Research article

Improving the Productivity and Nutritional Values of Sweet Potato (*Ipomoea batatas* L.) with a Combination of Soil and Foliar Zinc

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Abstract

Keywords

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Sweet potato (*Ipomoea batatas* L.) is an important crop and is a staple food in many countries across the globe; since they are a good source of nutrients including zinc (Zn). Zn is essential for plant growth and development, and a zinc deficiency can significantly impact crop productivity as well as the nutritional quality of the produce. The value of enrichment with Zn in many crops by applying Zn either to foliar or soil through agronomic biofortification has been investigated, but this information is still unavailable for sweet potatoes. Therefore, the current study aimed to evaluate the effect of soil and foliar Zn applications on yield, biochemical traits, and nutrient concentrations of different sweet potato genotypes. The

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study was conducted using a split-plot design with treatments of two doses (0 and 2.5 kg Zn ha^{-1}) of soil application and four doses (0, 15, 30, and 45 ppm) of foliar application of Zn on five sweet potato genotypes (SP-2, SP-14, SP-15, SP-16, SP-20). It was observed that growth and yield performance as well as nutrient concentrations in the tubers of sweet potatoes were greatly influenced by Zn application method and genotype. An increasing rate of foliar Zn, with or without soil-applied Zn, showed an increasing trend in amino acid, β-carotene, flavonoid, and phenolic content. The foliar Zn application had a more obvious effect on most of the examined traits than the soil Zn application and except for a few characteristics (dry matter and amino acids), most traits responded up to the foliar application of 15 ppm Zn, and thereafter no increase was seen with further increments of foliar Zn application.

1. Introduction

Sweet potato (*Ipomoea batatas* L.) is a highly versatile and widely consumed crop that is valued for its nutritional richness and adaptability to diverse growing conditions. The native of this crop originated in tropical America, and these days it is a popular starchy food crop grown in tropical and subtropical regions around the world. Compared to grain crops, sweet potato is a highly cherished tuber crop that has propitious nourishment and health features such as mono-caffeoyl quinic, phenolics, caffeoylquinic acids, caffeic acid, chlorogenic acid, hydroxybenzoic acids, p-coumaric acids, p-anisic acids, sinapic acid, anthocyanidins, anthocyanins, cyanidin, peonidin, pelargonidin, flavonoids, quercetin, apigenin, β-carotene, myricetin, alkaloids, lutein, phytosterols, luteolin, steroids, glycosides, saponins, and terpenoids [1]. In addition to starch and sugar, sweet potato also contains significant amounts of ascorbic acid, thiamine, riboflavin, niacin, and minerals including phosphorus (P), iron (Fe), and calcium (Ca). It is commonly used in curries, and it is also directly consumed after boiling or frying.

Zinc is a vital micronutrient that plays a crucial role in various physiological processes of plants, including growth, development, and overall nutrient uptake. It is particularly important for root crops like sweet potatoes, as they heavily rely on zinc for their root and tuber development. However, zinc deficiency in agricultural soils is a prevalent issue in many regions around the world, leading to reduced crop yields and compromised nutritional quality.

Africa and Asia account for nearly 90% and worldwide around 1.1 billion people are suffering from zinc (Zn) deficiency [2]. Growth retardation, a weakened immune system, and morbidity from infectious diseases have all been linked to Zn deficiency [3]. Non-pregnant non-lactating women (15-49 years) and pre-school-age children (6-59 months) in Bangladesh had a Zn deficiency rate of around 57.3% and 44.6%, respectively [4]. Contrary to developed nations, low-income nations like South Asia and sub-Saharan Africa often wean their children on homemade supplemental foods derived from cereals. These include diets made from rice, maize, sorghum, millet, corn, and wheat, which are naturally low in carotene (pro-vitamin A) [5] and high in antinutrients that prevent the absorption of nonheme Fe and Zn [6]. All these factors predispose these populations to micronutrient deficiencies and their ominous consequences.

A significant global effort has been made in the last 20 years to breed key food crops to increase the density of the three primary micronutrients (vitamin A, Fe, and Zn) through biofortification and other focused breeding [7]. Crop improvement nowadays is attempted to create agro-ecologically adaptable cultivars with higher levels of vitamins and minerals, as well as to ensure that climate-adapted germplasm and consumer-preferred traits are used in the production of biofortified crops [8, 9].

Sweet potatoes are a resilient food crop with a lot of potential to help alleviate world hunger [10] which have a wide range of genotypes that mature in 4-5 months, making them

compatible with several farming techniques intended to reduce food insecurity [8-10]. However, more germplasms should be tested for their micronutrient biofortification ability [11].

Zinc activates the majority of enzymes involved in carbohydrate metabolism, and it is essential for protein synthesis in plants. Zn deficiency causes amino acids in plant tissues and protein synthesis to decrease. Zn also influences pollen tube development, which aids in pollination [12, 13]. Zinc is necessary for the synthesis of tryptophan, which is connected to the synthesis of auxin [14, 15]. The importance of Zn to fundamental plant life processes, including nitrogen metabolism, nitrogen uptake, protein quality, increased photosynthesis through chlorophyll synthesis, carbon anhydrase activity, resistance to abiotic and biotic stresses, and defense against oxidative damage, was reported by several researchers [16-19].

