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Research article

Environmentally stable common bean genotypes for production in different agro-ecological zones of Tanzania

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ABSTRACT

Genotype by environment interaction (GxE) complicates the process of selecting genotypes suitable for quantitative traits like seed yield in beans, hence slows down the development and release of varieties by breeding programs. GxE study on seed yield in beans enables identification of stable genotypes across sites and best site(s) for discriminating the tested genotypes in terms of seed yield. The purpose of this study was to evaluate the influence of the environment, genotype, and genotype by environment interaction on seed yield stability and adaptability of common bean landraces, lines, and improved varieties across three different agro-ecologies in Tanzania. The 99 common bean genotypes (Landraces, lines, and improved varieties) were planted following alpha lattice design in three replications each contained five blocks with 20 plots. Soil properties from the experimental sites, days to 75% flowering, Seed yield, 100 seed weight, number of seeds/pod, and number of pods/plant were recorded. Data on seed yield and its components were analyzed using Additive main effect and multiplicative interaction (AMMI), genotype main effects plus genotype × environment interaction (GGE), and yield stability index (YSI). The AMMI revealed very highly significant ($P \leq 0.001$) effects of genotypes, environmental, and genotype × environment interaction on all the traits. AMMI analysis revealed that genotype main effects accounted for 39.3% of the total sum square of seed yield, whereas the environment and genotype × environmental interaction accounted for 31.4% and 26.8 % respectively. Genotype main effects largely influenced the variation in days to 75% flowering (55.5%), number of pods/plant (49.2%), number of seeds/pod (73.3%), and 100 seed weight (71.2%). Among soil properties recorded, available soil phosphorus, soil pH, soil exchangeable K, Ca, and Na had a strong positive association with common bean seed yield, while soil organic carbon and total nitrogen exhibited a strong negative association with seed yield. GGE revealed that E1 (TARI-Selian) was the most discriminative and representative site for common bean genotypes seed yield. Based on the yield stability index, the most stable and high seed yielding genotypes were ACC 714, Selian 14, Selian 9, Katuku, and Msolini. The identified high seed yielding and stable genotypes can be further tested in participatory variety selection involving farmers and later on released as varieties and can also be used for different breeding purposes in different agro-ecologies of Tanzania.

1. Introduction

Common bean (*Phaseolus vulgaris L.*) is a tropical diploid (2n = 22), self-pollinating crop, and a member of the Fabaceae family [1]. It contains vegetable protein, minerals (Ca, Cu, Fe, Mg, Mn, and Zn), vitamins (folate), and essential amino acids [2]. Common bean performs well in environmental conditions with a temperature of 15 °C–30 °C, rainfall of 300 mm–600 mm, and well-drained, loamy soils with pH ranging from 5.5 to 7.0 [3,4]. In Tanzania, common bean is mainly grown in altitudes above 1000 m.a.s.l. for home consumption and incomes [5]. Worldwide Tanzania is ranked number seven and the largest producer of common beans in Africa followed by Uganda and Kenya. It is mostly grown in the Lake zone, Southern highlands, Northern and Western Tanzania [6]. The total common bean production in Tanzania is 1,158,039 tonnes, produced within the area of 1,118,406 ha. The crop ranks number three and number five among staple crops grown in Tanzania in terms of production and area of production respectively [7].

Despite the importance of common bean for food and incomes in Tanzania, the crop has been reported to be affected by extreme environmental conditions including i) very low or very high rainfall (below

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300ml or above 600 ml) as such conditions result in intermittent and or terminal drought, which negatively affects photosynthesis, causing a reduction in plant sugars, energy, quality, and yield [8, 9]. Too much rainfall, results in water logging, causing poor gas exchange between root and soil pore spaces, it also causes foliar diseases and root rot, thus reduces yield [10]. ii) High temperatures, such as day temperature of above 30 °C and night temperature above 20 °C as these conditions cause flower bud, flower, and pod abortion resulting in common bean seed yield reduction [1, 11, 12]. iii) Poor soil fertility, such as low nitrogen and available phosphorus causes a reduction in common bean yield through the reduction in nitrogen fixation activities and photosynthesis [9]. Too acidic soils lead to aluminum toxicity which also reduces bean yield [13].

As a result of those environmental factors, common bean production and productivity in Tanzania continue to be very low 1,035.4 kg/ha [7], compared to the potential yield of 1500–3000 kg/ha (the majority of non-climbing cultivars) [14] or up to 6000 kg/ha for some climbing bean cultivars [15]. Nevertheless, the performance of beans and reaction to different environmental conditions vary between genotypes [16]. Thus there is a strong need to screen different bean genotypes so as to identify those with stability in performances irrespective of varied environmental conditions. This study was aimed at assessing the performance of different bean genotypes in different environments and identify a few with superior stabilities in yield and yield components across agro-ecologies for use in plant breeding programs targeting bean varietal development and release.

