by manually removing the unwanted plants from the pots. Micronutrient fertilizers were supplied as zinc sulfate heptahydrate ($ZnSO_4 \cdot 7H_2O$) and ferrous sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$) of analytical grade (≥98% purity) and applied at a concentration of 1.1% (w/v) for foliar treatments and 1.1 mg kg^{-1} soil for soil applications (Ram et al., 2024). This was conducted 4 weeks after emergence and during the flowering stage. Harvesting occurred when the grains reached a firm consistency but before they fully dried, to minimize losses caused by the shattering of finger millet. Hand harvesting was performed by cutting with a knife, and the harvested materials were dried using a solar drier. Following the grain harvest, stems were cut at the soil surface, and roots were left in place to avoid disturbing the pots and soil structure. They were thoroughly cleaned and solar dried prior to biomass estimation.

2.4 | Laboratory analysis

Total biomass (below- and aboveground) and grain from each treatment were oven dried at 70°C for 24 h and weighed. In the first year (2022), the experiment was partially damaged by stray animals, which resulted in insufficient samples to reliably estimate grain and biomass yield. However, the remaining samples were adequate for nutrient analysis (Zn and Fe), and these data were used to evaluate grain micronutrient concentrations. Finger millet grain mineral content was determined using an atomic absorption spectrophotometer (AAS). Two grams of finely ground grain flour from each treatment were ashed in a muffle furnace at 500°C–550°C, and the ash was subsequently digested in 0.3 M nitric acid following standard wet digestion procedures described by AOAC (2023). After filtration and dilution, samples were analyzed using AAS, with Zn measured at a wavelength of 213.9 nm (slit width 0.7 nm) and Fe at 248.9 nm (slit width 0.2 nm).

The two soil types used in the experiment were characterized for basic properties, which included pH, organic carbon, and texture. Soil pH was measured using a digital pH meter at a soil to water ratio of 1:2.5 (v/v) (Kyebogola et al., 2020); organic carbon was measured using Black and Walkley wet oxidation procedure (Mingorance et a. et al., 2007). Soil texture was determined using the hydrometer method (Bedaiwy, 2012). WHC was determined using core rings of known volume, which were labeled according to the corresponding treatments (Nelson et al., 2024). The rings with soil were saturated with water in a basin for 24 h, after which they were removed, weighed, recorded, and allowed to drain for 48 h. The drained samples were weighed and recorded (mass moist) prior to oven drying at 105°C for 24 h and weighed again (mass dry). WHC was then calculated from Equation (1).

$$\text{WHC} = \frac{\text{Mass (moist)} - \text{Mass (dry)}}{\text{Mass (dry)}} \times 100 \quad (1)$$

2.5 | Statistical analysis

Statistical analyses were performed using SAS software (version 9.4; SAS Institute Inc.). The PROC MIXED procedure was first used to evaluate the overall effects of season and soil type on response variables. Each treatment comprised four replicate pots, which were treated as independent experimental units; treatment means and standard errors (SEs) were computed across these replicates. When season or soil effects were significant ($p < 0.05$), data were analyzed and presented separately for each soil × season subset. Within each subset, we applied a one-way analysis of variance with treatment as the single factor and used Tukey's honestly significant difference (HSD) for mean separation at $\alpha = 0.05$ (95% confidence level). In tables, values are shown as mean ± SE, and the same lowercase letter indicates no significant difference between treatments at $\alpha = 0.05$. Further, linear regressions were used to assess relationships between grain Zn and Fe concentrations and soil properties (pH, organic carbon, and WHC). For each soil type, models were fitted in the sequence Fe with pH, Fe with organic carbon, Fe with WHC, Zn with pH, Zn with organic carbon, and Zn with WHC. For each model, outputs reported are root mean square error, R^2, F value, and p-value ($\Pr > F$).

3 | RESULTS

3.1 | Finger millet yield

Results for Alisol clearly show that soil-applied treatments increased grain yield compared with the control (1307 kg ha^{-1}; Table 3). Biochar with Fe was about 93% higher (2519 kg ha^{-1}). Biochar alone was about 79% higher (2334 kg ha^{-1}). Biochar with Zn was about 50% higher (1958 kg ha^{-1}). Biochar with the combination of Fe and Zn (BC + Fe + Zn) was about 37% higher (1796 kg ha^{-1}). According to Tukey's test, the soil-applied biochar with Fe was significantly higher than the soil-applied biochar with Zn and the soil-applied biochar with the combination of Fe and Zn. Biochar with Zn and biochar with the combination of Fe and Zn were statistically similar. Biochar alone was statistically similar to the highest-yielding group (which included BC, BC + Fe, and the foliar treatments).

Foliar-applied treatments also increased yield compared with the control (Table 3). Biochar with foliar Fe and Zn (BC + Fe + Zn foliar) was about 121% higher (2887 kg ha^{-1}). Biochar with foliar Fe (BC + Fe foliar) was about 114% higher (2798 kg ha^{-1}). Biochar with foliar Zn (BC + Zn foliar) was about 89% higher (2475 kg ha^{-1}). According to Tukey's test, the foliar treatments did not differ from one another. The foliar Fe and Zn treatment was significantly higher than the control, the soil-applied Zn treatment, and the soil-applied Fe and Zn combination treatment. It was statistically similar to biochar alone, to foliar Zn, and to soil-applied Fe.

Results for Ferralsol show that all treatments that included biochar increased grain yield compared with the control (849 kg ha^{-1}) as shown in Table 3. For soil-applied treatments, biochar alone was about 185% higher (2422 kg ha^{-1}), biochar with Zn was about 178% higher (2357 kg ha^{-1}), biochar with Fe was about 188% higher (2446 kg ha^{-1}), and biochar with the combination of Fe and Zn was about 165% higher (2250 kg ha^{-1}). According to Tukey's test, the soil-applied biochar treatments did not differ from one another, and each soil-applied biochar treatment yielded significantly more than the control.