Many studies reported that Zn application improved the growth and yield performance of several crops (e.g., alfalfa, wheat, maize, barley, and cotton) in Zn-deficient soils around the world [20-22]. Islam *et al.* [23] reported that Zn application enhanced the yield of Aman rice, maize, and chickpea by 11, 36 and 34%, respectively, compared to no Zn application. Yilmaz *et al.* [24] reported that the addition of Zn to the soil along with the foliar application, seed priming and foliar application of all three practices improved wheat grain production across cultivars by 260% when compared to no Zn practice. Although several studies have demonstrated the positive impact of both the soil and foliar sprays of Zn on many crops [25, 26], there is no work on sweet potatoes on whether soil application of Zn fertilizer will respond better to growth and yield, or whether foliar spray will outperform soil application.

We hypothesized that different promising germplasms may not respond to a combined or single application of foliar and soil application of Zn. The study was, therefore, conducted to evaluate the effects of Zn application either by foliar spray and/or directly at rhizosphere soil on the growth, yield, and biochemical characteristics as well as nutrient concentrations of some promising sweet potato genotypes. By investigating the effects of different zinc application rates and methods, we sought to provide valuable insight into optimizing zinc management practices for sweet potato cultivation.

2. Materials and Methods

2.1 Experimental site

The field experiments were carried out from October 2020 to February 2022 at the experimental field of the Regional Agricultural Research Station, Bangladesh Agricultural Research Institute, Burirhat, Rangpur (25°49’18” N 89°14’11” E). The experimental field soil was sandy loam, and the pH was classified as moderately acidic, with a range value of 5.5-6.5. Rainfall is summer dominant (June to September) with an annual average of 169 mm. The winter crop was 100% irrigated but the summer crop needed partial irrigation. A data logger was positioned close to the field trial to record daily maximum and minimum temperature and total rainfall data.

2.2 Plant materials

Five diverse sweet potato germplasms were collected from Bangladesh and Malaysia. The set of germplasm included four from Bangladesh Agricultural Research Institute, Bangladesh and one from Cameron Highland, Malaysia. The germplasm list is presented in Table 1. The vine transplanting was completed by the first week of October each year.

2.3 Treatments and experimental design

Five sweet potato germplasms were tested under different Zn application methods including two doses of soil application (0 and 2.5 kg Zn ha^{-1}) and four doses (0, 15, 30, and 45 ppm) of foliar application. The experiment was laid out following a split-split plot design with three replicates. The plot size was 2.5 m × 3 m with four rows where the row-to-row distance was 60 cm and the plant-to-plant distance was 30 cm.

Table 1. List of the germplasms studied in this experiment, along with their acquisition location

Sl. no.	Coll. no.	Location of collecting site
01	G1 (SP-2)	Bangladesh (Taiwan)
02	G2 (SP-14)	Bangladesh (CIP Material)
03	G3 (SP-15)	Bangladesh (CIP Material)
04	G4 (SP-16)	Bangladesh (Hybridization)
05	G5 (SP-20)	Malaysia

*Sl No.- Serial Number, *Coll. No.- Collection Number, *CIP- International Potato Centre

2.4 Crop management

The land was prepared with ploughing five times followed by land harrowing and rotor tilling for land leveling and soil pulverization. Finally, ridging was done using a spade, as the plot size was small. The crop was fertilized with a total of 250 kg urea (N source), 150 kg triple super phosphate (P source), 250 kg muriate of potash (K source), 70 kg gypsum (S source), 6 kg boric acid (B source) and cow dung 10 t ha^{-1}. The total urea was applied in two splits, one during final land preparation on the ridges/beds and the other at 35 days after sowing. Before planting, the vines were pre-treated with commercially available insecticides (namely, Admire (Imidacloprid-18.3%), and another systemic insecticide, Karate (Lambda cyhalothrin-2.5%). Vines were planted in the ridge so that 2-3 nodes were inserted in the soil. Recommended doses of glyphosate (Roundup) and glufosinate-ammonium (Basta) were applied to prevent the establishment of grasses and broadleaf weeds. Due to the prevalence of dry weather, three-time irrigation was applied each year.

2.5 Data recording

The number of branches and tubers $plant^{-1}$ was counted manually during the harvesting. An electrical balance was used to measure the fresh weight of tubers $plant^{-1}$ (g) and marketable yield (t ha^{-1}). The whole plot technique was used for measuring tuber weight and marketable yield. Dry matter (%) was measured through plant drying in the oven (72ºC for 72 h) and measured dry weight was converted into a percentage. ß-carotene content in sweet potato tuber (carotenoid pigments) was determined by reversed phase liquid chromatography in mg/100 g following a modified method [27, 28]. Carbon, nitrogen, and sulfur were determined by a vario MICRO CHNS analyzer. Zinc and potassium (K) were determined by an AR method, on an energy dispersive X-ray florescence spectrophotometer (EDXRF). Total phenol content was determined according to Singleton and Rossi and the Folin phenol reduction method [29]. Flavonoid content was determined according to Zhishen *et al*. [30] method. The amino acid was determined by an amino acid profiling technique according to Cooper *et al.* [31].