2. Materials and methods

2.1. Common bean genotypes

This study used ninety nine common bean genotypes to evaluate the effect of three different agro-ecologies on seed yield and yield components. Fifty nine local varieties were obtained from randomly selected farmers of the largest bean producer regions in the country; namely Morogoro, Mbeya, Arusha, and Kagera. Whereas thirty two improved cultivars that are recommended for cultivation in a wide range or specific environment and nine lines were obtained from research institutions, which include; Sokoine University of Agriculture (SUA), located in Morogoro, Tanzania Agricultural Research Institute (TARI) Uyole, Selian and Maruku stations found in Mbeya, Arusha and Kagera respectively. Geographical and weather description of Morogoro region [17, 18], Mbeya region [19, 20], Arusha region [20], and Kagera region [21] are presented in Table 1.

2.2. Description of test locations

The three field experiments of this study were planted at agricultural research stations (Selian and Uyole) of the Tanzania Agricultural Research Institute (TARI) and Sokoine University of Agriculture (SUA) (Figure 1). Geographical positions and altitude, where the field trials were planted at each test location are presented in Table 2.

2.3. Test locations field soil collection and analysis

Soil samples were collected at each test location field at a depth of 20 cm before planting. The soil samples were air-dried, ground, sieved using a 2.0 mm mesh and used in laboratory determination of soil physical and chemical characteristics. Texture of the soils were obtained using the hydrometer method whereas soil pH was determined on 2.5:1 water to soil suspension [22]. After soil pH determination, available phosphorus (AP) for TARI-Selian experimental field soil (basic) was determined using the Olsen method while that of SUA and TARI-Uyole soils (acidic), was determined using Bray 1 method [23]. Exchangeable bases (Ca, Mg, Na, and K) were extracted using ammonium acetate and determined by atomic absorption spectrophotometry. Walkley-Black wet combustion method was used to determine organic carbon (OC), whereas total nitrogen (TN) was measured using the Kjeldahl method [24].

2.4. Field trial details

The field experiments at all three test locations (TARI-Selian, SUA, and TARI-Uyole) were laid out in alpha lattice design with three replications, each replication containing five blocks of 20 plots. Every experimental plot was planted with one common bean genotype in two rows of 1.5 m length spaced at 50 cm apart. Within rows plants were spaced at 10 cm from one plant to another. Planting at TARI-Uyole and Selian station, was done on March 2018 and harvested on July 2018, whereas common bean genotypes planting at SUA was done on May 2018 and harvested on August 2018.

2.5. Data collection

Days to 75 % flowering in each genotype were observed and recorded during flowering time. At harvesting, all plants in a plot were harvested and heaped at the center of a plot. Ten plants were randomly selected and the number of pods in each of the selected plants was counted and recorded to determine the number of pods per plant. The number of seeds per pod was counted and recorded from twenty randomly selected pods. Pods were shelled and air-dried for three days, the weight of 100 seeds (g/100 seeds), and all seeds per plot (g/plot) were measured and recorded. The weight of seeds per plot was later converted into kg/ha. Besides, weather information recorded during the planting season at each experimental site was obtained from Tanzania meteorological authority (TMA).

2.6. Statistical analysis

Analysis of variance (ANOVA) on days to 75 % flowering, yield, and yield components from each test location, was performed using GenStat 15th edition statistical package, to determine significant variability among genotypes for yield and yield components. Common bean genotypes seed yield and yield components means were separated using Duncan's new multiple range test (DNMRT) methods at a 5% level of probability while Pearson's correlation was used to determine the relationship between the variables at a 5% level of probability.

Additive main effects and multiplicative interaction (AMMI) model [26] using GenStat 15th edition statistical package (equation 1), was used to assess the effect of genotype by environment interaction, analyze the ability of common bean genotype(s) to become well suited to an environment rather than modifying the environment (adaptability) and

Table 1. Geographical information and weather conditions of regions where seeds were obtained.

Region	Geographical position		Mean annual rainfall (mm)	Mean annual temperature (°C)
	Latitudes	Longitudes		
Morogoro	05°58′- 09°32′S	35°25′- 38°30′E	500–2200	18–30
Mbeya	07°00′- 09°35′S	32°00′- 35°00′E	650–2600	16–25
Arusha	02°00′- 06°00′S	35°00′- 38°00′E	250–1200	21–26
Kagera	01°00′- 02°45′S	30°25′- 32°40′E	500–2000	20–28

