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Genotype x environment interaction of selected common beans (*Phaseolus vulgaris* L.) on seed iron and zinc concentrations

*[1]MVILE, A. J., [1]NCHIMBI-MSOLLA, S., [1]TRYPHONE, G. M.

[1]Sokoine University of Agriculture, P.O. Box 3005, Chuo Kikuu, Morogoro, Tanzania

***Corresponding Author:** mvileadriano@gmail.com

Abstract

The study was conducted in three sub-ecological locations in Morogoro to assess the effect of environments on seed iron (Fe) and zinc (Zn) concentration. The specific locations were Ndole, Kasanga, and Mlali, each representing distinct environmental conditions. To achieve a comprehensive assessment, 30 bean genotypes were planted using a Completely Randomized Block Design in three replications. Data on seed Fe and Zn concentration among bean genotypes were collected and analyzed using Analysis of Variance (ANOVA). Additionally, a GGE biplot analysis was utilized to evaluate the stability of the bean genotypes in terms of their seed Fe and Zn concentrations across environments. The use of the GGE biplot provided a visual representation of the genotype's performance and stability, facilitating the identification of the most promising genotypes. The analysis of variance indicated that there was no significant difference ($P \leq 0.05$) in seed Fe concentration within each location, but a significant difference was revealed across locations. Seed Zn concentration showed a highly significant difference ($P \leq 0.001$) among bean genotypes both within and across locations. The average seed Fe concentration was 165.1 mg/kg in Ndole, 129.9 mg/kg in Kasanga, and 92.4 mg/kg in Mlali. For seed Zn concentration, the averages were 28.0 mg/kg, 26.9 mg/kg, and 32.8 mg/kg for Ndole, Kasanga, and Mlali, respectively. The GGE biplot revealed that the genotypes Maini Ndefu (G2), NUA-695 (G20), NUA-590 (G14), and Selian-10 (G24) exhibited high stability with high seed Fe concentration, while the genotypes Rojo (G3), Selian-10 (G24), TARI-06 (G30), and Uyole-04 (G27) exhibited high stability with high seed Zn concentration. Therefore, the best-performing genotypes identified in this study can be recommended for further research and potential release as enhanced varieties for bean farmers. These genotypes can potentially contribute to enhanced nutritional quality and agricultural productivity in the region.

Key words: *Common bean; genotype x environment interaction; iron and zinc concentration; Phaseolus vulgaris*

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Introduction

Common bean (*Phaseolus vulgaris* L.) is a widely produced crop and covers 50% of the consumed grain legumes worldwide (Rawal and Navarro, 2019). The crop has the added advantage of nitrogen fixation, hence playing a great role in crop rotation and intercropping farming systems. Common bean is very nutrient-dense and is a valuable source of proteins, fibre, vitamins, and minerals, including seeds with comparatively high levels of Fe and Zn (Bouis and Saltzman, 2017). The average bean seed Fe content is between 61 and 71 mg/kg, but it has been found that some genotypes have levels as low as 34 mg/kg or as high as 152 mg/kg. The average Zn concentration is between 28 and 31 mg/kg, with low and high levels of 18 and 77 mg/kg, respectively (Murube *et al.*, 2021).

Iron (Fe) and zinc (Zn) are two critical micronutrients that the body needs for growth, development, reproduction, and other physiological functions (Murarka *et al.*, 2015). Adults need 8 to 11 mg of zinc per day, whereas lactating and pregnant women need 11 to 13 mg. On the other hand, adults' daily Fe requirements are higher, ranging from 12 to 28 mg, and in pregnant and lactating women, the rise is from 30 to 38 mg (Dietary Reference Intakes, 2019). Micronutrient deficiency (Hidden Hunger) brought on by insufficient nutrition and trouble in absorbing nutrients from food staff resulted in a number of pathologies, such as anaemia, chronic diseases, reduced immunity, and delayed development (Philipo *et al.*, 2021). Fe and Zn deficiencies are most common in developing nations, such as sub-Saharan Africa and Central and South America (Rehman *et al.*, 2020). In Africa, Fe deficiency and anaemia are particularly common in children and pregnant women, limiting children's physical and mental development and reducing adults' capacity for reproduction (Mwangi *et al.*, 2021). In Tanzania, about 41% of children under age 5 and 35% of women aged 15-49 have Fe deficiency (NBS, 2011) and about 37.5% of the population is at risk of insufficient Zn intake, putting the country in the high-risk category for Zn deficiency (MHSW, 2015).