2.5.1 Total carotenoid content (TCC)

A sharp knife was used to carefully separate the fruit flavedo from the orange fruit rind's albedo to measure the TCC concentration. The flavedo portion of the rind and fruit carpel tissue was mixed/blended and homogenized separately. For carotenoid extraction, both blended and homogenized samples (2.0 g) of each replicate were weighed [32]. Whole carotenoid extraction was carried out with some adjustments, according to Chowdhury [27] and Lee and Castle [28]. Before being stored in a freezer at -30ºC for at least an hour before analysis, the samples were put into 50-mL graduated orange cap centrifuge tubes with an orange cap and 20 mL of extraction chemicals (hexane: ethanol, 50:50 v/v). The mixture was defrosted, stirred, and centrifuged at 29,000 g for 20 min (F14-14 50cy rotor, Thermo Scientific, USA) at 2ºC during the analysis. The tissue was shaken out of the tubes to extract all the carotenoids, which were then allowed to stand for 5 min to clearly separate. A 3-mL transfer pipette was used to transfer the carotenoid fraction from the top layer of hexane into 50-mL centrifuge tubes, and the tubes were then sealed. An ethanol-hexane solution (1:9) was used to rinse the sample residues, and deionized water was then used to flush out any leftover carotenoids. After at least 1 h in a -30ºC freezer, the sample was put in crushed ice. Hexane was used to change the recovered hexane's volume to 15 to 25 mL. Hexane was the only solvent utilized in the microplate for the blank. The following equation was used to calculate the TCC content of each fruit tissue sample:

$$(AV \times 106) / (A1\% \times 100G)$$

where 'A' stands for absorbance, 'V' stands for total volume used (e.g., 25 mL), A1% = 2500, and 'G' stands for sample in grams.

2.5.2 Analyses of phenol and flavonoids

With a few modifications, the Singleton and Rossi Folin phenol reduction method [29] was used to quantify the total phenol level. In an ice bath, 0.2 g of frozen sample was ground with 2 mL of 80% methanol and less sand before being ultrasonically processed for 30 min. The homogenates were centrifuged at 4°C, 2000 × g for 20 min, and the resulting supernatant was used for total phenolic content and DPPH free radical scavenging activity assay. Each reaction mixture contained 2 mL of 2% Na_2CO_3, 150 L of Sigma's Folin-reagent, Ciocalteu's and 200 L of supernatant. The reaction mixture was left to sit at 25°C in the dark for 20 min. The absorbance was then measured immediately at OD735 and a standard curve for the total phenol content was prepared using gallic acid.

Flavonoid content was calculated based on Zhishen *et al.* [30], 0.2 g of frozen sample was homogenized for 30 min in an ultrasonic bath with 2 mL of 1% HCl in methanol after being ground in an ice bath. The homogenate underwent a 20-minute centrifugation at 4°C and 2000 g. The flavonoid content was assessed from each supernatant. Then 300 µL 5% $NaNO_2$, 300 µL 10% AlCl3 and 300 µL supernatant were added in one tube. To allow for the reaction to occur, 2 mL of 1 M NaOH were added to the initial liquid after 6 min. Absorbance at OD510 was measured after 1 min.

2.5.3 Analysis of amino acids

An amino acid profiling technique was used for amino acid determination [30]. Each pre-ground sample, weighed 0.2 g, was added with 5 mL of 6N HCl. The protein was heated for 24 h at 110°C to begin the hydrolysis process. and then 4 mL of 2.5 mM alpha aminobutyric acid (AABA) was added as an internal standard. Using a 0.45m PTFE syringe filter, the volume was increased to 100 mL and filtered to 1.5 mL. In the Eppendorf tube, 70 µL borate buffer was added, followed by a 10

µL hydrolysate sample/standard. After vortexing, the solution was mixed with the 20 µL AccQ Fluor reagent and vortexed once more. The mixture was left at room temperature for 1 min. Each solution was put into vials and heated for 10 min at 55ºC before being analyzed by high-performance liquid chromatography (Waters Alliance e2695) with a fluorescence detector.

2.6 Statistical analysis

Data analysis was performed using JMP Pro13 (SAS Institute, San Francisco, CA, USA) to find out significant differences among treatments. Tukey's Honest Significant Difference (HSD) test was used to test the differences between the treatment means. A combined analysis was performed due to non-significant results of most parameters studied in the two trials.

3. Results and Discussion

3.1 Growth, yield and yield contributing characters

None of the growth parameters, yield and yield contributing characters were affected by the interactions of Zn soil application, foliar application, and genotype, however, their individual effects were significant (Table 2). Across the germplasms, the soil application of Zn had higher values for yield and all yield contributing characters than no Zn application. The length of the sweet potato main vine was 3.3% higher in soil-applied Zn as compared with no soil Zn. Similarly, ground coverage (%), tuber weight (g) plant^{-1}, number of tubers plant^{-1}, length of tubers (cm) and tuber diameter (cm) displayed similar trends to the length of the main vine.

There were no interactions between germplasm and Zn applications in both soil and foliar cases. The germplasms used in the present study had varied growth and yield parameters. The yield of the studied sweet potato genotypes ranged from 23.9 to 26.20 t ha^{-1} while the highest was recorded in genotype 5 (26.2 t ha^{-1}), followed by genotype 4 (25.5 t ha^{-1}). Genotype 1 had the lowest tuber yield (23.9 t ha^{-1}). Across genotypes, the application of foliar Zn showed an increasing trend in all traits related to growth, yield, and yield-contributing characters (Table 2). The length of the main vine had varied responses to foliar Zn application as compared to no foliar application.

The increase in the length of the main vine ranged from 8.3 to 10.9%. The highest increase in length of the main vine was recorded in the treatment with 45 ppm Zn foliar application. The increase in the number of branches displayed various values in responses to foliar Zn application with increases ranging from 6.0-7.6%. The tuber weight-plant^{-1} also increased with the foliar application of Zn while the weight showed a gradual increase with an increase in foliar application rate (Table 2). The increase in tuber weight plant^{-1} ranged from 15-21% while the highest increase was recorded from 45 ppm foliar Zn application. The number of tubers plant^{-1} also showed similar responses to foliar Zn application as of tuber weight/plant. The length and diameter of the tubers also increased with increasing rate of Zn in the foliar application (Table 2). With only 15 ppm Zn foliar application, the yield increase was recorded by 2.83 t ha^{-1}, and with 30 ppm, the yield increase was more than 3 t ha^{-1}. However, the yield did not increase further with the 45 ppm Zn foliar application, i.e., the yield increase was similar to the 30 ppm Zn foliar application. Across genotypes, the application of foliar Zn showed an increasing trend in all traits related to growth, yield, and yield-contributing characters (Table 2). Zn accumulation in sweet potato genotypes due to foliar application may be attributed to the accumulation of Zn in leaves through surface contamination of leaves by foliar application which accordingly may stimulate sweet potato plants to uptake more from the soil.