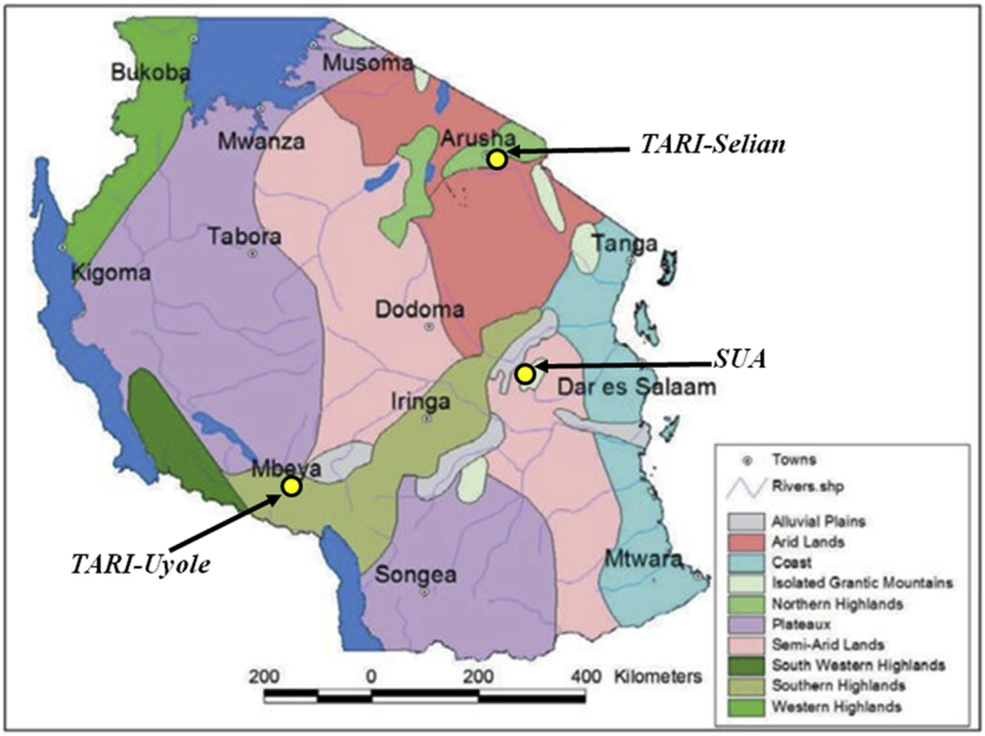

Figure 1. Map of Tanzania showing Agro-ecological zones [25], and the experimental sites (TARI-Selian, SUA, and TARI-Uyole).

Table 2. Geographical information of the test locations.

Test Location	Latitude	Longitude	Altitude (m.a.s.l)
TARI-Selian station	3° 22‘ S	36° 37‘ E	1430.0
SUA	6° 50‘ S	37° 39‘ E	541.7
TARI-Uyole station	8° 55' S	33° 30' E	1772.0

m.a.s.l = meters above sea level.

genotype's capability of performing more or less similar across several environments (stability).

$$Y_{ge} = \mu + \alpha_g + \beta_e + \Sigma_n \lambda_n \gamma_{gn} \delta_{en} + \rho_{ge} \quad (1)$$

Where ***Yge*** is the yield for genotype g in environment e, $\boldsymbol{\mu}$ is the grand mean, μg the mean for genotype g (over environments), and μe the mean for environment e (over genotypes), $\boldsymbol{\alpha g} = \mu g - \mu$ is the genotype deviation and $\boldsymbol{\beta e} = \mu e - \mu$ is the environment deviation, λn the singular value for n component, γgn be the eigenvector value for genotype g and let δen be the eigenvector value for environment e, ρge is the residual term. AMMI Stability Value (ASV) as explained by [27] was used to quantify and rank the common bean genotypes based on their yield stability (equation 2).

$$ASV = \sqrt{\left[\frac{SSIPC1}{SSIPC2}(IPC1)\right]^2 + (IPC2)^2} \quad (2)$$

Where $SSIPC1$ is the interaction principal component one sum of the square, $SSIPC2$ is the interaction principal component two sum of the square, $IPC1$ and $IPC2$ are interaction principal component 1 and 2 respectively.

Yield Stability Index (YSI_i) of each common bean genotype in terms of yield was calculated based on the rank of the ith genotype across environments based on AMMI Stability Value ($RASV_j$) and rank of the ith genotype based on mean yield across environments (RY_i) [28, 29] as

$$YSI_i = RASV_i + RY_i \quad (3)$$

The genotype main effect and genotype by environment interaction effect (GGE) biplot analysis was performed using PB Tools version 1.4. GGE biplot is based on tester centered data that is tester (environment) main effects (E) are removed, while the genotypes main effects (G) and genotypes by environment interaction main effects are retained and combined [30]. This study used GGE biplot analysis to visualize the correlation among the test locations and evaluate the discriminating power and representativeness of the test locations for the common bean genotypes in terms of seed yield and yield components.

3. Results

3.1. Test locations weather and soil physico-chemical characteristics

All the test locations received enough rainfall above 300 mm, though at different rates during common bean growing period. The crop requires rainfall above 300 mm for it to perform well. The other monthly weather parameters during the growing season are as presented in Table 3. The highest rainfall was recorded at TARI-Selian, followed by SUA, while the lowest rainfall was recorded at TARI-Uyole. The highest temperatures were recorded at SUA, Morogoro followed by TARI-Selian whereas TARI-Uyole recorded the lowest temperatures. The highest relative humidity at TARI-Selian and SUA was recorded in April, while TARI-Uyole recorded highest relative humidity in March. All the test locations recorded the lowest relative humidity in August.

