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Assessing iron and zinc micronutrient content of mungbean genotypes: Implications for nutritional quality improvement in Tanzania

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Abstract

Mungbean (*Vigna radiata*) is a globally significant legume, valued for its iron and zinc content, essential micronutrients that help reduce deficiencies in human populations. Despite its importance, the genetic and nutritional diversity of mungbean genotypes in Tanzania remains underexplored, particularly regarding micronutrient content. This study aimed at analyzing the seed micronutrient (iron and zinc) content among 35 mungbean genotypes from Tanzania, characterized by diverse agro-ecological zones. The field experiment was conducted during the 2023/2024 season at two locations, Miwaleni (Kilimanjaro) and SUA (Morogoro), using a Randomized Complete Block Design (RCBD) with three replications. Atomic Absorption Spectroscopy (AAS) was used to determine iron and zinc concentrations in the seeds, revealing significant variation ($p \leq 0.05$) among genotypes. Soil analysis at Miwaleni revealed neutral pH (6.97) with 3.2 ppm zinc and 156.7 ppm iron, while SUA soil had slightly acidic pH (6.17) with 4.2 ppm zinc and 88.7 ppm iron. Mungbean grains grown at Miwaleni exhibited higher iron content (92.2 ppm) compared to SUA (90.1 ppm), while zinc content was higher in grains from SUA (32.5 ppm) than Miwaleni (28.1 ppm). Among the genotypes, M10 had the highest iron content (98.3 ppm), and M7 had the highest zinc content (42.9 ppm), while M1 and M31 showed the lowest concentrations for these respective micronutrients. The study highlights significant variability in micronutrient content, suggesting potential for breeding programs to enhance nutritional quality. Genotypes M10 and M7 emerged as promising candidates for biofortification, offering potential avenues for improving micronutrient intake in populations reliant on mungbeans as a dietary staple. These findings contribute to breeding strategies and agricultural practices that could help combat micronutrient deficiencies in Tanzania, promoting better health outcomes for local communities.

Keywords: Mungbean, bio fortification, micronutrients, iron, zinc, malnutrition

1. Introduction

Mungbean (*Vigna radiata* (L.) Wilczek) is a short-duration, drought-tolerant crop cultivated worldwide for its edible grain, consumed in their dry form (Hou *et al.*, 2019) ^[16]. It stands as one of the significant crops globally, contributing substantially to agricultural productivity, economic benefit, and nutritional values. Mungbean stands as a valuable crop offering dryland smallholder farmers an opportunity to enhance the profitability and sustainability of their farms. Being well-known for its nutritional richness, this warm-season legume boasts grains abundant in protein, minerals, and vitamins. It is mainly grown in Asia, especially in countries like India, China, Pakistan, and Thailand, but it is also found in some areas of Africa and Australia, though to a lesser extent (Lambrides & Godwin, 2007) ^[24].

Integrating mungbean into cropping systems, particularly in Tanzania, is important for strengthening sustainability of agricultural practices. By diversifying local production systems and incorporating mungbean as a catch crop, farmers can augment their income while simultaneously enhancing soil fertility (Pataczek *et al.*, 2018) ^[35]. Covering over 7 million hectares globally (approximately 8.5% of the global pulse area), mungbeans boast an average yield of 721 kg ha⁻¹, with a yearly global production capacity of about 5.3 million tons (Hou *et al.*, 2019; Nair *et al.*, 2020) ^[16, 31]. Tanzania is one among several countries cultivating mungbean for both domestic consumption and exportation (Nair *et al.*, 2013) ^[31].

Approximately 217,000 hectares are dedicated to mungbean cultivation in Tanzania, primarily in regions like Simiyu, Morogoro, Mtwara, Tabora, and Kilimanjaro (Binagwa *et al.*, 2023) [21]. Despite this significant cultivation effort, mungbean production in Tanzania remains low, averaging to 0.336 t ha⁻¹, compared to its potential yield of over 1.5 t ha⁻¹ (Nair & Schreinemachers, 2020; Mmbando *et al.*, 2021) [31, 32].

Mungbeans offer a balanced diet rich in protein, dietary fiber, minerals, vitamins, and various bioactive compounds (Hou *et al.*, 2019) [16]. This is particularly important in Tanzania, where conditions like anaemia affect approximately 45% of children under five years old and 33% of women aged 15 to 49 due to iron deficiency (Mbwana, 2020) [28]. Mungbeans serve as an affordable source of minerals and protein, especially for vegetarians or those unable to afford animal proteins, with their protein being more readily absorbed than that found in other legumes (Yi-Shen *et al.*, 2018; Hou *et al.*, 2019) [46, 16].