Table 2. Effect of zinc soil application and foliar application on growth, yield, and yield contributing characteristics of sweet potato genotypes

Treatments	LMV (cm)	NB (90 DAP)	GC (%)	TW (kg)/ plant	NT/ plant	LT (cm)	DT (cm)	DM (%)	Yield (t/ha)
Zn Basal application (ZnB)									
ZnS_0	57.5^{b}	5.85^{b}	86.7^{b}	0.36^{b}	4.03^{b}	13.72^{b}	3.84^{b}	20.10^{b}	24.36^{b}
$ZnS_{2.5\ kg}$	59.4^{a}	6.07^{a}	89.8^{a}	0.38^{a}	4.36^{a}	14.70^{a}	4.14^{a}	21.53^{a}	25.30^{a}
CV (%)	5.54	5.94	6.83	10.14	7.98	11.24	6.61	11.42	7.70
Genotypes (G)									
G1	30.28^{e}	5.83^{c}	80.5^{c}	0.37^{b}	4.14^{b}	13.87^{bc}	4.02^{ab}	22.36^{a}	23.91^{c}
G2	50.94^{d}	6.15^{b}	97.3^{a}	0.35^{c}	4.12^{b}	14.73^{a}	4.13^{a}	19.61^{d}	24.05^{c}
G3	61.16^{c}	6.14^{b}	97.2^{a}	0.38^{ab}	4.13^{b}	14.57$_{ab}$	3.98^{ab}	21.02^{bc}	24.50^{bc}
G4	78.23^{a}	6.44^{a}	80.2^{c}	0.38^{ab}	4.27^{ab}	14.58^{ab}	3.88^{b}	21.24^{ab}	25.51^{ab}
G5	71.66^{b}	5.22^{d}	86.0^{b}	0.39^{a}	4.33^{a}	13.30^{c}	3.96^{b}	19.85^{cd}	26.20^{a}
CV (%)	5.57	5.70	6.27	10.10	8.08	10.74	6.58	10.92	8.10
Zn foliar application (ZnF)									
ZnF0	54.52^{b}	5.67^{b}	85.6^{b}	0.33^{c}	3.88^{b}	12.25^{c}	3.72^{b}	17.98^{c}	22.67^{b}
ZnF15 ppm	59.04^{a}	6.02^{a}	88.6^{a}	0.38^{b}	4.23^{a}	14.37^{b}	4.02^{a}	21.04^{cb}	25.40^{a}
ZnF30 ppm	59.74^{a}	6.05^{a}	89.0^{a}	0.39^{b}	4.32^{a}	14.93^{ab}	4.09^{a}	21.84^{b}	25.73^{a}
ZnF45 ppm	60.51^{a}	6.10^{a}	89.8^{a}	0.40^{a}	4.36^{a}	15.30^{a}	4.13^{a}	22.41^{a}	25.53^{a}
CV (%)	5.54	5.67	6.24	10.14	7.98	11.24	6.61	11.42	7.70
Significance level									
ZnB	**	**	***	***	**	***	**	***	***
G	***	***	***	***	***	***	***	***	***
ZnF	***	***	***	***	***	***	***	***	***
ZnB × G	ns	ns	ns	ns	ns	ns	ns	ns	ns
ZnB × ZnF	ns	ns	ns	ns	ns	ns	ns	ns	ns
G × ZnF	ns	ns	ns	ns	ns	ns	ns	ns	ns
ZnB× G × ZnF	ns	ns	ns	ns	ns	ns	ns	ns	ns

* means significant at 5% level of significance ** means significant at 1% level of significance, *** means significant at 0.1% level, ^{NS} means non-significant, length of the main vine (LMV), ground coverage (GC), number of branches (NB), tuber weight plant^{-1} (TW), number of tuber plant^{-1} (NT), length of tuber (LT), diameter of tuber (DT) and dry matter (DM)

The results of the current study related to foliar application of Zn in relation to growth, yield and yield contributing characters of crops particularly sweet potato and wheat were also confirmed by Badillo and Lopez [33] and Somayeh *et al*. [34]. Du *et al*. [35] also reported that foliar application of Zn precisely supplied Zn during the peak demand period of plants (for example, during early vegetative, reproductive, and late vegetative stages), and where inhibiting soil and climatic conditions hamper sufficient Zn uptake by plant roots. Zhang *et al.* [36] found that Zn deficiencies in rice crops can be remedied by foliar Zn application. Similarly, Zhang *et al.* [37] experimented with the application of Zn in green peas and revealed that the deficiencies of Zn can be resolved by foliar Zn fertilization. The finding in the present study is also at par with the results of Qinglong and Brown [38] who stated that a higher concentration of Zn in leaves is accumulated in leaf apoplastic space. The higher yield can be attributed to the positive role of Zn in photosynthesis, protein synthesis and assimilating carbohydrates that are eventually translocated to tuber roots [39].

3.2 Nutrient concentration of sweet potato

Nutrient concentration was not affected by the interactions of Zn soil application, foliar application, and genotype; however, their individual effects were significant except for sulfur (Table 3). Across

germplasm, carbon, N, protein, and K concentrations in sweet potato increased by 9.4, 7.48, 7.64, and 9.49%, respectively, due to soil application of Zn compared with no application (Table 3).