Test locations soil characteristics are presented in Table 4. Analysis of variance revealed no significant difference ($P \leq 0.05$) in sandy soil

Table 3. Test locations weather information during experimental period.

Month	TARI-Selian				SUA				TARI-Uyole			
	Max Temp (°C)	Min Temp (°C)	Rain (mm)	Rh (%)	Max Temp (°C)	Min Temp (°C)	Rain (mm)	Rh (%)	Max Temp (°C)	Min Temp (°C)	Rain (mm)	Rh (%)
March	28.9	19.3	302.7	83.0	30.4	21.2	186.7	82.0	23.4	14.6	156.7	92.6
April	24.3	17.5	195.3	88.0	28.9	21.1	228.6	87.0	23.7	14.8	149.9	84.8
May	22.9	17.4	137.5	87.0	28.4	19.9	111	86.0	23.6	11.2	29.5	74.2
June	22.3	14.5	7.4	83.0	28.3	17.1	6.4	80.0	22.5	7.9	0.0	71.0
July	22.1	14.3	0.8	78.0	27.1	16.8	33	76.0	21.9	8.9	0.0	72.0
August	23.4	13.4	1.8	76.0	28.5	16.5	0.0	71.0	24.7	7.8	0.0	70.0

Table 4. Characteristics of the test locations soils.

Soil Properties	Location			Mean	Optimal levels	CV%	LSD (0.05)	P-value
	Selian	SUA	Uyole					
Soil pH	7.15[a]	6.00[a]	5.84[a]	6.33	5.5–7.5	6.2	1.69	0.132
% Clay	28.12[b]	52.12[a]	30.12[b]	36.79		5.9	9.29	0.013
% Silt	22.92[a]	9.92[b]	22.92[a]	18.59		11.6	9.30	0.04
% Sand	48.96[a]	37.96[a]	46.96[a]	44.63		4.8	9.30	0.064
Soil textural class	SCL	SCL	C					
TN %	0.16[b]	0.25[a]	0.15[b]	0.19	0.25–0.5	4.4	0.04	0.011
OC %	2.21[b]	4.52[a]	1.92[b]	2.88	>2	8.2	1.01	0.013
P (mg/kg)	23.93[a]	2.24[c]	13.26[b]	13.14	20–100	15.9	9.01	0.018
Ca^{2+} ($CmolKg^{-1}$)	22.14[a]	8.14[b]	8.05[b]	12.78	>10	5.5	3.02	0.004
Mg^{2+} ($CmolKg^{-1}$)	5.15[a]	4.98[a]	2.61[b]	4.25	>1.5	2.8	0.52	0.004
Na^{+} ($CmolKg^{-1}$)	1.03[a]	0.48[c]	0.58[b]	0.70	<1.5	1.2	0.04	0.001
K^{+} ($CmolKg^{-1}$)	5.58[a]	0.96[c]	1.54[b]	2.69	0.6–2.0	0.8	0.09	0.001

C = Clay, SCL = Sand clay loam, Different letters among samples = significant differences by Duncan's new multiple range test ($p \leq 0.05$).

particles, whereas there was a significant difference ($P \leq 0.05$) in clay and silt soil particles among the test location soils. Soils at TARI-Uyole and TARI-Selian were classified as sandy clay loam while soils at SUA were classified as clay. Significant variations ($P \leq 0.05$) among the test location soils were observed in total nitrogen (TN), organic carbon (OC), and available phosphorus (P), a highly significant variation ($P \leq 0.01$) was observed in exchangeable calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) among the test location soils. Furthermore, soils from the test locations had no significant difference ($P \leq 0.05$) in soil pH.

3.2. Genotypes seed yield and yield components variation

The highest common bean seed yield was recorded at TARI-Selian, followed by TARI-Uyole and lastly SUA. Seed yield at TARI-Selian, ranged from 1252.1 to 5121.9 kg/ha with a mean of 2336.0 kg/ha, while at SUA, seed yield ranged from 668.5 to 2499.4 kg/ha with a mean yield of 1347.7 kg/ha, and at TARI-Uyole it has a range of 903.4–2773.1 kg/ha with mean yield of 1579.4 kg/ha. The large variation in seed yield among the common bean genotypes was observed at TARI-Selian due to the larger interquartile range of the box plot compared to the rest experimental sites (Figure 2D). TARI-Selian recorded the highest 100 seed weight compared to other experimental sites. Weight of 100 seeds per genotype at TARI-Selian had a range of 20.3–66.0 g with a mean of 42.9 g. At SUA, the weight of 100 seeds ranged from 15.6 to 44.9 g with a mean of 30.1 g, whereas at TARI-Uyole, the weight of 100 seeds had a range of 17.0–50.1 g with a mean of 32.7 g. There was greater variability in the weight of 100 seeds among genotypes at TARI-Selian compared to other sites. Most of the tested bean genotypes weighted 100 seeds below the mean in all sites (Figure 2C). The highest number of pods per plant and the largest variability among bean genotypes were recorded at TARI-Selian compared to other sites. Most of the bean genotypes at TARI-Selian and SUA had the number of pods per plant greater than their site means (Figure 2A). TARI-Selian recorded the largest variation and highest number of seeds per pod among the experimental sites (Figure 2B).