For foliar-applied treatments, biochar with foliar Zn was about 160% higher (2206 kg ha^{-1}) than the control, biochar with foliar Fe was about 175% higher (2337 kg ha^{-1}), and biochar with foliar Fe and Zn was about 229% higher (2794 kg ha^{-1}). According to Tukey's test, the foliar-applied treatments did not differ significantly from one another, and each foliar-applied biochar treatment yielded significantly more than the control. No significant differences were detected among any of the biochar-amended treatments when compared with each other in Ferralsol. Across the two soils, the average grain yield for all treatments was slightly higher in Ferralsol (2333 kg ha^{-1}) than in Alisol (2297 kg ha^{-1}), a difference of about 36 kg ha^{-1}, which corresponds to an increase of approximately 1.6%.

3.2 | Zn content of finger millet grains

Analysis of variance showed significant differences in grain Zn content of finger millet across treatments, soil types, and

TABLE 3 Mean grain and biomass (below- and aboveground) yield of finger millet grown in Alisol and Ferralsol under different treatments in 2023 at Gulu, Uganda.

		Alisol		Ferralsol	
		Grain (kg ha^{-1})	Biomass (kg ha^{-1})	Grain (kg ha^{-1})	Biomass (kg ha^{-1})
Sr. No.	Treatments	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
1	Control	1307c ± 82.1	4733b ± 219.3	849b ± 42.6	4772b ± 167.0
2	BC	2334ab ± 388.2	11,256a ± 560.0	2422a ± 114.3	9050a ± 1003.9
3	BC + Zn	1958b ± 62.0	9905a ± 219.0	2357a ± 213.2	8626a ± 1095.7
4	BC + Zn foliar	2475ab ± 232.6	10610a ± 459.6	2206a ± 320.8	8279a ± 418.1
5	BC + Fe	2519a ± 187.2	10381a ± 751.9	2446a ± 348.9	9594a ± 572.8
6	BC + Fe foliar	2798a ± 70.3	9415a ± 258.0	2337a ± 316.0	7932a ± 578.3
7	BC + Fe + Zn	1796bc ± 157.4	9965a ± 463.9	2250a ± 254.6	9503a ± 165.2
8	BC + Fe + Zn foliar	2887a ± 208.8	9944a ± 287.7	2794a ± 465.0	8334a ± 506.7
	p-value	$p = 0.0002$	$p < 0.0001$	$p = 0.0049$	$p = 0.0007$

Note: Different lowercase letters indicate significant differences across treatments using Tukey's honestly significant difference (HSD) ($\alpha = 0.05$). Control is without any treatment.
Abbreviations: BC, biochar; SE, standard error.

TABLE 4 Mean grain Zn content of finger millet grown in Alisol and Ferralsol under different treatments in 2022 and 2023 at Gulu, Uganda.

		Mean Zn content (mg 100 g^{-1})			
		Alisol		Ferralsol	
		Year 2022	Year 2023	Year 2022	Year2023
Sr. No.	Treatments	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
1	Control	22.4c ± 1.2	21.35b ± 1.6	15.9b ± 6.2	9.0b ± 3.8
2	BC	31.5abc ± 3.8	38.9a ± 4.0	32.0ab ± 5.8	33.3ab ± 2.6
3	BC + Zn	42.7a ± 0.7	41.8a ± 1.8	40.1a ± 2.4	35.7a ± 1.6
4	BC + Zn foliar	41.7a ± 1.3	43.7a ± 3.4	43.5a ± 1.6	39.6a ± 0.7
5	BC + Fe	28.1bc ± 5.2	35.0ab ± 3.3	28.0ab ± 4.3	28.5ab ± 2.6
6	BC + Fe foliar	25.3c ± 3.2	35.1ab ± 3.9	31.9ab ± 2.9	21.2a ± 6.5
7	BC + Fe + Zn	35.3abc ± 4.6	38.6ab ± 3.2	28.1ab ± 6.7	29.8ab ± 8.8
8	BC + Fe + Zn foliar	42.3ab ± 0.4	41.3a ± 0.8	33.0ab ± 3.2	30.1ab ± 8.8
	p-value	$p < 0.0001$	$p = 0.0006$	$p = 0.011$	$p = 0.015$

Note: Different lowercase letters indicate significant differences across treatments using Tukey's honestly significant difference (HSD) ($\alpha = 0.05$).
Abbreviations: BC, biochar; SE, standard error.

cropping seasons ($p < 0.05$). In Alisol, grain Zn content in 2022 was significantly higher in biochar-amended treatments compared to the control (22.4 mg 100 g^{-1}), with the highest values observed in the biochar + Zn treatments (42.7 mg 100 g^{-1} for soil application; 41.7 mg 100 g^{-1} for foliar application, Table 4). While Zn fertilization increased grain Zn relative to biochar alone, Tukey's HSD analysis indicated that differences between soil and foliar Zn applications under biochar were not statistically significant. In 2023, a similar pattern was observed, with the highest Zn content recorded in biochar + foliar Zn (43.7 mg 100 g^{-1}) and biochar + soil Zn (41.8 mg 100 g^{-1}, Table 4), both significantly higher than the control (21.35 mg 100 g^{-1}) but not different from each other or from biochar alone.

In Ferralsol, treatment effects were also significant in both years ($p < 0.05$). In 2022, the highest grain Zn was recorded in biochar + foliar Zn (43.5 mg 100 g^{-1}), significantly higher than the control (15.9 mg 100 g^{-1}) but statistically similar to biochar + soil Zn (40.1 mg 100 g^{-1}, Table 4) and other biochar-based treatments. In 2023, the trend was consistent, with the highest Zn content observed in biochar + foliar Zn (39.6 mg 100 g^{-1}, Table 4), although this did not differ significantly from soil-applied Zn under biochar (35.7 mg 100 g^{-1}, Table 4). Overall, Zn fertilization in combination with biochar increased grain Zn content relative to the control, but foliar and soil applications under biochar produced similar results in most cases.

TABLE 5 Mean grain Fe content of finger millet grown in Alisol and Ferralsol under different treatments in 2022 and 2023 at Gulu, Uganda.