Mungbean has high iron (Fe) and zinc (Zn) content, making it a valuable crop for addressing micronutrient deficiencies in humans, particularly in developing countries (Gahlot *et al.*, 2020) [12]. Iron deficiency can lead to anemia, while zinc deficiency impairs immune function and growth, making these nutrients vital for public health (Barla *et al.*, 2022) [3]. Recent research has focused on improving the bioavailability of these micronutrients in mungbean, exploring genetic diversity, and identifying Quantitative Trait Loci (QTLs) linked to higher Fe and Zn content. This is important because while mungbeans are naturally rich in these minerals, enhancing their concentrations through breeding programs can help combat malnutrition at a population level. Several studies in the last few years have focused on the genetic improvement of mungbean for micronutrient content (Jamal *et al.*, 2018; Singh *et al.*, 2017) [19]. These studies have highlighted the potential of mungbean to contribute significantly to addressing iron and zinc deficiencies in the human diet, particularly in regions where rice (*Oryza sativa*) and wheat (*Triticum aestivum*) dominate, which are often low in these micronutrients. Researchers have identified QTLs associated with increased mineral content and are using molecular tools to develop mungbean varieties with enhanced nutritional profiles (Singh *et al.*, 2017; Vu *et al.*, 2022) [42].

Considering that landraces have been cultivated in the same soil for generations, it is likely that farmers have selected high-yielding types over the years (Pinheiro *et al.*, 2010) [36]. However, farmers who cultivate landraces specific to one agroecological zone may not have knowledge of, or access to, other landraces grown in different agroecological areas. This limited exposure to genetic variation from other regions can restrict the genetic diversity available to farmers, further narrowing the scope for selecting and breeding for improved traits such as higher yields, disease resistance, and nutritional quality. Nevertheless, limited knowledge about these genetic resources hinders breeders from fully utilization of this crop (Vir *et al.*, 2016) [44]. Based on 2018 data, malnutrition for children under five is a significant public health concern in Tanzania with a stunting prevalence of 32% (Kanire *et al.*, 2024) [20]. Regions such as Ruvuma and Iringa, exhibit stunting rates exceeding 40%, highlighting severe nutritional deficiencies in these areas. Despite this, there has been progress, with remarkable reductions in stunting prevalence in regions like Dodoma and Morogoro between 2014 and 2018 (Fumbwe *et al.*, 2021) [11]. Addressing Malnutrition requires several approaches, including interventions to improve dietary diversity and nutritional intake. Being high in nutritional value (rich in protein, vitamins, and minerals), mungbean can play an important role in this context. Mungbeans offer a cost-effective and sustainable source of essential nutrients (Keatinge *et al.*, 2011) [21]. In Tanzania,

promoting the cultivation and consumption of mungbeans, particularly in regions with high rates of Malnutrition, will enhance dietary diversity and combat micronutrient deficiencies among vulnerable groups.

Furthermore, integrating mungbeans into local agricultural systems can contribute to food security and livelihood improvement, particularly for smallholder farmers. Encouraging the adoption of mungbean cultivation practices alongside nutrition education initiatives can lead to long-term improvements in health outcomes, aligning with the broader goals of reducing Malnutrition and promoting sustainable development in African countries (Mmbando *et al.*, 2021.) [29]. Therefore, the aim of this research was to assess the genetic diversity among mungbean Genotypes alongside their nutritional quality focusing on the micronutrient content (iron and zinc) in dry grains.

2. Materials and Methods

2.1 Description of the study sites

Field experiments were conducted at Miwaleni, located in the Kilimanjaro region, and the Sokoine University of Agriculture (SUA) Model Training Farm in Morogoro region. These sites were selected for their diverse climatic, soil, and topographical characteristics, which are favourable for agricultural research and Mungbean production.

Miwaleni is situated at an elevation of 720 meters above sea level, in a range of from 3.4330° S to 3.4350° S and 37.4490° E to 37.4510° E (Fig. 1). The area experiences a tropical semi-arid climate, with reddish-brown soils that are well-drained and nutrient-rich, particularly in calcium (Ca), magnesium (Mg), and potassium (K)—key elements that promote healthy plant growth (Becker *et al.*, 2019). The area receives an annual rainfall ranging between 500 and 700 mm, and temperatures vary from 10 °C to 39 °C throughout the year, creating a suitable environment for crop cultivation (Ringo *et al.*, 2015) [38].