The highest seed yielding genotype at TARI-Selian was Cheupe, closely followed by Uyole 84 and Selian 05. Among the common bean genotypes harvested at SUA, Jabeyila recorded the highest seed yield, followed by Cheupe and Mwamikola. At Uyole-Mbeya, the highest seed yielding genotypes was Selian 14, followed by DOOR 500 and Selian 15 (Table 5).

At TARI-Selian, the highest number of pods per plant was recorded from Cheupe followed by Ruondera and Kaisho kamugole. Cheupe also recorded the highest number of pods per plant at SUA, closely followed by Jabeyila and Mwamikola, whereas Wifi nyegela had the highest number of pods per plant at TARI-Uyole, followed by Kikobe and DOOR 500. In terms of the number of seeds per pod, Malirahinda, Cheupe, and Ngoma za bahaya were the best three genotypes at TARI-Selian. At SUA the best three genotypes in the number of seeds per pod were Kaempu, Kikobe, and Kyakaragwe, whereas Cheupe, kamosi, and kaempu had the highest number of seeds per pod at TARI-Uyole (Table 6). The highest 100 seed weight-containing common bean genotypes at TARI-Selian were Lyamungo 90, CAL96, and Msolini, Whereas Lyamungo 90, Msolini, and Selian 15 recorded the highest 100 seed weight at SUA. At TARI-Uyole Selian 15, Msolini and Uyole 94 were the highest 100 seed weight-containing common bean genotypes. The earliest flowering 3 common bean genotypes at TARI-Selian were Jesca, Kigoma, and Selian 12, whereas Pesa, Rojo, and Zawadi flowered early at SUA. At Uyole Calma Uyole, Kigoma, and Kintuntunu were observed as the earliest flowering common bean genotypes (Table 7).

Across locations, there was highly significant ($P < 0.001$) effects of genotypes, environments, and genotype by environment interaction on the days to 75% flowering, number of pods per plant, number of seeds per pod, the weight of 100 seeds and seed yield (kg/ha). Mean seed yield across sites ranged from 1085.2 to 3068.7 kg/ha with a grand mean of

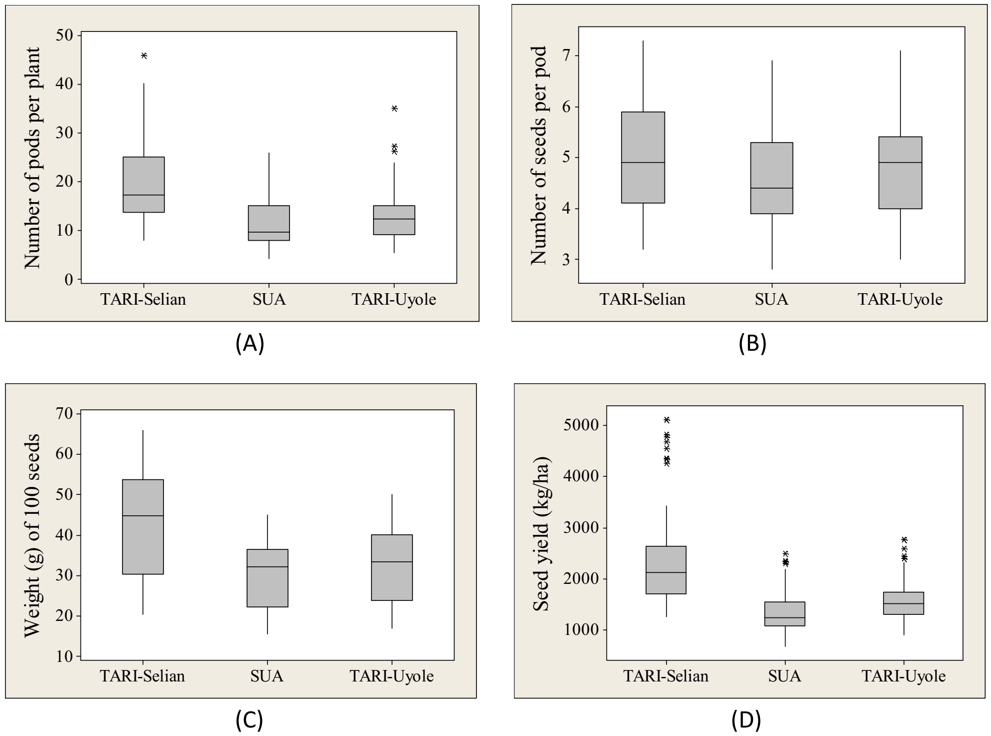

Figure 2. Distribution and comparison of 99 common bean genotypes seed yield and yield components across sites (TARI-Selian, SUA and TARI-Uyole); (A) Number of pods per plants; (B) Number of seeds per pod; (C) 100 seed weight; (D) Seed yield.