		Mean Fe content (mg 100 g^{-1})			
		Alisol		Ferralsol	
		Year 2022	Year 2023	Year 2022	Year 2023
Sn	Treatments	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
1	Control	4.5b ± 1.1	4.3b ± 1.9	3.2b ± 0.6	3.4b ± 1.1
2	BC	10.5ab ± 1.3	8.6ab ± 1.6	7.6ab ± 2.6	9.7ab ± 2.2
3	BC + Zn	5.13b ± 1.0	6.7ab ± 2.1	4.3b ± 1.6	5.6ab ± 1.6
4	BC + Zn foliar	5.2b ± 1.4	4.7ab ± 0.7	9.0ab ± 1.7	5.9ab ± 1.8
5	BC + Fe	7.6ab ± 1.0	9.2ab ± 1.6	4.9ab ± 0.4	8.9ab ± 2.1
6	BC + Fe foliar	12.6a ± 3.0	13.3a ± 1.8	11.0a ± 1.1	12.4a ± 1.1
7	BC + Fe + Zn	5.0b ± 2.0	9.3ab ± 2.2	5.2ab ± 1.1	4.8ab ± 1.2
8	BC + Fe + Zn foliar	7.3ab ± 1.8	9.6ab ± 2.4	5.9ab ± 1.3	8.8ab ± 2.0
	p-value	$p = 0.021$	$p = 0.042$	$p = 0.01$	$p = 0.017$

Note: Different lowercase letters indicate significant differences across treatments using Tukey's honestly significant difference (HSD) ($\alpha = 0.05$).
Abbreviations: BC, biochar; SE, standard error.

3.3 | Fe content of finger millet grains

Analysis of variance revealed significant differences in Fe content of grain of finger millet between the two soil types and cropping seasons ($p < 0.05$) as presented in Table 5. In Alisol, the highest grain Fe content in the year 2022 was observed in the biochar-amended treatment receiving foliar Fe fertilizer (12.6 mg 100 g^{-1}), which was significantly higher than the control (4.5 mg 100 g^{-1}, Table 5) but not significantly different from other biochar-amended Fe treatments. In the year 2023, a similar trend was observed, with the highest Fe content recorded in the biochar + foliar Fe treatment (13.3 mg 100 g^{-1}, Table 5), showing a 209% increase over the control (4.3 mg 100 g^{-1}), while differences between soil and foliar Fe applications under biochar were not statistically significant.

In Ferralsol, grain Fe content was also significantly affected by treatment in both years ($p < 0.05$) (Table 5). In the year 2022, the highest Fe content (11.0 mg 100 g^{-1}) was recorded in the biochar + foliar Fe treatment, significantly higher than the control (3.2 mg 100 g^{-1}) but not significantly different from soil-applied Fe with biochar. In the year 2023, the biochar + foliar Fe treatment again showed the highest Fe concentration (12.4 mg 100 g^{-1}), a 265% increase over the control (3.4 mg 100 g^{-1}), while differences with soil-applied Fe under biochar were not statistically significant. Overall, foliar Fe application with biochar tended to produce the highest grain Fe concentrations, though in most cases these were comparable to soil-applied Fe under biochar.

3.4 | Soil properties

Soil properties were measured on samples taken at the end of the season. Soil pH was significantly affected by the treatments in Alisol ($p = 0.0025$) but not in Ferralsol ($p = 0.4082$; Table 6). In Alisol, application of Fe fertilizer through the soil (BC + Fe) significantly lowered pH to 5.11 compared to the control (5.29). Although not significant for Ferralsol, an increase in soil pH from 5.79 to 6.18 was observed under biochar-only treatments. The largest pH increase in Ferralsol was 6.18 under biochar alone, compared to the control at 5.79. In Alisol, SOC was significantly higher in most biochar-amended treatments compared to the control (0.34%), ranging from 0.45% to 0.84%, with the highest SOC observed in the biochar-alone (BC) treatment (0.84%, $p < 0.0001$). In Ferralsol, SOC was numerically higher under biochar treatments compared to the control (0.72%), ranging from 0.92% to 1.42% (in the BC + Fe + Zn foliar treatment), although differences among treatments were not statistically significant ($p = 0.4617$). Results showed that the biochar amendments enhanced SOC in both soils. Biochar application also improved soil WHC in both soil types (Table 6). In Alisol, WHC increased significantly under biochar-amended treatments, ranging from 5.93% in the control to 12.22% in the biochar + Fe + Zn foliar treatment ($p < 0.0001$). In Ferralsol, WHC was higher in biochar treatments compared to the control (10.18%), ranging from 10.09% to 12.22%, although these differences were not statistically significant ($p = 0.2913$). These results indicate that biochar amendments can enhance soil water retention.

Regression analysis was conducted to evaluate the relationship between soil properties and grain micronutrient content (Table 7). In Alisol, grain Zn content showed a significant positive correlation with SOC (OC; $p = 0.0002$) and WHC ($p < 0.0001$), and a weak but significant relationship with soil pH ($p = 0.0385$). In contrast, grain Fe content in Alisol was not significantly related to any of the measured soil parameters ($p > 0.05$). In Ferralsol, no significant relationships were

TABLE 6 Mean value of post soil properties of Alisol and Ferralsol receiving different treatments at Gulu, Uganda.

		Alisol			Ferralsol		
		pH	SOC (%)	WHC (%)	pH	SOC (%)	WHC (%)
Sr. No.	Treatment	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
1	Control	5.29a ± 0.21	0.34c ± 0.05	5.93b ± 0.59	5.79a ± 0.08	0.72a ± 0.16	10.18a ± 0.98
2	BC	5.66a ± 0.21	0.84a ± 0.09	11.52a ± 0.63	6.18a ± 0.17	1.23a ± 0.13	11.52a ± 0.63
3	BC + Zn	5.48a ± 0.09	0.75a ± 0.03	10.09a ± 0.26	5.47ab ± 0.09	1.39a ± 0.50	10.09a ± 0.26
4	BC + Zn foliar	5.38a ± 0.23	0.69a ± 0.07	11.34a ± 0.84	5.54ab ± 0.11	0.92a ± 0.29	11.34a ± 0.84
5	BC + Fe	5.11a ± 0.15	0.55ab ± 0.03	10.43a ± 0.52	5.03b ± 0.25	1.00a ± 0.18	10.43a ± 0.52
6	BC + Fe foliar	5.33a ± 0.14	0.45bc ± 0.02	10.80a ± 0.80	5.68ab ± 0.18	1.08a ± 0.24	10.80a ± 0.80
7	BC + Fe + Zn	5.04a ± 0.03	0.67a ± 0.09	10.10a ± 0.30	5.60ab ± 0.08	1.31a ± 0.13	10.10a ± 0.30
8	BC + Fe + Zn foliar	5.48a ± 0.11	0.59ab ± 0.04	12.22a ± 0.81	5.67ab ± 0.17	1.42a ± 0.08	12.22a ± 0.81
	p-value	$p = 0.0025$	$p = 0.4617$	$p = 0.2913$	$p = 0.4082$	$p < 0.0001$	$p < 0.0001$

Note: Different lowercase letters indicate significant differences using Tukey's honestly significant difference (HSD) ($\alpha = 0.05$).
Abbreviations: BC, biochar; SE, standard error; SOC, soil organic carbon; WHC, water-holding capacity.