The SUA Model Training Farm lies at an elevation of approximately 525 meters, which is situated between 6.8495° S and 6.8501° S and 37.6540° E and 37.6550° E (Shaaban & Kisetu, 2014) [40]. This site is characterized by a tropical savanna climate, marked by distinct wet and dry seasons. The annual rainfall ranges between 600 to 1,000 mm, and temperatures fluctuate between 20 °C and 32 °C (Saria *et al.*, 2018) [39]. The soils at SUA are sandy clay loam, slightly acidic with a pH of 6, moderately fertile, and well-drained, containing important nutrients like potassium and calcium (Saria *et al.*, 2018; Tryphone & Thomas, 2023) [39].

2.2 Plant materials

Thirty-five mungbean genotypes were selected for this study. Among these, 31 were sourced from the National Plant Genetic Resource Centre (NPGRC), displaying a diverse array of mungbean germplasm. Additionally, four other genotypes were obtained from Tanzania Agricultural Research Institute (TARI), each representing unique varieties resulting from their specialized breeding programs. The 31 mungbean genotypes obtained at TNPGRC were collected from different agro-ecological zones of Tanzania. The study purposively chooses genotypes obtained from various collection sites to represent a wide range of environmental conditions, soil compositions, and cultural practices prevalent in mungbean-growing regions nationwide. This geographical diversity ensures an appropriate sampling of mungbean genetic variation within Tanzania's agricultural context showing description and information regarding the specific collection sites and associated geographic characteristics (Table 1).

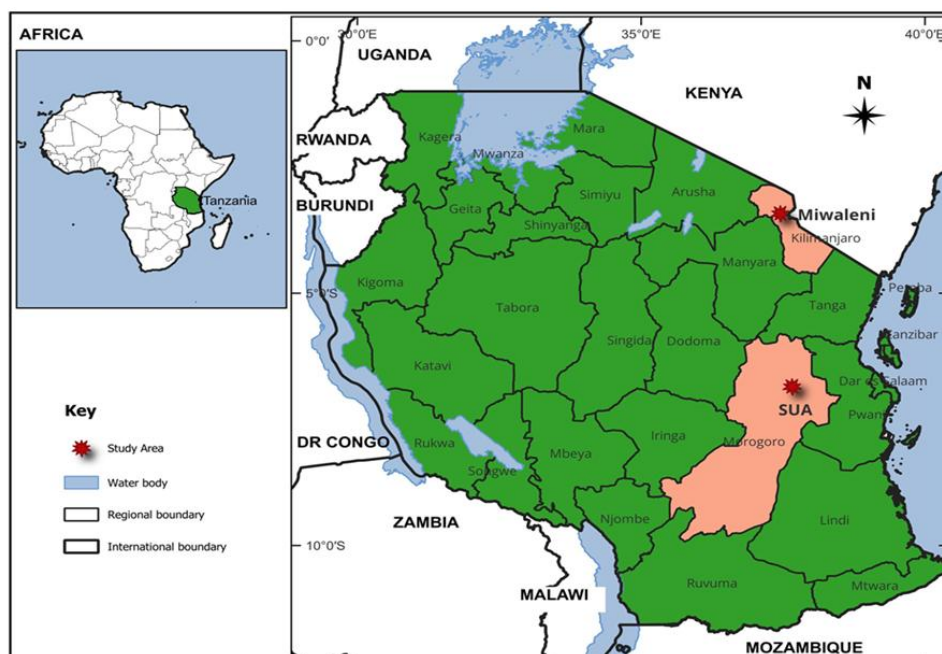


Fig 1: A map of Tanzania showing sites where the experiment was conducted. The asterisks on the map indicate the locations of the fields experiments.

Table 1: Mungbean genotypes collected from various agro-ecological zones of Tanzania, as listed in the TNPGRC catalogue of legume seed genotypes for ex situ conservation.