The germplasms used in the present study had different N, protein, S, and Zn concentrations; however, they had similar C and Zn concentrations (Table 3). Among the germplasms, germplasm 3 had the highest N concentration, which was followed by germplasm 2 and germplasm 5. Similarly, germplasm 3 had the highest protein concentration (Table 3). The germplasms also varied in S concentration, with the highest concentration (0.64 g 100 g^{-1}) recorded for germplasm 1, followed by germplasm 2 and 5 (Table 3). Application of foliar Zn showed an increasing trend in nutrient concentrations of sweet potato ($p<0.05$). The C concentration in sweet potato had varied responses to foliar Zn application as compared to no foliar application ($p\leq0.001$). The C concentration in sweet potato ranged from 38.6 to 42.4 g/100g while the highest increase was recorded from the 45 ppm foliar Zn application. The N concentration in the sweet potato also varied with the Zn application ($p<0.001$). The N content ranged from 7.43-8.30 g/100 g, with the highest value being recorded for 30 ppm Zn foliar application. The further increase in Zn concentration in foliar application up to 45 ppm did not increase N concentration (Table 3).

The N, K and S concentrations increased in sweet potato genotype in the present study. When applied in the soils, Zn is less available to plants because it is adsorbed on hydroxides (particularly those of iron) and carbonate surfaces [40]. Zinc interacts with N [41] and K [42] positively in plants. In the present study, the application of Zn in soil and to foliage might have interacted positively with S, producing an increase in the concentration of the nutrient. There have been reports of both antagonistic and synergistic effects of Zn × S interaction. According to Shah and De Datta [43], the application of 100 kg S ha^{-1} resulted in a modest drop in the Zn concentration in rice plants. However, Cui and Wang [44] showed a significant rise in Zn concentration in spring wheat with the application. Baudh and Prasad [45] also reported a favorable Zn-S interaction in regard to growth characteristics, yield attributes, and mustard yield (*Brassica campestris*). Foliar application of Zn is, therefore, suggested as a measure to improve soil health and crop performance. However, very few studies have been conducted on sweet potatoes and more studies are needed if a decisive conclusion is to be reached.

3.3 β-Carotene, flavonoid and phenolic compound of sweet potato

The soil Zn application had significant effects on β-carotene and flavonoid, but not on phenolic compound concentrations in sweet potatoes (Table 4). The germplasms used in the present study had varied β-carotene, flavonoid and phenolic compound concentrations (Table 4).

All the germplasms had varied β-carotene, ranging from 10.8 to 14.5 mg/100 g of which the highest was recorded from germplasm 1 and the lowest was recorded from germplasm 5. In the case of flavonoids, among the germplasms, germplasm 4 had the highest flavonoid concentration (291 mg/g) which was followed by germplasm 2 (279 mg/g) and germplasm 1 (278 mg/g) (Table 4). On the other hand, germplasm 3 had the highest phenolic compound concentration (260 mg/g) and was closely followed by germplasm 2 with 256 mg/g phenolic compound concentration ($p>0.05$). The lowest phenolic compound concentration was recorded in germplasm 5 (176 mg/g) which was much lower than the other germplasms studied (Table 4).

The β-carotene, flavonoid and phenolic compound concentrations in sweet potato edible varied with foliar application of Zn ($p\leq0.05$; Table 4). The highest β-carotene increase was recorded when foliar Zn was applied at a 45-ppm rate (31.7%), while the foliar application of Zn at 15 and 30 ppm increased β-carotene by 28 and 31%, respectively ($p\leq0.001$). Sun *et al*. [46] also harvested sweet potatoes with higher β-carotene content with the application of Zn, compared to no Zn application. Tumwegamire *et al*. [47] put forward that a child of around 5 to 8 years old could be served more than 350% β-carotene if 250 g of deep orange-fleshed sweet potato was consumed. Sun

et al. [46] reported a higher result of β-carotene content in sweet potato genotypes in the greenhouse environment for normal genotypes when Zn and Fe were applied in the canopy as a foliar spray. They stated that spraying with Zn-containing fertilizer can increase the β-carotene content of sweet potato genotypes effectively. Flavonoid concentration in sweet potatoes showed a similar increasing trend to β-carotene. The highest increase (13.1% compared to no Zn application) in flavonoid concentration was recorded with 45 ppm Zn foliar application. The highest phenolic compound in sweet potato (261 mg/g) was also recorded with 45 ppm foliar application ($p>0.001$).

The present study revealed an increased phenolic content in sweet potato, which was likely attributed to external Zn applications. A similar result was also reported by Khorsandi and Yazdi [48] in pomegranate, with increased phytoestrogen after applying Zn-containing fertilizer [48]. Likewise, Rossiter [49] found increased isoflavone content in clover seedlings with foliar Zn application. In addition, Venkatesan *et al*. [50] reported on tea leaves with a highly significant amount of polyphenols content. They also found a strong positive correlation between Zn content in leaves and phenol content. Above all, Marschner [51] established the fundamental relationship between Zn content and protein and carbohydrate metabolism in plants. He also showed that balanced Zn concentration was indispensable to cell differentiation and development.