TABLE 7 Regression analysis for the soil factors influencing Zn and Fe content of finger millet grains.

Alisol				
Parameters	**Root MSE**	***R*-squared**	***F* Value**	**Pr > *F***
Zn—pH	7.98	0.14	4.69	0.0385*
Zn—OC	6.8	0.37	17.83	0.0002*
Zn—WHC	6.11	0.49	29.24	<0.0001*
Fe—pH	4.31	0.02	0.69	0.414 ns
Fe—OC	4.36	0	0.01	0.933 ns
Fe—WHC	4.16	0.09	2.91	0.0984 ns
Ferralsol				
Zn—pH	13.27	0	0.01	0.9062 ns
Zn—OC	12.75	0.08	2.55	0.121 ns
Zn—WHC	12.75	0.08	2.54	0.1215 ns
Fe—pH	4.2	0	0.07	0.788 ns
Fe—OC	4.19	0	0.09	0.7702 ns
Fe—WHC	4.02	0.08	2.7	0.1105 ns

Abbreviations: MSE: mean square error; ns, not significant; WHC, water-holding capacity.
*denotes significant differences at $p < 0.05$.

observed between grain Zn or Fe content and any soil property ($p > 0.05$), indicating that the influence of OC, WHC, and pH on micronutrient accumulation was more pronounced in Alisol than in Ferralsol.

4 | DISCUSSION

4.1 | Grain and biomass yield

In this study, the grain yield of finger millet was generally higher in Ferralsol than in Alisol, likely due to differences in soil texture and baseline organic carbon content (1% in Ferralsol vs. 0.6% in Alisol; Table 2). Biochar application significantly increased grain yield in both soil types, which can be attributed to improvements in soil physical and chemical properties such as WHC and pH (Table 6). These findings are consistent with previous reports where biochar amendment improved crop yield by enhancing soil fertility and water retention (Borchard et al., 2019; Obia et al., 2020). Similarly, Taheri et al. (2024) reported a 58% increase in millet yield following biochar-amended saline-sodic and calcareous soil, while Bakar et al. (2015) observed rice yield increases of 141%–472% with oil palm fruit bunch biochar application. Further, Hossain et al. (2010) also reported a 64% increase in cherry *(Prunus avium*) and tomato (*Solanum lycopersicum*)

yield where 10 t ha^{-1} of wastewater sludge biochar was applied to chromosol type soil. Collectively, these studies support the notion that biochar enhances crop productivity through improvement of nutrient availability, water retention, and other soil properties, which aligns with the yield increase observed in our experiments.

Further, the addition of micronutrient fertilizers (Zn and Fe) in biochar-amended soils significantly influenced finger millet yield (Table 3). Foliar applications of Zn and Fe at tillering and flowering stages consistently resulted in higher grain yield compared to soil application, for instance, in Alisol, BC + Fe foliar (2798 kg ha^{-1}) outperformed BC + Fe (2519 kg ha^{-1}), and BC + Fe + Zn foliar (2887 kg ha^{-1}) was significantly higher than BC + Fe + Zn (1796 kg ha^{-1}), although in some cases differences were not statistically significant. The trend supports the efficacy of foliar application. Moreover, this finding aligns with earlier studies where foliar micronutrient application improved crop productivity; for example, Vijayakumar et al. (2020) reported an increase in finger millet yield from 1613 to 2258 kg ha^{-1} with foliar $ZnSO_4$ + $FeSO_4$ in NPK-treated soils, while Narimani et al. (2010) observed a 6.6% wheat yield increase with foliar micronutrient application. Zeidan et al. (2010) similarly reported enhanced grain attributes with foliar Zn and Fe application in wheat. The yield increase observed in our study may be attributed to the role of Zn and Fe in chlorophyll formation, starch metabolism, and enzyme activities such as carbonic anhydrase, which accelerate carbohydrate formation in C4 plants (Kryvoruchko, 2017). Foliar application facilitates rapid absorption of micronutrients through leaves, promoting cell division, elongation, chlorophyll content, and photosynthesis, and enhances translocation of photosynthates from source to sink (Ren et al., 2025). Overall, both biochar and micronutrient fertilization contributed to higher grain and biomass yield, with biochar likely improving nutrient availability and WHC, and foliar application aiding rapid nutrient uptake.