Environments, specifically soil nutritional status, influence the level of Fe and Zn concentration in common beans. Plants planted in nutrient-deficient soils face difficulties retaining sufficient nutrients in the seeds (Graham *et al.*, 2001). It has been found that the problem of Zn deficiency is extensively spread in environments with soil having a low level of Zn (Cakmak, 2008). Variations in seed Fe and Zn in the common bean are attributable to differences in genotypes and the environments, including the nature of the soil. Soil physical and chemical characteristics, involving pH and organic matter, have a significant effect on nutrient uptake and solubility (Cakmak, 2008).

Genotype and genotype x environment (GGE) is mostly used for studying the adaptability and stability of genotypes, as it provides mega environment analysis, genotype evaluation, and a test site for the target environment (Yan *et al.*, 2007). When there is genotype x environment interaction (GEI) indicates that both environment and genotypes affect the phenotypic expression of the trait. The objective of this study was to investigate the genotype x environment interaction and stability of the selected common bean genotype to retain seed Fe and Zn concentration levels across the environments.

Materials and methods

Characteristics of the study area

Three trials were set in different sub-ecological locations within the Morogoro region (Ndole, Kasanga, and Mlali). Ndole is located within the Mvomero district at Latitude 6° 9' 21.1"S, Longitude 37° 23' 23.9"E, and Elevation 759m above sea level. Mlali is also located within the Mvomero district at Latitude 6^{o} 57′38.25″ S, Longitude 37^{o} 32'47.19" E, and an elevation of 590m above sea level. Kasanga is located in Morogoro municipality at Latitude 6^{o}50′20.61″ S, Longitude 37^{o}38'20.43" E, and elevation 505m above sea level. Morogoro region receives annual bimodal rainfall, March-May, which is considered a long rain season and November-December (short rain season) in some places, while in other places rain season is from November-May, which ranges from 500 to 2200 mm. The region has an average annual temperature of 18 °C in the highlands and 30 °C in the lowlands.

Soil sampling and analysis

A total of 10 sub-samples were systematically gathered from various points within the experimental area, each at a depth of 0-20 cm. These samples were carefully combined through rigorous mixing to produce a homogeneous composite sample weighing 1 kg, which was then delivered to the Department of Soil and Geological Sciences at Sokoine University of Agriculture for detailed laboratory analysis. Upon receipt, the composite soil samples underwent a meticulous process: they were air-dried over a period of 5 days to ensure complete moisture removal. Subsequently, the dried samples were finely ground to achieve a consistent texture suitable for further analysis. The prepared soil material was then sieved using a mesh size of 2.0 mm to remove any coarse debris and ensure uniformity for subsequent testing. The laboratory analysis encompassed a comprehensive suite of parameters essential for assessing soil quality and fertility. This included determination of soil pH, levels of exchangeable bases (such as Mg, Ca, K, and Na), measurement of cation exchange capacity (CEC), quantification of micronutrients (Fe and Zn), evaluation of available phosphorus (P), as well as assessment of organic carbon (OC) content and total nitrogen (N). The analytical methodologies followed were based on the established protocols outlined by Haluschak (2006), ensuring consistency and reliability in the results obtained.

Weather data of the study area

Weather data, including Rainfall, Temperature, and Relative humidity, were precisely recorded every month throughout the trial periods at each location (Ndole, Kasanga, and Mlali). These data points serve as critical indicators of the environmental conditions prevailing in each area, offering valuable insights into the seasonal variations and climatic influences impacting the outcomes of the study. The comprehensive collection of these measurements enhances our understanding of how local weather patterns may have influenced the results observed across different experimental locations.

Source of bean genotypes

In total, 30 genotypes of common beans (Table 1) were carefully selected for this study based on their desirable agronomic and nutritional traits. These genotypes were sourced from diverse institutions and locations to ensure a broad representation. Specifically, 14 genotypes were acquired from the International Center for Tropical Agriculture (CIAT) in Uganda, 11 genotypes originated from the Tanzania Agricultural Research Institute (TARI)-Selian Centre in Arusha, and 4 genotypes were obtained from Sokoine University of Agriculture (SUA) in Morogoro. Additionally, farmers from each trial location (Ndole, Kasanga, and Mlali) contributed a local check variety, representing the bean cultivars typically grown in those regions. A local check (Soya Kijivu) used was the same in each trial location. A local check served as a standard against which the performance of the introduced genotypes could be evaluated. The selection process aimed to encompass a wide range of genetic diversity and adaptability to various environmental conditions, ensuring a robust evaluation of agronomic performance, nutritional quality, and potential for local adoption and improvement of common bean varieties.