S/N	*Genotype	District	Latitude	Longitude	Local name
1	M26 (T3244)	Sikonge	-5.8522222	33.02972222	Ndulu
2	M12 (T3270)	Sikonge	-5.9352778	32.74083333	Ndulu
3	M14 (T2233)	Kisangi	-8.917593	39.51231	Choroko
4	M8 (T2237)	Lindi	-8.96667	39.4	Choroko
5	M18 (T2799)	Mahenge	-8.9158333	36.82388889	Choroko
6	M10 (T2809)	Pangani	-8.8636111	36.72583333	Choroko
7	M1 (T2819)	Pangani	-5.4027778	38.98555556	Choroko
8	M30 (T2836)	Muheza	-4.965	38.97638889	Choroko
9	M9 (T2923)	Tunduru	-11.288889	37.37916667	Choroko
10	M24 (T3200)	Tabora	-5.1155556	33.12916667	Kapala
11	M21 (T2320)	Lindi	-10.1364	39.892	Jimweda
12	M13 (T3853)	Nachingwea	-10.055556	38.645	Choroko
13	M5 (T3978)	Musoma	-1.9488889	33.54305556	Ebhisanda
14	M29 (T4175)	Biharamulo	-3.0055556	31.77277778	Nduku
15	M31 (T4621)	Misungwi	-2.9463889	32.91555556	Nduru
16	M28 (T4464)	Lindi	-9.7905556	39.59944444	Choroko
17	M6 (T4662)	Kwimba	-2.9391667	33.46111111	Ndulu
18	M16 (T4510)	Liwale	-9.7872222	38.50972222	Choroko
19	M19 (T4529)	Liwale	-9.7383333	37.78722222	Mbwako
20	M22 (T4580)	Magu	-2.4194444	33.77694444	Mahuri Nduru
22	M3 (T3774)	Newala	-11.03583	39.3525	Jimweda
23	M2 (T4658)	Misungwi	-2.842963	33.081714	Nduku
24	M11 (T3132)	Tabora	-4.7230556	29.87222	Kafuto
25	M20 (T3457)	Igunga	-4.444722	33.4486	Shili-Dundugala
26	M15 (T3370)	Sikonge	-4.697222	33.510277	Kafuto
27	M27 (T2442)	Kilwa Masoko	-8.917593	39.51231	Choroko
28	M25 (T334)	Vwawa	-9.1101	32.9381°	Choroko
29	M17 (650)	Bunda	-2.018532	33.874614	Choroko
30	M4 (T3339)	Urambo	-5.0777	32.0695	Choroko
31	M7 (T4631)	Misungwi	-2.85	33.08333	Nduru
32	M33 (TARI G GRAM 1)	TARI	-3.364284	36.634774	TARI G GRAM 2
33	M32 (TARI G GRAM 2)	TARI	-3.364284	36.634774	TARI G GRAM 1
34	M34 (Nuru)	TARI	-3.364284	36.634774	Nuru
35	M35 (Imara)	TARI	-3.364284	36.634774	Imara

*Genotypes M1 to M35 refer to the specific names of the varieties listed above, with the original names provided in parentheses.

2.3 Experimental design

Field trials were conducted at two sites (Miwaleni and SUA)

following a Randomized Complete Block Design, such that each genotype was replicated three times. Due to rain seasonal

variations, field experiment at Miwaleni site was conducted from March to June 2023 during long rainy season. On the other hand, field experiment at SUA was conducted from August to October 2023 during short rainy season, with supplemental

irrigation. Climatic information during the period of cropping in each site is presented in Fig. 2. Two row plots of 1.5 m in length with a spacing of 0.5 m between rows and 0.25 m between holes in the row were used.

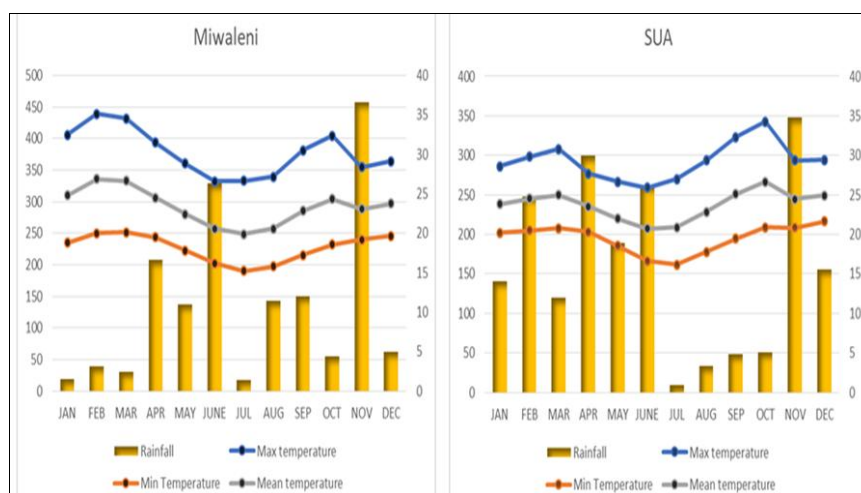


Fig 2: Climatic conditions of the experimental sites during cropping cycles (data source: Tanzania Meteorological Authority)