4.2 | Grain Zn and Fe content

Soil amendment with biochar significantly increased Zn and Fe content in finger millet grains in both Ferralsol and Alisol across the two seasons (Tables 4 and 5). Interestingly, biochar treatment alone resulted in higher grain Zn and Fe content than the control, demonstrating the biochar's intrinsic value as a micronutrient source. This is likely due to the high Zn (8.9 mg kg^{-1}) and Fe (508 mg kg^{-1}) content of the pigeon pea biochar compared to baseline soil levels (1.1 mg kg^{-1} Zn and 56 mg kg^{-1} Fe), indicating that the biochar itself contributed substantially to grain micronutrient enrichment. However, treatments where biochar was combined with micronutrients particularly through foliar application often resulted in the highest numerical values for grain Zn and Fe content. Foliar applications of Fe and Zn in biochar-amended soils further enhanced grain micronutrient concentrations in both soil types compared to their respective soil application treatments. For example, in Alisol 2023, BC + Fe foliar (13.3 mg 100 g^{-1}) resulted in the highest Fe content, significantly outperforming BC + Fe (9.2 mg 100 g^{-1}) (Table 5). This increase is attributed to more efficient nutrient absorption through leaves and the role of biochar in increasing nutrient availability in the soil (Yadav et al., 2023). Improved nutrient availability, especially nitrogen, promotes the formation of Zn- or Fe-chelating nitrogenous compounds necessary for transporting Zn and Fe within the plant (Cakmak et al., 2010). These results are consistent with previous studies showing that foliar micronutrient application increases grain Zn and Fe content (Anwar et al., 2022; Khobragade et al., 2022; Saleem et al., 2016). Saleem et al. (2016) reported maximum increases of 55% and 51.8% for Zn and Fe, respectively, following foliar application of 0.1% $ZnSO_4$ and $FeSO_4$ compared to soil application. Khobragade et al. (2022) recorded high Fe content of 15.08 mg 100 g^{-1} following foliar application of $FeSO_4$ (1%), while Anwar et al. (2022) reported increases of 34 mg kg^{-1} Zn and 0.3 mg kg^{-1} Fe in maize grains with 0.1% $ZnSO_4$ and 0.3% $FeSO_4$ foliar application. The enhanced absorption is supported by the mechanism described by Reddy et al. (2018), whereby positively charged nutrient ions are efficiently taken up through negatively charged leaf cuticle pores. Overall, the increase in grain Zn and Fe content observed in this study confirms the hypothesis that biochar and foliar micronutrient fertilization can effectively enhance micronutrient density in finger millet.

4.3 | Soil properties

Soil amendment with biochar slightly increased soil pH in both Alisol and Ferralsol compared to the control (Table 6), with biochar pH recorded at 9.7 and baseline soils at 5.7 (Alisol) and 5.6 (Ferralsol). The observed increase in pH was marginal, yet it contributed to creating a more favorable soil chemical environment without reducing micronutrient availability, as evidenced by higher grain Zn and Fe concentrations in biochar-amended treatments. Regression analysis (Table 7) revealed that pH had a nonsignificant relationship with Fe content in both soils, while Zn content was significantly positively correlated with pH in Alisol ($p = 0.0385$). This suggests that, in Alisol, even small increases in pH can slightly enhance Zn availability and uptake by finger millet. The improvement in grain Zn and Fe content may also be attributed to the high intrinsic Zn and Fe content of pigeon pea biochar (8.9 mg kg^{-1} Zn and 508 mg kg^{-1} Fe), which supplements the soil micronutrient pool directly. In addition, biochar can stimulate

soil microbial activity, particularly mycorrhizal fungi, which increases the mobilization of micronutrients such as Zn, Fe, and P, improving their availability for plant uptake (Thingujam et al., 2019). While previous studies have reported that increased pH can reduce Zn availability through enhanced adsorption to soil particles (Vahedi et al., 2022), the pH range observed in this study remained below the threshold at which nutrient adsorption would limit uptake. Overall, the combined effects of biochar's chemical composition and pH buffering likely contributed to maintaining or improving micronutrient availability, supporting the observed increases in grain Zn and Fe content in both soils.

Biochar amendment also increased SOC in both soils, with the increase more pronounced in Alisol (Table 6). The wet oxidation method used may underestimate black carbon content, but the observed SOC enhancement still played a role in micronutrient dynamics. Regression results showed that SOC was significantly associated with grain Zn ($p = 0.0002$) in Alisol, confirming that organic carbon promotes soluble complex formation and micronutrient availability (Gerke, 2022; Thingujam et al., 2019). However, the relationship between SOC and grain Fe content in Alisol was not significant ($p = 0.933$), indicating that the increase in grain Fe was likely driven more by the biochar's direct nutrient contribution or other factors rather than SOC alone. Enhanced SOC likely improved nutrient retention and availability in the soil solution, supporting plant growth and contributing to higher Zn accumulation in grains.

WHC was significantly increased in the coarser-textured Alisol ($p < 0.05$) but not in the finer-textured Ferralsol (Table 6). This improvement in Alisol likely facilitated better nutrient diffusion and uptake, particularly for Zn, which regression analysis confirmed was strongly influenced by WHC ($p < 0.0001$). In Ferralsol, no significant effect of WHC on grain Zn or Fe was observed, suggesting that biochar's intrinsic nutrient content had a greater role in micronutrient accumulation in finer soils (Knoblauch et al., 2021; Obia et al., 2016). Overall, the combined effects of increased SOC and WHC under biochar amendment enhanced micronutrient availability and uptake, supporting the hypothesis that improved soil properties contribute to higher grain Zn and Fe content in finger millet. These results are consistent with previous findings showing that biochar can improve soil water retention and nutrient availability, especially in coarse-textured soils (Wei et al., 2023; Yu et al., 2013; C. X. Zhao et al., 2009).

5 | CONCLUSION

This study evaluated the effects of biochar and micronutrient (Zn and Fe) fertilizers on grain yield and nutritional quality of finger millet grown in Alisol and Ferralsol. Results showed that the Biochar amendment alone significantly improved grain Zn and Fe content compared to the control. While foliar application of Fe resulted in the highest grain Fe concentrations, the differences between foliar and soil application of micronutrients under biochar were not always statistically significant, particularly for Zn. Zinc fertilization further enhanced grain Zn concentration, particularly under biochar-amended soils, while foliar Fe application consistently resulted in the highest grain Fe content across seasons. However, improvements due to micronutrient fertilization were soil-specific and not always significantly different from biochar alone for all parameters. Grain Zn accumulation was significantly associated with SOC and WHC in Alisol, highlighting the importance of improved soil properties in micronutrient enrichment. Based on these findings, the combined use of biochar and targeted micronutrient fertilization, especially foliar application, can be recommended as a soil-specific agronomic strategy to enhance finger millet productivity and nutritional quality. Such integrated management practices have the potential to contribute to the development of nutrient-dense crops and support efforts aimed at alleviating hidden hunger in regions with micronutrient-deficient soils.