Table 1

Selected common bean genotypes, seed size, and collection sources

Genotype	Source	Seed Size	Genotype	Source	Seed Size
NUA-642	CIAT	Large	NUA-714	CIAT	Large
Maini Ndefu	TARI-Selian	Medium	KT-002	SUA	Large
Rojo	SUA	Large	SUA-90	SUA	Medium
Lyamungo 90	TARI-Selian	Large	Jesca	TARI-Selian	Large
NUA-692	CIAT	Large	NUA-695	CIAT	Large
Selian 94	TARI-Selian	Large	ADP-190	SUA	Large
NUA-636	CIAT	Large	Selian 97	TARI-Selian	Large
NUA-735	CIAT	Large	Mashamba-PYT-4	TARI-Selian	Medium
Calima	TARI-Selian	Large	Selian 10	TARI-Selian	Small
NUA-708	CIAT	Large	NUA-682	CIAT	Large
NUA-660	CIAT	Large	NUA-672	CIAT	Large
NUA-256-4	TARI-Selian	Large	Uyole-04	TARI-Uyole	Medium
NUA-746	CIAT	Large	NUA-527	CIAT	Large
NUA-590	CIAT	Large	Local Check	Ndole	Large
NUA-629	CIAT	Large	TARI-06	TARI-Selian	Large

Experimental design

The field experiment was organized using a Randomized Complete Block Design (RCBD) with three replications at each of the trial locations (Ndole, Kasanga, and Mlali). Each replication consisted of 30 experimental plots, each measuring 1m x 4m and accommodating 2 rows of plants per plot. Planting was staggered across locations, commencing in Ndole on January 5, 2022, followed by Kasanga on April 20, 2022, and Mlali on May 17, 2022. Seeds were sown at a spacing of 20cm x 50cm within each plot, with one seed per hill. Fourteen days after emergence, nitrogen in the form of Urea was applied at a rate of 35 kg N/ha to enhance plant growth. Throughout the growth cycle, three rounds of weeding were conducted at three-week intervals, and pest control was managed by spraying Dudu Acelamectin (5% EC) to ensure optimal plant health and performance of the common bean crops. The entire field operation, from planting to harvesting, was executed collaboratively with the participation of twenty (20) trained farmers at each location. Their involvement was integral as these trials were conducted directly in their fields, aligning the experimental conditions closely with real-world farming practices. This approach not only facilitated effective management and monitoring but also fostered local knowledge exchange and the adoption of improved agricultural techniques within the farming communities.

Data collection

Fe and Zn Determination

Common bean pods that had reached physiological maturity were carefully harvested, and the seeds were subsequently air-dried, shelled, and individually stored in designated paper bags corresponding to each genotype. Upon arrival at the laboratory, the air-dried seeds underwent grinding using a Cyclotec 1093 Sample Mill, with 5.0 g of each genotype processed to ensure uniformity in subsequent analysis. The determination of Fe and Zn contents in the seeds employed the Atomic Absorption Spectrophotometer (AAS) technique, following the protocol outlined by Estefan *et al.* (2013). For each genotype, 0.5 g of dry, ground common bean seeds was weighed and placed into porcelain crucibles. These crucibles were then carefully positioned in a furnace and subjected to a controlled temperature of 550°C for a period of five hours to incinerate the samples into ashes. After the completion of the burning process, the furnace was allowed to cool naturally. Once cooled, the ashes were dissolved in 10 ml of 6 N HCl solution, thoroughly mixed, and filtered through Whatman No. 42 filter paper to remove any solid residues. Following filtration, each filtrate was adjusted to a final volume of 25 ml by adding 15 ml of distilled water. Subsequently, the concentrations of Fe and Zn in the solutions were quantified using the Atomic Absorption Spectrophotometer (AAS). The machine operated at specific wavelengths of 248.3 nm for Fe and 213.9 nm for Zn to accurately determine the elemental concentrations in the seed samples from all tested bean genotypes across the three designated locations. This meticulous process ensured precise measurement and comparison of Fe and Zn levels, crucial for assessing the nutritional characteristics of the different common bean genotypes under the study.

Data analysis

The analysis of variance (ANOVA) for seed iron (Fe) and zinc (Zn) concentrations was conducted using the GenStat (16th Edition) statistical package with a significance level of $P \leq 0.05$. Performance means were separated by Tukey's Range Test (TRT). The genotype by environment interaction was evaluated using ANOVA, where a significant interaction indicated that Fe and Zn concentrations were influenced by the environment. To assess the stability of bean genotypes for seed Fe and Zn concentrations across three experimental locations, a GGE biplot (Genotype and Genotype × Environment) was performed. This was generated using R statistical software (Version 4.2.2) with the Metan package. The GGE biplot, introduced by Yan *et al*. (2000), helps in selecting high-performing, stable, and adaptable genotypes for multiple environments. The GGE biplot model, based on Gauch (2006), was formulated as follows:

$$Yhij = \mu + Eh + Gi + GEhi + Bj(h) + ehij,$$

where μ represents the population means for seed Fe or Zn concentration, Eh is the environmental effect, Gi is the genotypic effect, $GEhi$ is the genotype x environment interaction, $Bj(h)$ is the block effect, and $ehij$ is the random error. The biplots of GGE were composed using the general mean and IPCA score, with settings of Centering = 2, SVP = 1, and Scaling = 0.