2.4 Data collection

Soil samples were collected at a depth of 0 to 20 cm before experiments for each site. The composite soil samples were air-dried, crushed and sieved through 2 mm wire-mesh. These composite soil samples were then used for various laboratory analyses. The analyses conducted on the soil samples included soil pH measured in a soil-to-water ratio of 1:2.5 suspensions using a pH meter (MacLean, 1982). Available phosphorus (P) was extracted using the Bray 1 method (Bray & Kurtz, 1945). Additionally, exchangeable calcium (Ca) and magnesium (Mg) were quantified using atomic absorption spectrophotometry, while potassium (K) and sodium (Na) were extracted using ammonium acetate and analysed by flame emission spectrophotometry. Cation exchange capacity (CEC) was analysed using the ammonium acetate saturation method at pH 7.0 (Chapman, 1973)^[7]. Total nitrogen (N) was measured using the Kjeldahl method. Finally, the DTPA extractable copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) were quantified using atomic absorption spectrophotometry (Lindsay & Norvell, 1978)^[26]. For the plant data at harvest, pods from each plot were sun-dried before manual threshing. The threshed grains were dried to a moisture content of 13% before sending for laboratory micronutrient analysis. Seed samples from each genotype and replication were placed in individual paper bags. For micronutrients analyses, 30 g of seeds from each genotype and replication were placed in an oven at 135 °C for 2 hours before grinding. Using a Cyclotec 1093 sample mill, the seeds were ground into a fine powder to ensure uniformity for subsequent procedures. Following grinding, 0.5 grams of the ground seed samples were weighed and transferred into porcelain crucibles. These crucibles were then placed in a furnace and heated at 550 °C for 5 hours, transforming the samples into ashes. After heating, the ashes were allowed to cool to room temperature (~25 °C). The cooled ashes were dissolved in 10 millilitres of 6 N HCl, thoroughly mixed, and diluted with distilled water to a total volume of 25 millilitres after 10 minutes. The solutions were filtered using Whatman No. 42 filter paper to remove solid particles and impurities. The filtrates were then analysed to determine the concentrations of Zn and Fe. Using the Atomic Absorption Spectrometer (AAS) method specified by the AOAC (1995)^[1] protocol, the concentrations of these essential

micronutrients were measured to assess the nutritional composition of the mungbean genotypes under investigation.

2.5 Statistical data analyses

A two-way analysis of variance (ANOVA) was conducted, employing a split-plot design where sites constituted the main plots and genotypes represented the sub-plots, with replications treated as a random effect. However, due to the significant interactions between sites and genotypes, the analysis was subsequently refined to a one-way ANOVA for clearer insights. Comparisons for the effects of genotypes on the measured parameters were conducted using standard errors of differences of means (S.E.D.) through Tukey's post hoc test. Additionally, site-specific correlations were calculated for the concentrations of zinc and iron measured in plant genotypes compared to those in the soil.

3. Results

The soil nutrient analysis from Miwaleni and SUA sites showed differences and similarities in their properties (Table 2). At Miwaleni, the soil had a neutral pH of 6.97, while at SUA site was slightly acidic with a pH of 6.08. Both sites exhibited very low levels of Ca, N, and K. However, Mg levels varied significantly between the sites. Miwaleni had low Mg levels ($0.44 \text{ cmol}_{(+)} \text{ kg}^{-1}$), whereas SUA had high Mg levels ($3.12 \text{ cmol}_{(+)} \text{ kg}^{-1}$), which may require site-specific nutrient management approaches. The cation exchange capacity (CEC) was low at both sites, with values of $9.4 \text{ cmol}_{(+)} \text{ kg}^{-1}$ at Miwaleni and $10.1 \text{ cmol}_{(+)} \text{ kg}^{-1}$ at SUA, indicating limited soil fertility.

Phosphorus was medium at Miwaleni (14.23 mg kg^{-1}) and low at SUA (9.55 mg kg^{-1}), pointing to a potential need for P supplementation at SUA. Micronutrient analysis revealed high levels of Fe and Zn at both sites. Fe levels were 156.74 ppm at Miwaleni and 88.71 ppm at SUA, while Zn concentrations were 3.19 ppm at Miwaleni and 4.17 ppm at SUA. These high levels are beneficial for plant health but may require monitoring to prevent toxicity. The neutral pH at Miwaleni supports a wide variety of crops, including mungbean (Okalebo *et al.*, 2002).

Moreover, the micronutrient profile, particularly the high concentrations of Fe and Zn, found beneficial for crop growth and raises the need for careful monitoring to avoid toxicity,

especially at Miwaleni where Fe levels are particularly elevated. The pH differences also indicate that specific soil amendments like lime application might be needed at SUA to adjust the slightly acidic pH and create a more neutral environment conducive for crop growth. In contrast, the neutral pH at Miwaleni is already well-suited for a broad range of crops,

including mungbean, and may require less intervention in this regard. These differences in soil properties suggest that a one-size-fits-all approach to soil management would not be effective across the two sites, and customized amendments tailored to each site's specific deficiencies and excesses are essential for optimizing crop yield and health.