AUTHOR CONTRIBUTIONS

Alinafe Manjawire: Data curation; formal analysis; investigation; methodology; writing—original draft. **Peter Omara**: Data curation; formal analysis; investigation; methodology; writing—original draft; writing—review and editing. **Vegard Martinsen**: Funding acquisition; methodology; resources; supervision; validation; visualization; writing—review and editing. **Rajiv Kumar Srivastava**: Writing—review and editing. **Fred Otim**: Investigation; methodology; supervision; writing—review and editing. **Tonny L. Provin**: Writing—review and editing. **Ronnie Schnell**: Writing—review and editing. **Alfred Obia**: Conceptualization; data curation; funding acquisition; methodology; project administration; resources; software; supervision; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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REFERENCES

Anwar, Z., Basharat, Z., Hafeez, M. B., Khan, S., Zahra, N., Rafique, Z., & Maqsood, M. (2022). Biofortification of maize with zinc and iron not only enhances crop growth but also improves grain quality. *Asian Journal of Agriculture and Biology*, *2022*(2), 79. https://doi.org/10.35495/ajab.2021.02.079

AOAC. (2023). AOAC official method 999.11. Lead, cadmium, copper, iron, and zinc in foods: Atomic absorption spectrophotometry after dry ashing. In G. W. Latimer, Jr. (Ed.), *Official methods of analysis of AOAC International* (22nd ed.). AOAC Publications. https://doi.org/10.1093/9780197610145.003.1788

Apori, S. O., & Byalebeka, J. (2021). Contribution of corncob biochar to the chemical properties of a ferralsol in Uganda. *Arabian Journal of Geosciences*, *14*(13), Article 1290. https://doi.org/10.1007/s12517-021-07722-y

Azeem, A., Khan, S., Zia Ul Haq, M., Shafiq, S., Aslam, M. T., Munir, S., & Sikandar Zaman, M. (2025). Biofortification strategies for enhancing crop nutritional value: A review of methods, challenges, and future directions. *Discover Plants*, *2*(1), Article 185. https://doi.org/10.1007/s44372-025-00276-3

Bakar, R. A., Razak, Z. A., Ahmad, S. H., Seh-Bardan, B. J., Tsong, L. C., & Meng, C. P. (2015). Influence of oil palm empty fruit bunch biochar on floodwater pH and yield components of rice cultivated on acid sulphate soil under rice intensification practices. *Plant Production Science*, *18*(4), 491–500. https://doi.org/10.1626/pps.18.491

Baronti, S., Alberti, G., Vedove, G. D., di Gennaro, F., Fellet, G., Genesio, L., Miglietta, F., Peressotti, A., & Vaccari, F. P. (2010). The biochar option to improve plant yields: First results from some field and pot experiments in Italy. *Italian Journal of Agronomy*, *5*(1), 3–11. https://doi.org/10.4081/ija.2010.3

Bedaiwy, M. N. A. (2012). A simplified approach for determining the hydrometer's dynamic settling depth in particle-size analysis. *Catena*, *97*, 95–103. https://doi.org/10.1016/j.catena.2012.05.010

Borchard, N., Schirrmann, M., Cayuela, M. L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizábal, T., Sigua, G., Spokas, K., Ippolito, J. A., & Novak, J. (2019). Biochar, soil and land-use interactions that reduce nitrate leaching and N2O emissions: A meta-analysis. *Science of the Total Environment*, *651*, 2354–2364. https://doi.org/10.1016/j.scitotenv.2018.10.060

Bouis, H. E., & Welch, R. M. (2010). Biofortification—A sustainable agricultural strategy for reducing micronutrient malnutrition in the global south. *Crop science*, *50*, S-20–S-32. https://doi.org/10.2135/cropsci2009.09.0531

Cakmak, I., Pfeiffer, W. H., & McClafferty, B. (2010). Biofortification of durum wheat with zinc and iron. *Cereal Chemistry*, *87*(1), 10–20. https://doi.org/10.1094/CCHEM-87-1-0010

Dhaliwal, S. S., Sadana, U. S., Khurana, M. P. S., Dhadli, H. S., & Manchanda, J. S. (2010). Enrichment of rice grains with zinc and iron through ferti-fortification. *Indian Journal of Fertilisers*, *6*(7), 28–35. http://www.faidelhi.org

Ebanyat, P., de Ridder, N., de Jager, A., Delve, R. J., Bekunda, M. A., & Giller, K. E. (2010). Impacts of heterogeneity in soil fertility on legume-finger millet productivity, farmers' targeting and economic benefits. *Nutrient Cycling in Agroecosystems*, *87*(2), 209–231. https://doi.org/10.1007/s10705-009-9329-9

Garg, M., Sharma, N., Sharma, S., Kapoor, P., Kumar, A., Chunduri, V., & Arora, P. (2018). Biofortified crops generated by breeding, agronomy, and transgenic approaches are improving lives of millions of people around the world. *Frontiers in Nutrition*, *5*, Article 12. https://doi.org/10.3389/fnut.2018.00012

Gebreyohannes, A., Shimelis, H., Mashilo, J., Odeny, D. A., Tadesse, T., & Ojiewo, C. O. (2024). Finger millet (*Eleusine coracana*) improvement: Challenges and prospects—A review. *Plant Breeding*, *143*(3), 350–374. https://doi.org/10.1111/pbr.13169

Gerke, J. (2022). The central role of soil organic matter in soil fertility and carbon storage. *Soil Systems*, *6*(2), Article 33. https://doi.org/10.3390/soilsystems6020033

Han, S. M., Devaraj, S., Derraik, J. G., Vickers, M. H., Huang, F., Dubascoux, S., Godfrey, K. M., Chan, S. Y., Pang, W. W., Thakkar, S. K., & Cutfield, W. S. (2023). A nutritional supplement containing zinc during preconception and pregnancy increases human milk zinc concentrations. *Frontiers in Nutrition*, *9*, Article 1034828. https://doi.org/10.3389/fnut.2022.1034828

Hossain, M. K., Strezov, V., Yin Chan, K., & Nelson, P. F. (2010). Agronomic properties of wastewater sludge biochar and bioavailability of metals in production of cherry tomato (*Lycopersicon esculentum*). *Chemosphere*, *78*(9), 1167–1171. https://doi.org/10.1016/j.chemosphere.2010.01.009

ICRISAT. (2024). *Finger millet overview*. https://www.icrisat.org/crops/finger-millet/overview

Kasule, F., Kakeeto, R., Tippe, D. E., Okinong, D., Aru, C., Wasswa, P., Oduori, C. A., & Adikini, S. (2023). Insights into finger millet production: Constraints, opportunities and implications for improving the crop in Uganda. *Journal of Plant Breeding and Crop Science*, *15*(4), 143–164.