Table 3. Effect of zinc soil application and foliar application on the nutrient concentration of sweet potato genotypes

Treatment	Carbon (g/100 g)	Nitrogen (g/100 g)	Protein (g/100 g)	Sulfur (g/100 g)	Zinc (g/100 g)	Potassium (g/100 g)
Zn basal application (ZnB)						
ZnS0	39.43^{b}	7.75^{b}	48.4^{b}	0.52	1.10^{b}	47.4^{b}
ZnS 2.5 kg	43.14^{a}	8.33^{a}	52.1^{a}	0.52	1.17^{a}	51.9^{a}
CV (%)	7.10	8.06	6.58	13.25	6.47	7.92
Genotypes (G)						
G1	41.1	7.24^{c}	45.3^{c}	0.64^{a}	1.11	49.7bc
G2	41.3	8.30^{b}	51.9^{b}	0.56^{b}	1.13	48.4c
G3	41.2	10.2^{a}	63.8^{a}	0.46^{c}	1.12	51.6b
G4	41.9	6.33^{d}	39.6^{d}	0.37^{d}	1.19	57.7^{a}
G5	41.0	8.12^{b}	50.8^{b}	0.56^{b}	1.10	41.0d
CV (%)	7.15	8.16	7.18	12.95	5.97	8.12
Zn soil application (ZnF)						
ZnF_0	38.6b	7.43^{b}	46.4^{b}	0.52	0.81^{c}	46.5^{b}
ZnF15 ppm	41.9a	8.15^{a}	50.9^{a}	0.51	0.90^{c}	50.0^{a}
ZnF30 ppm	42.3a	8.30^{a}	51.9^{a}	0.52	1.21^{b}	51.1^{a}
ZnF45 ppm	42.4a	8.28^{a}	51.7^{a}	0.52	1.61^{a}	51.1^{a}
CV (%)	7.10	8.06	6.58	13.25	6.47	7.92
Level of Significance						
ZnB	***	***	***	ns	**	***
G	ns	***	***	***	ns	***
ZnF	***	***	***	ns	***	***
ZnB × G	ns	ns	ns	ns	ns	ns
ZnB × ZnF	ns	ns	ns	ns	ns	ns
G × ZnF	ns	ns	ns	ns	ns	ns
ZnB × G × ZnF	ns	ns	ns	ns	ns	ns

Here, * means significant at 5% level of significance ** means significant at 1% level of significance, *** means significant at 0.1% level, and ^{NS} means non-significant.

Table 4. Effects of soil and foliar application of zinc on quality and composition of sweet potato genotypes

Treatments	β-Carotene (mg/100g)	Flavonoid (mg/g)	Phenolic Compound (mg/g)
Zn basal application (ZnB)			
ZnS0	12.51^{b}	268^{b}	233
ZnS 2.5 kg	12.78^{a}	280^{a}	238
CV (%)	7.89	6.35	5.42
Genotypes (G)			
G1	14.50^{a}	278^{ab}	247^{a}
G2	13.10^{b}	279^{ab}	256^{a}
G3	12.65^{b}	270^{b}	260^{a}
G4	12.14^{c}	291^{a}	238^{a}
G5	10.84^{d}	252^{c}	176^{b}
CV (%)	7.92	7.06	4.82
Zn foliar application (ZnF)			
ZnF_0	10.30^{b}	260^{b}	205^{c}
ZnF15 ppm	13.24^{a}	264^{a}	233^{ab}
ZnF30 ppm	13.48^{a}	271^{a}	243^{b}
ZnF45 ppm	13.57^{a}	294^{a}	261^{a}
CV (%)	8.12	6.45	5.32
Level of Significance			
ZnB	*	*	ns
G	***	***	***
ZnF	***	***	***
ZnB × G	ns	ns	ns
ZnB × ZnF	ns	ns	ns
G × ZnF	**	**	ns
ZnB × G × ZnF	ns	ns	ns

* means significant at 5% level of significance, ** means significant at 1% level of significance, *** means significant at 0.1* level of significance, ^{NS} means non-significant, LSD means Least Significant Difference and CV mean coefficient of variation.

3.4 Interaction effect of foliar Zn application and germplasm on β-carotene and flavonoid concentration

Application of foliar Zn at increasing rates showed an increasing trend of β-carotene and flavonoid concentration in sweet potato germplasms (Figure 1). The β-carotene concentration in sweet potato raged from 9.43 to 15.66 mg/100 g while the highest value was recorded at 45 ppm Zn foliar application for Germplasm 1. Similar to the β-carotene, flavonoid concentration also increased with increase in Zn foliar application, and the highest value was recorded from Germplasm 1 when applied foliar Zn at 45 ppm followed by Germplasm 4 (Figure 2). Other germplasms also showed higher β-carotene and flavonoid concentrations in response to foliar Zn applications compared to no foliar Zn application indicating that a little Zn application as the foliar spray was able to increase their concentration in sweet potato (Figure 2).

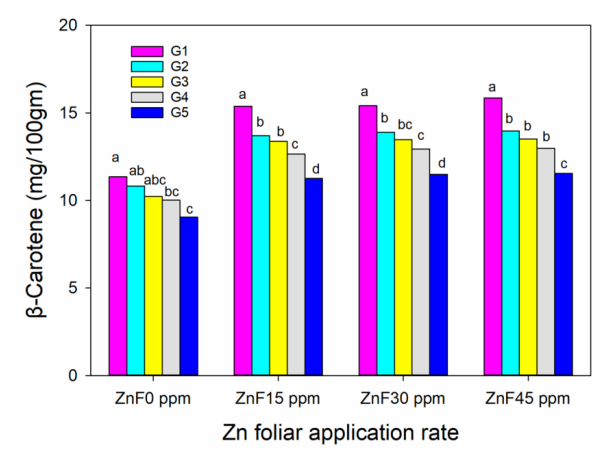

Figure 1. β-carotene (mg/100gm) as influenced by the interaction of sweet potato germplasm and Zn foliar application