Table 2: Soil properties of the study sites

Soil properties	Miwaleni site		SUA site	
	Values	Ratings*	Values	Ratings*
pH (H ₂ O) 1:2.5	6.97	Neutral	6.08	Slightly acid
Ca (cmol(+) kg ⁻¹)	1.35	Very low	1.07	Very low
Mg (cmol(+) kg ⁻¹)	0.44	Low	3.12	High
K (cmol(+) kg ⁻¹)	0.29	Low	0.32	Low
Na (cmol(+) kg ⁻¹)	0.16	Low	0.02	Very low
CEC (cmol(+) kg ⁻¹)	9.4	Low	10.1	Low
N (%)	0.084	Very low	0.031	Very low
P (mg kg ⁻¹)	14.23	Medium	9.55	Low
Cu (ppm)	17.91	High	0.31	High
Fe (ppm)	156.74	High	88.71	High
Mn (ppm)	112.21	High	231.95	High
Zn (ppm)	3.19	High	4.17	High

*Ratings are based on compilation of Okalebo *et al.* (2002)^[33].

The micronutrient content of mungbean grains from two sites and genotypes is presented in Table 3. The Fe content was significantly ($p < 0.001$) higher at the Miwaleni site (92.207 ppm) compared to the SUA site (90.079 ppm), while the Zn content was higher at SUA (32.503 ppm) than at Miwaleni (28.007 ppm), indicating significant differences between sites.

Among the genotypes, M10 had the highest Fe content (98.26 ppm) and M7 had the highest Zn content (42.86 ppm). In contrast, M2 had significantly ($p < 0.001$) the lowest Fe content (68.86 ppm) and M31 had the lowest Zn content (20.04 ppm), signifying significant variation among genotypes.

Table 3: Mean Fe and Zn concentrations (ppm) in mungbean grains at different sites and genotypes

Genotypes*	Miwaleni site		SUA site	
	Fe	Zn	Fe	Zn
M1	85.35mn	30.17e-h	84.87m	38.9c
M10	98.82a	38.82a	97.69ab	44.02b
M11	97.99ab	31.79de	96.79abc	38.44c
M12	81.88p	30.92efg	78.06op	36.18de
M13	87.8L	27.84i-n	88.01kL	32.23hij
M14	87.16Lm	27.73j-n	85.85Lm	31.16ijk
M15	84.56no	29.41f-k	82.32n	36.14de
M16	93.05h-k	23.02qrs	91.28hij	29.12kLm
M17	94.42e-i	26.15mno	93.25e-h	28.99kLm
M18	93.1h-k	26.6L-o	91.99g-j	33.09g-j
M19	93.45h-k	29.99e-i	90.63ij	33.16f-i
M2	74.33q	26.23mno	63.39q	32.74hij
M20	94.83d-h	24.96opq	86.63Lm	26.93mn
M21	82.97op	22.61rst	76.22p	26.36n
M22	92.31jk	28.19h-m	91.5hij	30.96ijk
M23	91.71k	26.62L-o	89.7jk	27.71Lmn
M24	93.24h-k	26.58L-o	92.49f-i	27.66Lmn
M25	92.28jk	26.96L-o	90.96hij	28.25Lmn
M26	83.52nop	20.63tu	78.69o	24.05o
M27	96.07b-f	21.43st	96.38a-d	23.07op
M28	92.33ijk	24.79o-r	93.08e-h	27.63Lmn
M29	96.51d-e	31.74de	98.13ab	37.65cd
M3	92.21jk	27.44k-n	91.01hij	31.19ijk
M30	97.25abc	23.84pqr	95.18cde	27.96Lmn
M31	96.05b-f	18.84u	87.2Lm	21.24p
M32	95.99b-f	31.44def	92.5f-i	35.12efg
M33	95.65c-g	29.92e-j	96.95abc	34.2e-h
M34	96.91a-d	26.17mno	94.13d-g	30.91jk
M35	98.73a	25.65nop	94.65c-f	29.74KL
M4	96.14b-f	36.33b	98.25a	48.12a
M5	94.06f-j	28.74g-L	92.53f-i	35.36ef
M6	93.74g-k	33.24cd	91.81g-j	38.11cd

M7		96.92a-d	39.84a		95.85bcd	45.88b
M8		93.05h-k	34.49bc		90.32ijk	38.79c
M9		92.85h-k	21.1st		93.15e-h	26.55n
Mean		92.21	28.01		90.08	32.51
S.E.D.		0.5283	0.5612		0.5839	0.5515
F pr.		<0.001	<0.001		<0.001	<0.001

*Means in the same column with different letter(s) differ significantly at $p \leq 0.05$.