Kätterer, T., Roobroeck, D., Andrén, O., Kimutai, G., Karltun, E., Kirchmann, H., Nyberg, G., Vanlauwe, B., & Röing de Nowina, K. (2019). Biochar addition persistently increased soil fertility and yields in maize-soybean rotations over 10 years in sub-humid regions of Kenya. *Field Crops Research*, *235*, 18–26. https://doi.org/10.1016/j.fcr.2019.02.015

Khobragade, N., Patil, K. D., Dodake, S. B., Gavit, S., Jadhav, A., Joke, A., & Bhuvad, D. (2022). Agronomic biofortification of finger millet with calcium and iron by using different sources in lateritic soils of Konkan. *Pharma Innovation*, *11*(1), 864–866.

Knoblauch, C., Priyadarshani, S. R., Haefele, S. M., Schröder, N., & Pfeiffer, E. M. (2021). Impact of biochar on nutrient supply, crop yield and microbial respiration on sandy soils of northern Germany. *European Journal of Soil Science*, *72*(4), 1885–1901. https://doi.org/10.1111/ejss.13088

Kryvoruchko, I. (2017). Zn-use efficiency for optimization of symbiotic nitrogen fixation in chickpea (*Cicer arietinum* L.). *Turkish Journal of Botany*, *41*(5), 423–441. https://doi.org/10.3906/bot-1610-6

Kyebogola, S., Burras, L. C., Miller, B. A., Semalulu, O., Yost, R. S., Tenywa, M. M., Lenssen, A. W., Kyomuhendo, P., Smith, C., Luswata, C. K., Majaliwa, M. J. G., Goettsch, L., Colfer, C. J. P., & Mazur, R. E. (2020). Comparing Uganda's indigenous soil classification system with World Reference Base and USDA Soil Taxonomy to predict soil productivity. *Geoderma Regional*, *22*, Article e00296. https://doi.org/10.1016/j.geodrs.2020.e00296

Major, J., Rondon, M., Molina, D., Riha, S. J., & Lehmann, J. (2010). Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and Soil*, *333*(1), 117–128. https://doi.org/10.1007/s11104-010-0327-0

Mantel, S., Dondeyne, S., & Deckers, S. (2023). World reference base for soil resources (WRB). *Encyclopedia of Soils in the Environment*, *4*, 206–217.

Mingorance, M. D., Barahona, E., & Fernández-Gálvez, J. (2007). Guidelines for improving organic carbon recovery by the wet oxidation method. *Chemosphere*, *68*(3), 409–413. https://doi.org/10.1016/j.chemosphere.2007.01.021

Monika, G., Melanie Kim, S. R., Kumar, P. S., Gayathri, K. V., Rangasamy, G., & Saravanan, A. (2023). Biofortification: A long-term solution to improve global health-a review. *Chemosphere*, *314*, Article 137713. https://doi.org/10.1016/j.chemosphere.2022.137713

Narimani, H., Rahimi, M. M., Ahmadikhah, A., & Vaezi, B. (2010). Study on the effects of foliar spray of micronutrient on yield and yield components of durum wheat. *Archives of Applied Science Research*, *2*(6), 168–176.

Nelson, J. T., Adjuik, T. A., Moore, E. B., VanLoocke, A. D., Ramirez Reyes, A., & McDaniel, M. D. (2024). A simple, affordable, do-it-yourself method for measuring soil maximum water holding capacity. *Communications in Soil Science and Plant Analysis*, *55*(8), 1190–1204. https://doi.org/10.1080/00103624.2023.2296988

Obia, A., Cornelissen, G., Martinsen, V., Smebye, A. B., & Mulder, J. (2020). Conservation tillage and biochar improve soil water content and moderate soil temperature in a tropical Acrisol. *Soil and Tillage Research*, *197*, Article 104521. https://doi.org/10.1016/j.still.2019.104521

Obia, A., Mulder, J., Martinsen, V., Cornelissen, G., & Børresen, T. (2016). In situ effects of biochar on aggregation, water retention and porosity in light-textured tropical soils. *Soil and Tillage Research*, *155*, 35–44. https://doi.org/10.1016/j.still.2015.08.002

Ojok, J., Omara, P., Opolot, E., Odongo, W., Olum, S., Gijs, D. L., Gellynck, X., De Steur, H., & Ongeng, D. (2019). Iodine agronomic biofortification of cabbage (*Brassica oleracea* var. *capitata*) and cowpea (*Vigna unguiculata* L.) is effective under farmer field conditions. *Agronomy*, *9*(12), Article 797. https://doi.org/10.3390/agronomy9120797

Omara, P., Aula, L., Otim, F., Obia, A., Souza, J. L. B., & Arnall, D. B. (2022). Biochar applied with inorganic nitrogen improves soil carbon, nitrate and ammonium content of a sandy loam temperate soil. *Nitrogen*, *3*(1), 90–100. https://doi.org/10.3390/nitrogen3010007

Pal, V., Kaur, S., Sharma, V., Kaur, M., Verma, G., Sheoran, P., Bárek, V., Brestic, M., Parvez Kabir, M., & Hossain, A. (2026). Agronomic biofortification with micronutrients: An efficient approach to increase nutritional quality in crops and combat hidden hunger. *Journal of Agriculture and Food Research*, *25*, Article 102465. https://doi.org/10.1016/j.jafr.2025.102465

Ram, S., Malik, V. K., Gupta, V., Narwal, S., Sirohi, M., Pandey, V., Gupta, O. P., Misra, A. K., & Singh, G. (2024). Impact of foliar application of iron and zinc fertilizers on grain iron, zinc, and protein contents in bread wheat (*Triticum aestivum* L.). *Frontiers in Nutrition*, *11*, Article 1378937. https://doi.org/10.3389/fnut.2024.1378937