Results

Soil and weather data of the study area

The soil analysis results indicated that iron (Fe) levels were high in Kasanga and Ndole, but medium in Mlali (Table 2). Zinc (Zn) concentrations were high in Mlali and Ndole, measuring 2.14 mg/kg and 1.86 mg/kg, respectively. According to Noulas *et al*. (2018), a Zn concentration above 1.5 mg/kg, as determined by the DTPA extraction method, is adequate for most crops. Soil pH values ranged from 6.85 at Ndole to 6.92 at Mlali, both considered medium for plant growth. Nitrogen levels were low across all locations. Phosphorus (P), Cation Exchange Capacity (CEC), and Calcium (Ca) were generally medium in Mlali and low in Ndole and Kasanga. The soil texture was classified as sandy clay loam in Mlali and Kasanga and sandy loam in Ndole. Organic carbon content was high in Mlali and medium in Ndole and Kasanga, indicating that Mlali's soil had more organic matter compared to the other two locations. From the recorded monthly weather data (Table 3), Ndole had the highest rainfall (277.4mm), while Mlali had the lowest (0.0mm). Mlali's low rainfall necessitated irrigation. In Ndole, rainfall persisted from the experiment's start until harvest, peaking in January and April. Kasanga's maximum rainfall occurred in the first two months after planting. Temperature varied across locations, with Ndole recording the highest (23.4°C) in January and the lowest (20.1°C) in Kasanga and Mlali in July. Kasanga and Mlali had a maximum relative humidity of 85% in April and May. Generally, rainfall was reliable from January to April in Ndole and Kasanga but not from May to August, requiring irrigation.

Table 2

Physical and chemical properties of the experimental soils

Parameter	Mlali	Remark	Ndole	Remark	Kasanga	Remark
pH in Water	6.92	Medium	6.85	Medium	6.89	Medium
Organic Carbon (%)	2.24	High	1.56	Medium	1.54	Medium
Total N (%)	0.14	Low	0.11	Low	0.12	Low
Bray-1-P (mg/kg)	20.25	Medium	12.87	Low	0.55	Low
CEC (cmol(+)/kg)	18.56	Medium	10.68	Low	12.42	Low
Exchangeable Ca (cmol(+)/kg)	5.3	Medium	3.48	Low	3.74	Low
Exchangeable Mg (cmol(+)/kg)	2.13	Medium	1.06	Medium	1.64	Medium
Exchangeable K (cmol(+)/kg)	3.87	High	1.96	High	1.56	High
Exchangeable Na (cmol(+)/kg)	6.71	High	4.16	High	5.43	High
DTPA Fe (mg/kg)	21.13	Medium	79.14	High	54.49	High
DTPA Zn (mg/kg)	2.14	High	1.86	High	0.78	Low
Particle size analysis						
%Clay	31.04		17.04		33.04	
%Silt	13.28		7.28		3.28	
%Sand	55.68		75.68		63.68	
Textural class	Sandy Clay Loam		Sandy Loam		Sandy Clay Loam	

Table 3

The study area's average monthly rainfall, temperature, and relative humidity

	Ndole			Kasanga			Mlali		
	Temp (^oC)	Rain (mm)	RH (%)	Temp (^oC)	Rain (mm)	RH (%)	Temp (^oC)	Rain (mm)	RH (%)
January	23.4	277.4	77.0						
February	23.3	151.3	83.0						
March	23.2	144.1	77.0						
April	22.5	242.6	82.0	23.2	207.7	85.0			
May				22.5	132.4	71.0	22.5	91.1	85.0
June				20.2	19.4	66.0	20.2	11.9	71.1
July				20.1	12.1	69.0	20.1	14.6	66.0
August							20.9	0.0	69.0