The correlations between Fe and Zn concentrations in both grains and soils (Table 4), showed that at Miwaleni, Fe and Zn concentrations in the plant grain showed a weak positive correlation ($r = 0.22$), indicating minimal relationship between the levels of these micronutrients within the grains. In contrast, Fe and Zn concentrations in the soil displayed perfect correlations ($r = 1$), both with each other and with Fe and Zn levels in the plant, as shown by negligible correlation values close to zero ($4.70E-16$ for Fe in the soil and Fe in the plant, and similarly low values for Zn correlations). This suggests no direct association between soil Fe/Zn content and their respective plant concentrations at Miwaleni.

At SUA site, the Fe and Zn concentrations in the grain also exhibited a weak positive correlation ($r = 0.25$), similar to Miwaleni. However, the soil micronutrient correlations at SUA were distinct. The correlation values between Fe in the soil and Fe in the plant, and between Zn in the soil and Zn in the plant, were extremely close to zero ($-1.06E-15$), implying no significant relationship between the soil and plant micronutrient concentrations. Additionally, like Miwaleni, the correlations between Fe and Zn in the soil were perfect ($r = 1$), suggesting a high interdependence of soil micronutrient levels but little direct influence on plant micronutrient concentrations.

Table 4: Site-specific correlations between Fe and Zn concentrations in grains and soils

Site	Micronutrients				
Miwaleni		Fe (in plant)	Zn (in plant)	Fe (in soil)	Zn (in soil)
	Fe (in plant)	1			
	Zn (in plant)	0.22	1		
	Fe (in soil)	$4.70E-16$	$1.38E-16$	1	
	Zn (in soil)	$4.70E-16$	$1.26E-16$	1	1
SUA		Fe (in plant)	Zn (in plant)	Fe (in soil)	Zn (in soil)
	Fe (in plant)	1			
	Zn (in plant)	0.25	1		
	Fe (in soil)	$-1.06E-15$	$-1.06E-15$	1	
	Zn (in soil)	$1.06E-15$	$1.05E-15$	1	1

4. Discussion

The contrasting environmental conditions between Miwaleni and the SUA sites highlight the diverse agro-ecological potential across Tanzania, underscoring the importance of local environmental factors in shaping agricultural outcomes. Tanzania's agro-ecological diversity including coastal, highland, and varied soil types—promotes genetic variation in mungbean genotypes. This genetic variability is crucial for the development of mungbean varieties with desirable traits such as disease resistance and drought tolerance, which enhance the crop's resilience to climate change. Such genetic diversity supports breeding programs that aim to improve mungbean production sustainability, which is vital for food security and agricultural resilience. Understanding these site-specific environmental differences is essential for optimizing crop production strategies, particularly for nutrient-rich crops like mungbeans, which contribute significantly to food security and improved nutritional outcomes.

A critical evaluation of soil productivity and the nutritional quality of mungbean genotypes is essential for optimizing both crop yield and human nutrition, especially in regions where mungbean is a dietary staple (Khoshgofarmanesh *et al.*, 2010)^[23]. Mungbean, a versatile leguminous crop, thrives under diverse agro-climatic conditions and contributes substantially to food security due to its rich nutritional profile (Pratap *et al.*, 2021)^[37].

Soil analysis from the Miwaleni and SUA sites revealed considerable variation in pH levels and macronutrients such as calcium (Ca), magnesium (Mg), potassium (K), nitrogen (N), and phosphorus (P), consistent with findings from other mungbean-growing regions, including Myanmar and Nepal (Bam *et al.*, 2022; Htwe *et al.*, 2023; Islam *et al.*, 2024)^[2, 17, 18].

These results emphasize the significance of soil nutrient availability in promoting optimal mungbean growth and nutrient assimilation. For example, Bam *et al.* (2022)^[2] stressed the importance of nutrient management to enhance yield, while Htwe *et al.* (2023)^[17] demonstrated the benefits of co-applying phosphorus (P) and potassium (K) fertilizers for improved nutrient uptake. Similarly, Islam *et al.* (2024)^[18] showed that additional potassium fertilization can mitigate drought stress and improve crop performance in mungbean production.

The nutrient variability observed in Miwaleni and SUA resonates with patterns reported in other mungbean-growing regions like India, Bangladesh, and Thailand (Das *et al.*, 2016; Ha *et al.*, 2018)^[10], underscoring the need for site-specific soil fertility management to maximize both crop productivity and nutritional quality. Synthesizing the findings from various studies indicates that targeted nutrient management strategies are vital for enhancing mungbean cultivation, thereby improving both agricultural outputs and nutritional quality.