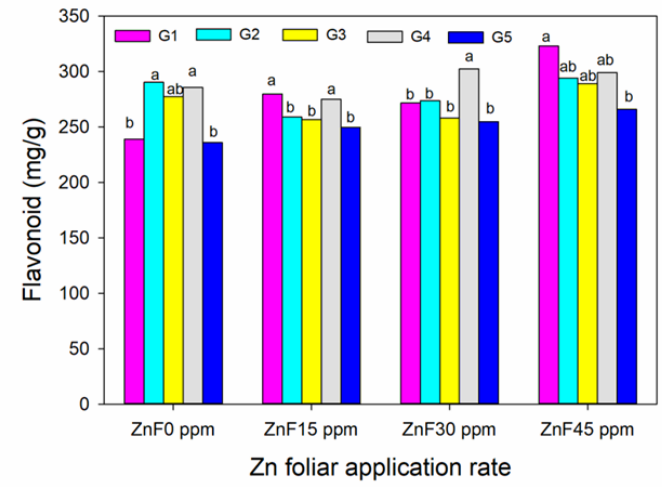

Figure 2. Flavonoid (mg/g) as influenced by the interaction of sweet potato germplasm and Zn foliar application

3.5 Amino acids

Amino acids except isoleucine were not affected by the Zn basal application but were affected by the foliar applications and genotype (Table 5). Except for the effect by genotype of zinc foliar applications on the amino acids such as threonine and valine, all other interactions were not significant. Considering the germplasms, Germplasm 3 had a higher concentration of most amino acids. On the other hand, germplasm 4 had the highest concentrations of histidine, threonine and valine. The irregular variation of the tested sweet potato genotypes indicates that all the genotypes had inherent quality particularly amino acids (Table 5).

Table 5. Effect of soil and foliar application of zinc on amino acid composition of sweet potato germplasms

Treatments	Histidine	Isoleucine	Leucine	Lysine	Methionine	Phenylalanine	Threonine	Tryptophan	Valine
Zn basal application (ZnB)									
ZnS0	147	246^{b}	359	269	125	293	281	155	318
ZnS 2.5 kg	146	248^{a}	362	269	125	294	281	156	317
CV (%)	5.93	4.86	5.96	6.13	7.14	8.07	7.10	6.13	5.98
Genotypes (G)									
G1	150^{b}	243c	362^{c}	244^{d}	128^{a}	261^{c}	302^{b}	166^{b}	335^{b}
G2	152^{ab}	246^{ab}	354^{b}	256^{c}	124^{b}	277^{b}	260^{d}	144^{c}	281^{d}
G3	129^{c}	250^{a}	375^{a}	297^{a}	129^{a}	327^{a}	234^{e}	174^{a}	331^{b}
G4	153^{a}	249^{a}	366^{b}	272^{b}	119^{c}	326^{a}	339^{a}	145^{c}	346^{a}
G5	150^{b}	247^{a}	345^{d}	277^{b}	124^{b}	277^{b}	272^{c}	146^{c}	296^{c}
CV (%)	5.85	5.90	5.98	6.33	7.24	8.12	7.10	6.03	5.98
Zn soil application (ZnF)									
ZnF_0	141^{d}	240^{d}	352^{c}	258^{c}	120^{b}	283^{d}	269^{d}	145^{d}	308^{d}
ZnF15 ppm	144^{c}	245^{c}	357^{c}	266^{b}	123^{b}	291^{c}	277^{c}	153^{c}	315^{c}
ZnF30 ppm	149^{ab}	250^{b}	364^{b}	274^{ab}	128^{a}	297^{b}	286^{b}	158^{b}	321^{b}
ZnF45 ppm	152^{a}	254^{a}	370^{a}	280^{a}	130^{a}	303^{a}	293^{a}	164^{a}	328^{a}
CV (%)	6.43	5.20	6.46	5.53	6.54	7.97	6.90	5.93	5.98
Level of Significance									
ZnB	ns	*	ns	ns	ns	ns	ns	ns	ns
G	***	**	***	***	***	***	***	***	***
ZnF	***	***	***	***	***	***	***	***	***
ZnB × G	ns	ns	ns	ns	ns	ns	ns	ns	ns
ZnB × ZnF	ns	ns	ns	ns	ns	ns	ns	ns	ns
G × ZnF	ns	ns	ns	ns	ns	ns	**	ns	**
ZnB × G × ZnF	ns	ns	ns	ns	ns	ns	ns	ns	ns

* means significant at 5% level of significance, ** means significant at 1% level of significance, *** means significant at 0.1* level of significance, ^{NS} means non-significant, LSD means Least Significant Difference and CV mean coefficient of variation.

Application of foliar Zn at an increasingly higher rate showed an increasing concentration of amino acids (Table 5). Although the highest amino acids were recorded with the 45 ppm Zn foliar application, the amino acids increasing rates were significantly higher up to 30 ppm Zn foliar application. The highest increase of amino acid concentration was recorded in tryptophan (13.1%) with 45 ppm foliar Zn application, relative to no Zn application, however, contrasting with no Zn application, histidine, lysine and threonine showed 7.8%, 8.52% and 8.92% increases due to 45 ppm Zn foliar application, respectively.