Seed Fe and Zn concentrations

Analysis of variance revealed no significant differences (P≤0.05) in the seed Fe concentration among the tested bean genotypes within each location (Table 5). Among the three locations, the highest range of seed Fe concentrations (107.2-223.3mg/kg) was recorded in Ndole, while the lowest range (82.01-112.7mg/kg) was recorded in Mlali. In Ndole, Lyamungo 90 (223.3mg/kg) followed by Rojo (221.5mg/kg) and Mashamba-PYT-4 (209.7mg/kg), recorded the highest seed Fe concentrations, while Calima (110.6mg/kg) and SUA-90 (107.2mg/kg) recorded the lowest concentrations. In Kasanga, the highest concentrations recorded were 169.8mg/kg (NUA-695), followed by 148.6mg/kg (Local Check), while the lowest concentration was 81.1mg/kg (NUA-735). The highest concentration recorded in Mlali was 112.75mg/kg (NUA-636), followed by 106.1mg/kg (NUA-642), while the lowest concentration was 82.01mg/kg (NUA-256-4). A combined analysis of variance for seed Fe concentration revealed no significant difference (P≤0.05) among the tested bean genotypes. However, the genotype by environment (G x E) interaction analysis revealed a significant interaction (P≤ 0.05) for seed iron (Fe) concentration (Table 4).

Given seed Zn concentration, the results revealed that there were highly significant differences (P≤0.001) in Zn concentration among the bean genotypes in Ndole and Mlali and moderately significant variations (P≤0.05) in Kasanga (Table 5). The highest seed Zn concentration in Ndole was 35.3mg/kg (Selian 10), followed by 34.44mg/kg (Maini Ndefu), while the lowest concentration was 22.66mg/kg (NUA-708), preceded by 22.94mg/kg (Calima). The Local check seed Zn concentration (24.77mg/kg) was lower than most of the tested bean genotypes, which could be due to the added nutritional advantage found in the improved bean genotypes. In Mlali, Selian 94 (40.35mg/kg) followed by NUA-642 (39.40mg/kg) were the leading bean genotypes in seed Zn concentration, while the lowest concentration was recorded in NUA-692 (20.67mg/kg). The concentration of seed Zn in Kasanga ranged from 20.4-37.2mg/kg, whereby Maini Ndefu (37.3mg/kg) followed by Rojo(32.4mg/kg) were the leading genotypes, while NUA-735 (20.4mg/kg) was the genotype with the lowest concentration. A combined analysis of variance revealed a highly significant difference (P<0.001) in seed Zn concentration among the bean genotypes, ranging from 26.01-36.69mg/kg (Table 5). Maini Ndefu (36.69mg/kg) followed by NUA-642 (34.03mg/kg) were found to be the best-performing bean genotypes in seed Zn concentration, while NUA-590 (26.01mg/kg) recorded the lowest concentration. However, the G x E interaction was not significant (P≤0.05), implying that the tested bean genotype's seed Zn concentrations were less sensitive to production environments (Table 4). The same goes for Steckling *et al*. (2017), who testified on the effect of genotype and genotype x environment interaction on the concentration of Zn in common beans.

Table 4

Mean square for combined analysis of variance for Fe and Zn concentration.

Variable	Genotype (G)	Location (E)	Genotype x Location (GxE)
Fe(mg/kg)	1319.2NS	118983.7*	1400.8*
Zn (mg/kg)	56.56***	867.12NS	27.18NS

NS: No Significance *, **, ***, Significance difference 0.05, 0.01, 0.001, respectively.