Reddy, B. H., Bulbule, A. V., Gajbhiye, P. N., & Patil, D. S. (2018). Effect of foliar application of plant nutrients on growth and yield of finger millet. *International Journal of Current Microbiology and Applied Sciences*, *7*(03), 2203–2209. https://doi.org/10.20546/ijcmas.2018.703.260

Ren, C., Zhang, Y., Xue, X., Zhao, C., Luo, X., Zhan, S., Wang, W., Li, Q., Chen, M., & Wu, D. (2025). Spraying micronutrients improves nitrogen use efficiency and rubber tree (*Hevea brasiliensis*) seedling growth by enhancing the interplay of nitrogen metabolism, root development, and photosynthesis. *Industrial Crops and Products*, *236*, Article 121867. https://doi.org/10.1016/j.indcrop.2025.121867

Saleem, I., Javid, S., Bibi, F., Ehsan, S., Niaz, A., & Ahmad, Z. A. (2016). Biofortification of maize grain with zinc and iron by using fertilizing approach. *Journal of Agriculture and Ecology Research International*, *7*(4), 1–6. https://doi.org/10.9734/JAERI/2016/24532

Singh, H., Northup, B. K., Rice, C. W., & Prasad, P. V. (2022). Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: A meta-analysis. *Biochar*, *4*(1), Article 8. https://doi.org/10.1007/s42773-022-00138-1

Singh, R., Prasad, S. K., & Singh, M. K. (2014). Effect of nitrogen and zinc fertilizer on Zn biofortification in pearlmillet (*Pennisetum glaucum*). *Indian Journal of Agronomy*, *59*(3), 474–476. https://doi.org/10.59797/ija.v59i3.5635

Singh Yadav, S. P., Bhandari, S., Bhatta, D., Poudel, A., Bhattarai, S., Yadav, P., Ghimire, N., Paudel, P., Paudel, P., Shrestha, J., & Oli, B. (2023). Biochar application: A sustainable approach to improve soil health. *Journal of Agriculture and Food Research*, *11*, Article 100498. https://doi.org/10.1016/j.jafr.2023.100498

Taheri, M. A. R., Astaraei, A. R., Lakzian, A., & Emami, H. (2024). The role of biochar and sulfur-modified biochar on soil water content, biochemical properties and millet crop under saline-sodic and calcareous soil. *Plant and Soil*, *499*(1), 221–236. https://doi.org/10.1007/s11104-023-05912-z

Teklu, D., Gashu, D., Joy, E. J. M., Lark, R. M., Bailey, E. H., Wilson, L., Amede, T., & Broadley, M. R. (2023). Impact of zinc and iron agronomic biofortification on grain mineral concentration of finger millet varieties as affected by location and slope. *Frontiers in Nutrition*, *10*, Article 1159833. https://doi.org/10.3389/fnut.2023.1159833

Thingujam, U., Kundu, D., Khanam, R., Mondal, S., & Hazra, G. C. (2019). Soil available zinc and its relationship with soil properties in rice soils of West Bengal, India. *International Journal of Current Microbiology and Applied Sciences*, *8*(8), 486–491. https://doi.org/10.20546/ijcmas.2019.808.056

Vahedi, R., Rasouli-Sadaghiani, M. H., Barin, M., & Vetukuri, R. R. (2022). Effect of biochar and microbial inoculation on P, Fe, and Zn bioavailability in a calcareous soil. *Processes*, *10*(2), Article 343. https://doi.org/10.3390/pr10020343

Van Zwieten, L., Kimber, S., Morris, S., Chan, K. Y., Downie, A., Rust, J., Joseph, S., & Cowie, A. (2010). Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant and Soil*, *327*, 235–246. https://doi.org/10.1007/s11104-009-0050-x

Vijayakumar, M., Sivakumar, R., & Tamilselvan, N. (2020). Effect of zinc and iron application on yield attributes, available nutrients status and nutrient uptake of finger millet under rainfed condition. *International Journal of Current Microbiology and Applied Sciences*, *9*(5), 3237–3246. https://doi.org/10.20546/ijcmas.2020.905.384

Wang, S., Xu, L., & Hao, M. (2022). Impacts of long-term micronutrient fertilizer application on soil properties and micronutrient availability. *International Journal of Environmental Research and Public Health*, *19*(23), 16358. https://doi.org/10.3390/ijerph192316358

Wei, B., Peng, Y., Lin, L., Zhang, D., Ma, L., Jiang, L., Li, Y., He, T., & Wang, Z. (2023). Drivers of biochar-mediated improvement of soil water retention capacity based on soil texture: A meta-analysis.

Geoderma, *437*, Article 116591. https://doi.org/10.1016/j.geoderma.2023.116591

Yu, O. Y., Raichle, B., & Sink, S. (2013). Impact of biochar on the water holding capacity of loamy sand soil. *International Journal of Energy and Environmental Engineering*, *4*(1), 1–9. https://doi.org/10.1186/2251-6832-4-44

Zeidan, M. S., Mohamed, M. F., & Hamouda, H. A. (2010). Effect of foliar fertilization of Fe, Mn and Zn on wheat yield and quality in low sandy soils fertility. *WJAS*, *6*(6), 696–699.

Zhao, C. X., He, M. R., Wang, Z. L., Wang, Y. F., & Lin, Q. (2009). Effects of different water availability at post-anthesis stage on grain nutrition and quality in strong-gluten winter wheat. *Comptes Rendus Biologies*, *332*(8), 759–764. https://doi.org/10.1016/j.crvi.2009.03.003

Zhao, D., Huang, Y., Wang, B., Chen, H., Pan, W., Yang, M., Xia, Z., Zhang, R., & Yuan, C. (2023). Dietary intake levels of iron, copper, zinc, and manganese in relation to cognitive function: A cross-sectional study. *Nutrients*, *15*(3), Article 704. https://doi.org/10.3390/nu15030704

Zulfiqar, U., Ayub, A., Hussain, S., Ahmad, M., Rehman, A., Ishfaq, M., Ali, M. F., Shabaan, M., & Yong, J. W. H. (2024). Iron biofortification in cereal crops: Recent progress and prospects. *Food and Energy Security*, *13*(4), Article e547. https://doi.org/10.1002/fes3.547

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