1736.9 kg/ha. AMMI analysis showed that the main effects of genotypes and environment accounted for 39.3 % and 31.4 % of seed yield treatment some of the squares respectively, whereas genotype × environment interaction effect represented 26.8 % of seed yield treatment some of the squares. The two interaction principal component axes (IPCA 1 and IPCA 2) were both highly significant ($P \leq 0.001$) for seed yield and accounted for 83.2 and 16.8 % respectively of the genotype by environment interaction for seed yield (Table 8).

The main effects of genotypes, environment, and genotype × environment interaction accounted for 55.5%, 5.5%, and 36.7% of the days to 75% flowering treatment some of the squares respectively. The two interaction principal component axes (IPCA 1 and IPCA 2) were both highly significant ($P \leq 0.001$) for days to 75 flowerings and accounted for 67.8 and 32.1% respectively of the genotype by environment interaction for days to 75% flowering. Genotype main effect accounted for 49.2%, while environmental main effect and genotype by environment interaction accounted for 26.0% and 21.9% of the number of pods/plant total sum square respectively. Of the interaction, IPCA1 accounted for 74.6% of the interaction sum of squares while IPCA2 accounted for 25.4% (Table 9).

The contribution of genotype main effect on the number of seeds/pod and 100 seed weight total sum square was larger 73.3% and 71.2% respectively, compared to environmental main effect which contributed 2.4% of the number of seeds per pod total sum of a square and 22.9% of 100 weight total sum of the square. Genotype by environment effect accounted for 18.7% of the number of seeds per pod total sum square and 5.8% of 100 seed weight total sum square. IPCA1 and IPCA2 for both 100 seed weight and the number of seeds/pod were highly significant difference ($P \leq 0.001$) (Table 10).

3.3. AMMI stability value and yield stability index for seed yield

The AMMI-1 biplot (Figure 3) elaborates genotypic and environmental additive main effects against their corresponding first interaction principal component axis (IPCA1). Common bean genotypes placed on the right-hand side of the midline have higher seed yield compared to those on the left-hand side of Figure 3. Genotype G74 (Selian 14) and G35 (Kikobe) had low IPCA1 scores close to zero and high seed yield. This indicates that the genotypes were less involved in genotype by environment interaction, therefore these were the most stable and high yielding genotypes. On the other hand, genotype G93 (Uyole 84), G69 (Selian 06), and G68 (Selian 05) exhibited the highest positive genotype by environment interaction while G99 (Zawadi) and G62 (Raja) expressed the highest negative genotype by environment interaction. Among the three environments, Uyole-Mbeya (E3) had a low contribution to genotype by environment interaction, whereas Selian-Arusha (E1) and SUA-Morogoro (E2) showed larger environmental main effects with high contributions to genotype by environment interaction.

Based on additive main effects and multiplicative interaction (AMMI) stability value (ASV) on seed yield of the harvested 99 common bean genotypes across locations, the genotypes were ranked based on least scores, whereby, low score indicates the most stable genotype. ASV ranked ACC 714 as the most stable genotype due to the lowest ASV followed by Bangaya akatebe, Kaempu, Pasi, and SMC 18. Selian 06 was ranked the most unstable genotype due to the highest ASV. The sum of seed yield and AMMI stability rankings also known as Yield Stability Index (YSI) ranked ACC 714 as the highest seed yielding and stable common bean genotypes across sites, followed by Selian 14, Selian 9, Katuku, and Msolini. SUA 90 was ranked the most unstable common bean genotypes based on YSI (Table 5).

3.4. Experimental sites discriminating power and representativeness on genotypes seed yield

The GGE biplot (Figure 4) shows the discriminating power and representativeness of the experimental sites on the seed yield of the common bean genotypes. An experimental site with a longer vector from the origin of the biplot had a larger discriminating ability for superior seed yield genotypes, while those with a shorter vector had low discriminating power. The experimental site vector with a small

Table 5. Test locations seed yield mean and ranking of 99 common bean genotypes based on seed yield, AMMI stability value (ASV), and yield stability index (YSI).