The role of soil properties in micronutrient accumulation, particularly iron (Fe) and zinc (Zn), in mungbean grains was evident, as significant differences were observed in Fe and Zn concentrations between the Miwaleni and SUA sites. Miwaleni exhibited higher Fe concentrations, while SUA had elevated Zn levels. These differences likely arise from variations in soil chemistry, environmental conditions, and nutrient availability, which have been shown to influence the micronutrient content of legumes (Haider *et al.*, 2021)^[14]. These findings are particularly important in regions where iron and zinc deficiencies are prevalent in human diets.

Genotypic differences in Fe and Zn accumulation were also observed, with specific genotypes, such as M10, consistently demonstrating superior micronutrient content. Genotype M10

exhibited the highest concentrations of both Fe and Zn, making it a promising candidate for biofortification efforts aimed at enhancing the nutritional quality of mungbean crops. The observed genotypic variability emphasizes the importance of selecting and breeding genotypes with superior nutritional traits (Kgokong, 2022; Laskar *et al.*, 2023) ^[22, 25]. Incorporating these high-nutrient genotypes into breeding programs has the potential to improve both crop yields and the nutritional value of mungbeans, particularly in regions where micronutrient deficiencies are a concern.

Interestingly, correlation analysis revealed negligible relationships between soil Fe and Zn concentrations and those in mungbean grains at both the Miwaleni and SUA sites. These results suggest that soil micronutrient content may not directly translate into higher concentrations in plant tissues, highlighting the complexity of nutrient uptake and assimilation in mungbean. Similar observations have been reported in mungbean agroecosystems in Pakistan, Nepal, and Sri Lanka (Singh, 2013; Binagwa *et al.*, 2020) ^[4]. Although genotypes M10 and M4 exhibited the highest levels of Fe and Zn, these findings suggest that optimal micronutrient content in mungbean grains cannot be solely attributed to soil micronutrient levels (Chauhan & Williams, 2018; Rao *et al.*, 2016; Ong *et al.*, 2023) ^[8, 15, 34]. The low correlation coefficients ($r = 0.22$ for Zn in plant vs. Zn in soil at Miwaleni, and $r = 0.25$ at SUA) indicate that factors beyond soil micronutrient content—such as microbial activity, plant physiological responses, and agronomic practices—play significant roles in nutrient assimilation (Musini *et al.*, 2024; Chu *et al.*, 2024) ^[30, 9].

These results highlight the necessity for integrated approaches that combine effective soil nutrient management with the selection of high-nutrient genotypes. Such strategies are essential for optimizing both productivity and nutritional quality in mungbean cultivation, ensuring that the crop contributes to food security and human health.

The study's findings emphasize the importance of applying targeted soil management practices, such as adjusting pH and applying specific fertilizers, to correct local nutrient imbalances and enhance micronutrient uptake. Furthermore, breeding programs should prioritize the development of genotypes that excel not only in productivity but also in their ability to accumulate higher levels of essential micronutrients such as Fe and Zn. Combining these practices will enable mungbean cultivation to play a significant role in improving food security and human health, particularly in regions where mungbean serves as a staple crop.

5. Conclusion and Recommendations

This study highlights the critical interplay between soil properties and genotype selection in optimizing mungbean productivity and nutritional quality. Significant differences in soil nutrient content at the Miwaleni and SUA sites highlight the necessity for site-specific soil management practices. The observed variations in iron and zinc concentrations in mungbean grains—shaped by both environmental factors and genetic diversity—emphasize the need for tailored approaches to improve crop performance. Genotypes like M10, noted for their higher micronutrient content, show promise for enhancing the nutritional profile of mungbean. The weak correlation between soil and plant micronutrient levels indicates that nutrient uptake is influenced by factors beyond soil nutrient availability, reflecting the complexity of nutrient acquisition.

To bolster mungbean production and its nutritional value, breeding programs should prioritize genotypes with elevated

micronutrient levels, like M10, to combat regional deficiencies. Additionally, an integrated approach combining effective soil management with the selection of nutrient-dense, high-yielding genotypes can enhance both agronomic performance and nutritional contributions.

Further research is essential to explore the genetic and physiological mechanisms behind iron and zinc uptake in mungbean, facilitating the development of genotypes that utilize soil micronutrients more efficiently. Long-term monitoring of soil and plant nutrient levels is crucial to mitigate risks of micronutrient toxicity, particularly in areas with high iron concentrations. Adopting sustainable agricultural practices will help maintain soil health and ensure ongoing production of high-quality mungbean. These strategies can collectively improve mungbean yields, enhance its nutritional benefits, and contribute to broader food security efforts.

6. Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

7. Author contributions

- **THT:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.
- **LAC:** Supervision, Validation, Visualization, Writing – review & editing. **HGS:** Supervision, Validation, Visualization, Writing – review & editing.

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9. Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

10. Publisher's note

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