Table 5

Mean Fe and Zn concentration for the tested bean genotypes in three locations

Genotype	**Code**	**Fe concentration (mg/kg)**				**Zn concentration (mg/kg)**			
		Ndole	**Kasanga**	**Mlali**	**Combined**	**Ndole**	**Kasanga**	**Mlali**	**Combined**
ADP-190	G21	112.5	147.3	95.0	118.3	25.9	26.0	34.3	28.7
Calima	G9	110.6	138.0	92.8	113.8	22.9	32.0	32.3	29.1
Jesca	G19	188.1	125.7	82.4	132.0	26.2	26.9	30.3	27.8
KT-002	G17	200.3	128.1	85.7	138.1	28.6	26.1	32.1	28.9
Local Check	G29	139.1	148.6	89.1	125.6	24.8	28.8	32.4	28.7
Lyamungo 90	G4	223.3	110.7	103.5	145.8	26.3	22.6	35.4	28.1
Maini Ndefu	G2	199.9	148.2	92.1	146.8	34.4	37.2	38.5	36.7
Mashamba-PYT-4	G23	209.7	137.9	93.9	147.2	30.1	22.8	32.0	28.3
NUA-256-4	G12	162.7	114.0	82.0	119.6	26.8	24.2	29.1	26.7
NUA-527	G28	175.7	130.4	93.3	133.2	30.2	25.3	33.9	29.8
NUA-590	G14	180.2	135.0	85.1	133.4	27.1	24.0	26.9	26.0
NUA-629	G15	168.3	121.8	98.6	129.6	27.5	26.3	34.1	29.3
NUA-636	G7	137.3	142.5	112.7	130.8	25.1	25.2	33.7	28.0
NUA-642	G1	144.0	132.6	106.1	127.6	33.6	29.1	39.4	34.0
NUA-660	G11	179.9	113.4	85.1	126.1	28.5	22.5	29.7	26.9
NUA-672	G26	176.1	129.1	83.8	129.6	28.7	25.9	30.1	28.2
NUA-682	G25	152.6	123.7	83.4	119.9	27.4	27.3	30.5	28.4
NUA-692	G5	140.9	135.3	83.8	120.0	26.7	31.2	20.7	26.2
NUA-695	G20	181.2	169.8	95.6	148.9	30.7	29.9	29.5	30.0
NUA-708	G10	144.7	139.9	100.6	128.4	22.7	28.0	32.6	27.8
NUA-714	G16	137.1	141.8	105.7	128.2	24.5	26.2	33.6	28.1
NUA-735	G8	148.9	81.1	95.5	108.5	25.1	20.4	33.0	26.2
NUA-746	G13	155.4	148.2	86.6	130.1	25.9	26.8	29.8	27.5
Rojo	G3	221.5	137.4	91.9	150.3	28.6	32.4	37.3	32.8
Selian 10	G24	190.8	144.7	94.9	143.5	35.3	31.1	34.9	33.8
Selian 94	G6	142.0	102.9	104.4	116.4	28.2	24.4	40.4	31.0
Selian 97	G22	141.1	124.3	89.2	118.2	25.3	25.4	32.4	27.7
SUA-90	G18	107.2	116.3	83.9	102.5	28.5	26.1	33.7	29.4
TARI-06	G30	181.2	105.9	84.6	123.9	32.5	27.1	35.4	31.7
Uyole-04	G27	201.4	122.4	91.4	138.4	31.6	26.2	34.7	30.8

Mean	165.1	129.9	92.4	129.2	28	26.9	32.8	29.2
LSD	70.43	51.39	19.14	29.34	5.24	9.72	6.25	4.17
CV%	26.1	24.2	12.7	24.4	11.5	22.1	11.7	15.3
SE	43.09	31.45	11.71	31.53	3.21	5.95	3.82	4.48
P-Value	>0.05	> 0.05	>0.05	>0.05	<0.001	> 0.05	<0.001	<0.001

LSD: Least significant difference (5%), CV (%): Coefficient of variation, SE: Standard error

Mean performance vs. stability for seed Fe and Zn

The GGE biplot revealed that the total variation of the Fe concentration was 95.22%, composed of PC1 (73.18%) and PC2 (22.04%) (Figure 1). The PC1 score indicates the level of Fe and Zn concentration for the tested common bean genotypes: PC1 > 0 indicates a high level of seed micronutrients (Fe and Zn), whereas PC1 < 0 indicates a low level. The PC2 score derived from the multilocation tests indicates a genotype's stability. The PC2 score approaching zero signifies the genotypes are stable (Pobkhunthod *et al.*, 2022). The genotypes Rojo (G3), Maini Ndefu (G2), Mashamba-PYT-4 (G23), and Selian-10 (G24) exhibited notably high Fe concentrations in Ndole, indicating their potential to accumulate iron effectively in that environment (Figure 1). Conversely, in Kasanga, the genotype NUA-695 (G20) stood out with significantly higher Fe concentrations than other genotypes tested. In Mlali, most genotypes showed Fe concentrations close to the grand mean, reflecting relatively uniform iron accumulation across different varieties in this location. The highest Fe concentration observed was in genotype NUA-636 (G7), followed closely by NUA-642 (G1) and NUA-714 (G16), suggesting these genotypes possess a higher capacity for Fe accumulation under the specific conditions of Mlali. Among the genotypes that displayed stability in Fe concentration across locations, Maini Ndefu (G2), NUA-695 (G20), NUA-590 (G14), and Selian-10 (G24) were notable, consistently maintaining elevated Fe levels irrespective of the trial location. Conversely, genotypes such as NUA-527 (G28), NUA-672 (G26), and NUA-629 (G15) demonstrated stability but with Fe concentrations closer to the overall mean, indicating reliable performance without extreme deviations in iron accumulation. In contrast, genotypes NUA-256-4 (G12), Selian-94 (G6), NUA-682 (G25), and Selian-97 (G22) exhibited high stability across locations but with Fe concentrations below the grand mean, suggesting their consistent but comparatively lower iron accumulation potential. Considering Zn concentration, the GGE biplot analysis revealed that the total variation among the genotypes was captured predominantly by PC1 and PC2, which accounted for 51.83% and 30.74% of the variation, respectively, adding 82.57% (Figure 2). The biplot analysis highlighted distinct patterns in Zn concentration across different genotypes and trial locations.