GN	Genotype	Common bean seed yield (kg/ha)				Common bean genotypes ranking						
		Selian	Uyole	SUA	Mean	IPCA1	IPCA2	ASV	$RASV_i$	RY_i	YSI_i	$RYSI_i$
1	ACC 714	2629^{no}	1888^{g-l}	1639^{h-m}	2052^{j-n}	0.06	0.24	0.4	1	22	23	1
2	Bagara Ompigize	2041^{xyz}	1681^{j-t}	1278^{o-A}	1667^{w-E}	3.09	2.76	15.6	43	43	86	35
3	Bangaya Akatebe	1863^{A-D}	1029^{C-F}	893^{H-M}	1261^{R-W}	-0.22	-1.33	1.7	2	92	94	45
4	Bilfa 4	1708^{E-J}	1507^{m-z}	811^{KLM}	1342^{M-T}	2.97	6.71	16.2	45	86	131	77
5	Bilfa Uyole	2400^{qrs}	1347^{s-C}	919^{F-M}	1555^{D-K}	-4.26	2.06	21.2	51	57	108	58
6	Buji	1694^{F-K}	1414^{m-B}	1358^{m-y}	1489^{F-M}	6.01	-1.53	29.9	69	64	133	78
7	Burushu	2637^{n}	1096^{A-F}	1542^{j-p}	1758^{t-A}	-4.04	-9.75	22.3	55	39	94	44
8	CAL 96	1884^{ABC}	903^{F}	1456^{k-t}	1414^{K-S}	2.42	-10.27	15.8	44	71	115	66
9	Calima Uyole	1403^{O-R}	1141^{y-F}	1239^{p-E}	1261^{R-W}	7.13	-3.45	35.5	76	93	169	96
10	Cheupe	5122^{a}	1957^{f-l}	2353^{ab}	3144^{a}	-21.19	-11.50	105.7	96	1	97	49
11	Chumba Neroza	3175^{hi}	1602^{l-x}	1260^{p-B}	2012^{k-o}	-9.14	0.19	45.3	86	23	109	60
12	CODMLB 033	2518^{n-q}	1645^{k-v}	1732^{f-k}	1965^{n-q}	0.72	-4.21	5.5	9	27	36	6
13	DOR 500	3012^{jk}	2772^{a}	1137^{u-J}	2307^{fgh}	-3.12	18.54	24.1	60	16	76	27
14	Fibea	2490^{pqr}	1728^{h-q}	1245^{p-C}	1821^{q-w}	-1.57	3.18	8.4	19	35	54	15
15	Jabeyila	2536^{n-q}	2393^{bcd}	2499^{a}	2476^{de}	8.41	-3.38	41.9	84	10	94	43
16	Jesca	1467^{M-P}	1328^{t-D}	1243^{p-D}	1346^{M-S}	7.30	-0.96	36.2	78	84	162	92
17	KAB o6F2-8-35	1758^{C-H}	1446^{m-A}	854^{J-M}	1353^{M-S}	2.43	5.21	13.1	32	81	113	62
18	KAB o6F2-8-36	2312^{stu}	1428^{m-B}	1093^{x-L}	1611^{z-H}	-1.94	1.12	9.7	25	52	77	28
19	Kabanima	1768^{C-G}	1257^{x-F}	936^{C-M}	1321^{N-U}	2.01	1.50	10.1	26	87	113	64
20	Kabumburi	1836^{B-E}	1171^{y-F}	1477^{j-t}	1495^{F-M}	4.21	-6.68	21.9	53	61	114	65
21	Kachele	2498^{opq}	1607^{l-x}	1225^{q-F}	1777^{s-y}	-2.29	1.70	11.5	27	37	64	20
22	Kaempu	2413^{qrs}	1762^{h-o}	1421^{l-v}	1865^{o-u}	0.43	1.54	2.6	3	33	36	9
23	Kainja	1628^{H-L}	1357^{q-C}	1106^{w-L}	1364^{L-S}	4.93	0.95	24.5	62	79	141	85
24	Kaisho kamugole	2824^{lm}	1609^{l-x}	858^{I-M}	1764^{t-z}	-7.90	5.90	39.6	82	38	120	67
25	Kakaritusi	1969^{yzA}	1604^{l-x}	1301^{o-z}	1624^{y-G}	3.63	1.48	18.1	47	49	96	48
26	Kamoshi	2093^{wxy}	1455^{m-A}	1116^{v-K}	1555^{D-K}	0.59	1.53	3.3	7	56	63	19
27	Kamosi	2212^{uvw}	1671^{k-t}	1531^{j-q}	1805^{r-x}	2.80	-0.85	13.9	35	36	71	25
28	Kanade	3260^{gh}	2160^{c-g}	1759^{f-j}	2393^{ef}	-4.58	1.64	22.8	56	11	67	21
29	Kashule	1559^{K-N}	940^{EF}	942^{C-M}	1147^{VW}	2.84	-2.77	14.4	36	98	134	80
30	Kasukari	2145^{vwx}	1660^{k-u}	1097^{x-L}	1634^{y-G}	0.82	4.60	6.1	10	46	56	16
31	Katuku	2833^{lm}	1954^{f-l}	1692^{g-l}	2160^{ijk}	-1.44	0.19	7.2	15	19	34	4