The increase in protein concentration ranged from 46.4-51.9g/100g while the highest increase (5.5%) was recorded for 30 ppm foliar Zn application (Table 3). Hemantaranjan and Garg [52] found that spraying Zn on leaves increases the availability of Zn, which increases the protein content in wheat grains. Starks and Johnson [53] conducted an experiment with ^{65}Zn label applied at the anthesis stage of wheat and recorded Zn absorption into the protein of grain, with the glutenin containing the most Zn. Another study reported that Zn finger protein's gene expression was regulated by Zn [54]. According to Read *et al.* [55], the stimulative effects of Zn on RNA concentration led to an increase in protein production, which in turn improved cell metabolism and organ growth. Other authors have also noted an increase in protein content following the administration of Zn [56-57]. With a proper supply of Zn to plants under Zn deficiency conditions in soils, the amino acid and amide concentrations in plants reduced at a faster rate which corresponds to an increase in free amino acids and amide concentrations, along with an increase in protein concentrations [56].

3.6 Interaction effects of Zn foliar application and germplasm on threonine and valine concentrations

The highest threonine and valine concentrations were recorded in germplasm 4 when there was no Zn foliar application, which meant that this germplasm may not respond to the foliar application (Figures 3 and 4). Germplasm 4 had an increased threonine concentration from 335 mg/g in control to 347 mg/g in 45 ppm. On the other hand, germplasm 1 had the highest increase (from 290 mg/g to 322 mg/g) of threonine when Zn was applied as a foliar spray at 45 ppm, compared to no foliar Zn application.

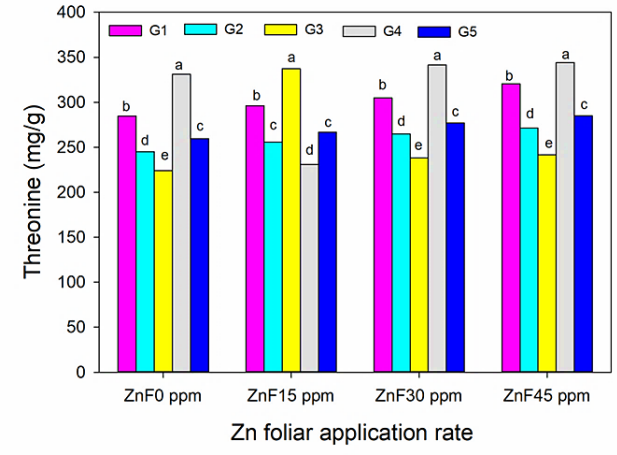

Figure 3. Threonine (mg/g) as influenced by the interaction of sweet potato germplasm and Zn foliar application

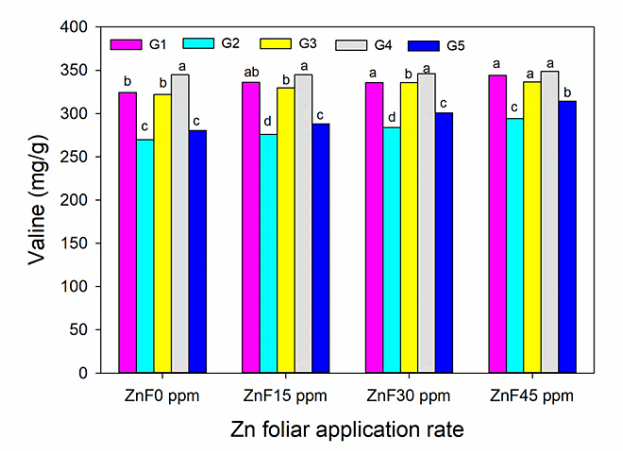

Figure 4. Valine (mg/g) as influenced by the interaction of sweet potato germplasm and Zn foliar application

In developed countries, several strategies, including foliar and soil fertilization, have been proposed and put into practice to address the issue of Zn shortage [59]. Agronomic biofortification would be a very appealing and practical method for efficiently addressing Zn deficiency-related health issues on a worldwide scale [17, 59]. Chelated Zn as Zn-EDTA, Zn-DTPA and commercial $ZnSO_4$ are the common sources of Zn for agricultural use [18]. Impurities of cadmium and other hazardous heavy metals have been found in the majority of commercial Zn fertilizers [59]. However, due to their higher molecular size, manufactured chelated Zn has substantially lower leaf penetration rates than free metal cations of Zn [60]. According to studies by Hurrell *et al*. [61] and Hurrell and Egli [62], phytic acid (PA) reduces the bioavailability of micronutrients like Zn [63]. Spraying foliar Zn fertilizer could considerably lower the amount of PA present in wheat grain [34]. As a result, the application of foliar Zn fertilizer to sweet potato leaves in this study may similarly lower the concentration of PA in the plant, which could further increase the bioavailability of Zn. However, the present study did not offer any pertinent results on PA concentration.

4. Conclusions

This study investigated the effects of combining soil and foliar applications of zinc on the productivity and nutritional values of sweet potatoes. Significant improvements in the nutritional values of sweet potatoes following the combined zinc application were observed. The levels of essential nutrients, β-Carotene, flavonoid, phenolic compound, and amino acids were significantly higher when Zn was applied as a foliar spray of 15 ppm and above. This suggests that soil application with foliar spray or only foliar spray of Zn treatment positively influences the nutritional quality of sweet potatoes, enhancing their potential as a valuable food source. The germplasms used in the current study showed a wider variation and irregular responses to foliar and soil application; however, all germplasms showed more enrichment of Zn and β-carotene when Zn was applied as foliar application. By adopting the combined soil and foliar application of zinc or only foliar application, farmers can enhance the productivity and nutritional values of sweet potatoes, thereby addressing malnutrition problems and improving human health. These findings contribute to the broader understanding of crop nutrition and offer practical solutions for enhancing food quality.

Continued research in this area will undoubtedly advance our knowledge and enable us to unlock the full potential of sweet potatoes as a nutritious and sustainable crop.

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