In Ndole and Kasanga, Maini Ndefu (G2) and Selian-10 (G24) stood out for their high levels of Zn concentration. Conversely, in Mlali, genotypes such as NUA-642 (G1), TARI-06 (G30), Selian-94 (G6), and Uyole-04 (G27) exhibited comparatively higher Zn concentrations. Regarding stability in Zn concentration across locations, genotypes Rojo (G3), Selian-10 (G24), TARI-06 (G30), and Uyole-04 (G27) demonstrated consistently high levels, suggesting they may perform reliably across diverse environmental conditions. On the contrary, genotypes KT-002 (G17), NUA-708 (G10), and NUA-256-4 (G12) were identified as stable but with lower levels of seed Zn concentration, indicating their consistent performance but less favourable Zn accumulation compared to other genotypes.

Figure 1

Mean performance vs. stability pattern of GGE biplot demonstrating interaction effect of 30 bean genotypes across three locations for seed Fe concentrations.

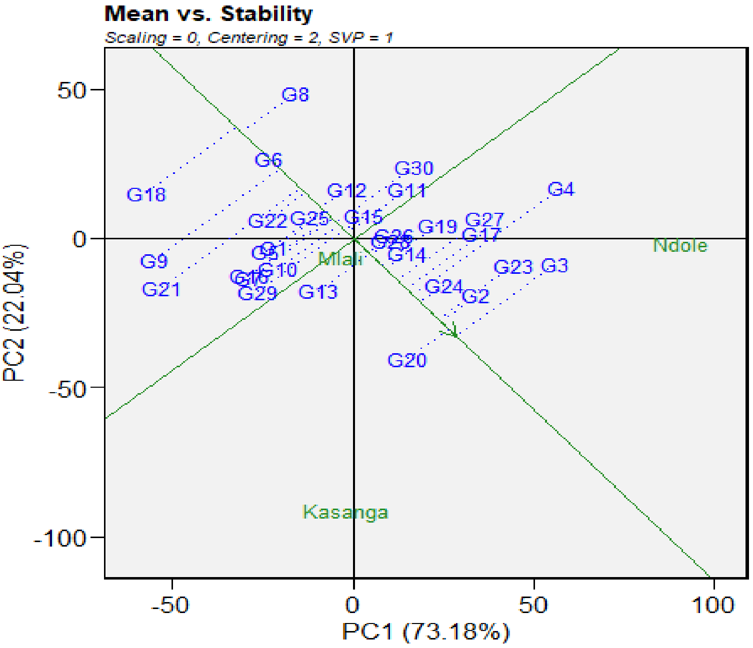
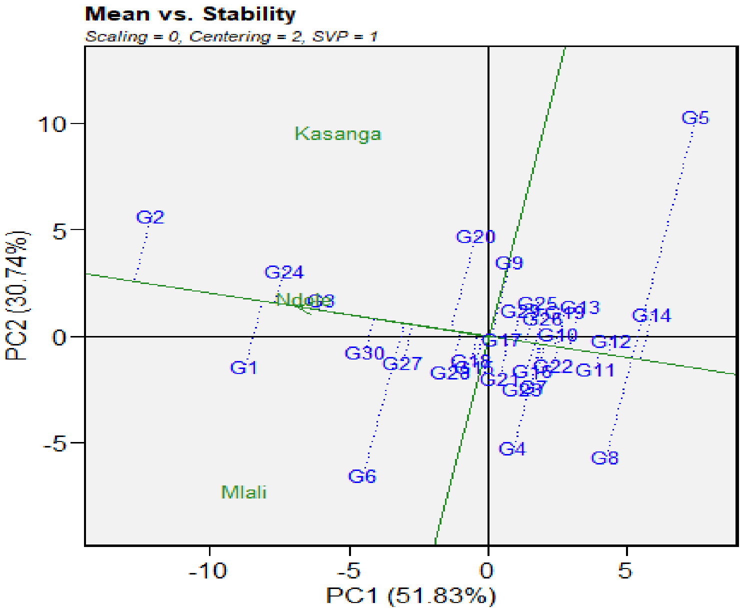


Figure 2

Mean performance vs. stability pattern of GGE biplot demonstrating interaction effect of 30 bean genotypes across three locations for seed Zn concentrations.



Discussion

The results revealed insignificant differences in seed Fe concentration within locations, but the genotype x environment (G x E) interaction was significant (P≤0.05) as indicated in Table 4. This implies that the genotypes had a slight difference in seed Fe concentrations but they were affected by the environments. Likewise, to Steckling *et al.* (2017) who reported the influence of Genotype and genotype-environment interaction on the concentration of Fe in common beans. The highest seed Fe concentration in bean genotypes observed in Ndole and Kasanga could be influenced by the nature of the soil (environment), which had a high concentration of Fe (Table 2), due to the fact that plants absorb and retain nutrients that are available in the soil (Havlin, 2020). Also, in Ndole, the rain was sufficient, which could be the reason for a recorded high level of seed Fe concentration. Philipo *et al*. (2020), found bean genotypes grown in sufficient and well-distributed rainfall had high levels of seed Fe concentration compared to those grown in areas with low rainfall or drought conditions. The statistical significance of this interaction underscores the importance of considering both genetic and environmental factors when evaluating seed Fe levels, as variations in environmental conditions can lead to significant differences in Fe concentration among the genotypes tested.

The observed differences in seed iron (Fe) and zinc (Zn) concentrations among the tested bean genotypes are likely influenced by the varying environmental conditions present at the three experimental locations. This finding aligns with the work of Phuke *et al*. (2017), who reported that variations in mean seed Fe and Zn concentrations in sorghum were attributed to different environmental conditions. Similarly, Zacharias *et al*. (2018) found that the same environmental differences contributed to variations in seed Fe and Zn concentrations in common beans. These studies highlight the significant role that environmental factors play in affecting the nutrient content of crops. It is crucial to consider these environmental influences when breeding and selecting genotypes for enhanced nutritional qualities, as they can substantially impact the stability and consistency of micronutrient concentrations across different growing conditions. This understanding can guide future research and agricultural practices aimed at optimizing the nutritional value of crops through both genetic and environmental management strategies.

The results indicated that the rankings of genotypes based on seed iron (Fe) concentration varied depending on the specific location (Figure 1). This suggests that the differences in environmental conditions significantly influenced the seed Fe concentration and stability of the tested bean genotypes. Such variation poses a challenge for plant breeders aiming to identify a genotype that will perform consistently across all test environments. Similar findings were reported by Philipo *et al*. (2020), where bean genotypes exhibited different levels of Fe and Zn concentrations due to the distinct environmental conditions they were exposed to. Additionally, the tested common bean genotypes showed differences in seed Fe and Zn concentrations across all three locations. Yeken *et al*. (2018) also noted variations in Fe and Zn content among 22 random populations of bean genotypes. These variations in seed Fe and Zn concentrations among the tested bean genotypes can serve as a valuable foundation for selecting and biofortifying broadly preferred common beans. The use of GGE biplots allows for the visualization of the relationship between genotypes and environments, demonstrating the adaptability and stability of genotypes across various contexts (Ukalski and Klisz, 2016). This tool helps plant breeders to better understand how genotypes perform in different environments, facilitating the selection of the most suitable candidates for breeding programs. Moreover, the common bean genotypes with the highest seed iron and zinc concentrations at each experimental site can be targeted for specific environmental breeding purposes. These genotypes, being well-adapted to their respective environments, offer a strategic advantage for breeding efforts aimed at enhancing nutritional quality in specific regions (Caligari and Forster, 2015). By focusing on these high-performing genotypes, breeders can develop new bean varieties that not only thrive in particular environments but also contribute to improving the nutritional status of the populations consuming them. This approach underscores the importance of integrating environmental considerations into breeding programs to achieve sustainable agricultural and nutritional outcomes.

Conclusion

This study has identified several bean genotypes that are both stable and exhibit high levels of seed iron (Fe) and zinc (Zn) concentrations. Specifically, the genotypes Maini Ndefu (G2), NUA-695 (G20), NUA-590 (G14), and Selian-10 (G24) have shown stability and high levels of seed Fe concentration. In addition, the genotypes Selian-10 (G24), TARI-06 (G30), and Uyole-04 (G27) have exhibited stability and high levels of seed Zn concentration. These identified candidates can be further evaluated across various agroecological zones to ensure the consistency of their seed Fe and Zn concentrations under different environmental conditions. This comprehensive evaluation is crucial for confirming their potential as reliable sources of these essential micronutrients. Ultimately, the successful candidates can be released as new bean varieties to enhance the nutritional and health status of consumers by providing higher dietary Fe and Zn. Moreover, these genotypes can serve as valuable resources for further research and development in other breeding programs aimed at improving the nutritional quality of beans and other crops.

Recommendations

The authors recommend further testing of these candidates across various agroecological zones to verify the consistency of their seed Fe and Zn concentrations. Such comprehensive evaluation is essential to confirm their adaptability and resilience in different environmental conditions. By doing so, researchers can assess the potential of these candidates as reliable sources of essential micronutrients. Ensuring their stability across diverse settings is crucial for their successful deployment in various agricultural landscapes. Ultimately, this rigorous testing process will benefit consumer health by improving the nutritional quality of crops.

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