32	Katuku2	4270^{e}	2063^{d-i}	820^{KLM}	2384^{ef}	-21.16	10.68	105.5	95	12	107	56
33	Kibugu	1734^{D-I}	1281^{v-E}	1114^{v-K}	1376^{L-S}	3.55	-0.37	17.6	46	75	121	71
34	Kigoma	1598^{I-M}	1400^{n-B}	1333^{m-y}	1444^{I-Q}	6.80	-1.27	33.8	75	68	143	86
35	Kikobe	3316^{fg}	2311^{b-e}	2011^{def}	2546^{d}	-2.98	0.49	14.8	38	9	47	11
36	Kilindi	1658^{G-K}	1246^{x-F}	1221^{q-F}	1375^{L-S}	4.83	-2.12	24.0	59	76	135	81
37	Kinyobya	1562^{K-N}	1141^{y-F}	1066^{y-L}	1256^{S-W}	4.44	-1.49	22.1	54	94	148	87
38	Kipapi	1775^{C-G}	1511^{m-y}	1487^{j-s}	1591^{B-J}	6.37	-1.92	31.6	71	54	125	73
39	Kisapuri	2364^{rst}	1395^{o-C}	1110^{v-L}	1623^{y-G}	-2.52	0.36	12.5	31	50	81	30
40	Kitebe	2520^{n-q}	1998^{e-k}	1242^{p-D}	1920^{n-s}	-0.72	6.98	7.8	17	31	48	12
41	Kituntunu	2900^{kl}	1188^{y-F}	1073^{x-L}	1720^{u-C}	-9.20	-2.89	45.7	87	41	128	74
42	Kyababikira	1782^{C-G}	1398^{n-B}	1297^{o-z}	1493^{F-M}	4.66	-1.11	23.1	58	62	120	68
43	Kyakaragwe	2424^{qrs}	1184^{y-F}	1178^{r-H}	1595^{A-I}	-3.65	-3.58	18.4	49	53	102	52
44	Lyamungo 85	1682^{F-K}	1720^{i-r}	1467^{j-t}	1623^{y-G}	8.12	1.44	40.3	83	51	134	79
45	Lyamungo 90	1356^{P-S}	1265^{w-E}	892^{H-M}	1171^{UVW}	6.06	2.77	30.2	70	96	166	95
46	Maharage Kamba	2764^{m}	1882^{g-l}	1167^{t-I}	1938^{n-r}	-4.21	5.93	21.7	52	29	81	29
47	Maharage Mbeya	2209^{uvw}	1891^{g-l}	1887^{e-h}	1996^{l-o}	5.93	-2.23	29.5	68	25	93	41
48	Malirahinda	2038^{xyz}	1427^{m-B}	1222^{q-F}	1562^{C-K}	1.67	-0.12	8.3	18	55	73	26
49	Masusu	3110^{ij}	1719^{i-s}	2186^{bcd}	2338^{e-h}	-2.36	-9.80	15.3	40	14	54	14
50	Meupe Uyole	1706^{E-J}	1427^{m-B}	1225^{q-F}	1453^{H-P}	5.14	0.32	25.5	64	67	131	76
51	Mshindi	1415^{OPQ}	1063^{B-F}	1370^{m-y}	1283^{Q-V}	7.46	-6.23	37.5	80	90	170	97
52	Msolini	2812^{lm}	2035^{e-j}	2098^{b-e}	2315^{fgh}	1.58	-3.77	8.7	21	15	36	5
53	Mwami Kola	2214^{uvw}	1886^{g-l}	2329^{abc}	2143^{i-l}	8.53	-7.92	43.0	85	20	105	55
54	Ngoma za bahaya	2150^{vwx}	1630^{l-w}	1208^{r-G}	1663^{x-E}	1.32	2.76	7.1	14	44	58	17
55	Ngwakungwaku	2892^{klm}	1511^{m-y}	2295^{abc}	2232^{ghi}	-0.33	-13.80	13.9	34	17	51	13
56	Njano fupi	1945^{zAB}	1150^{y-F}	1181^{r-H}	1426^{K-R}	1.20	-3.40	6.8	13	70	83	33
57	Njano Uyole	1456^{NOP}	1477^{m-z}	1103^{x-L}	1345^{M-S}	7.21	2.95	35.9	77	85	162	93

(continued on next page)

Table 5 (*continued*)

GN	Genotype	Common bean seed yield (kg/ha)				Common bean genotypes ranking						
		Selian	Uyole	SUA	Mean	IPCA1	IPCA2	ASV	$RASV_i$	RY_i	YSI_i	$RYSI_i$
58	Nyeupe Kubwa	4356^{e}	2440^{bc}	1886^{e-h}	2894^{b}	-13.98	2.37	69.4	91	4	95	46
59	Nyeupe ndogo	2469^{pqr}	1769^{h-n}	1538^{j-p}	1925^{n-s}	0.60	0.06	3.0	6	30	36	7
60	Pasi	2501^{opq}	1712^{i-s}	1439^{k-u}	1884^{o-t}	-0.58	0.48	2.9	4	32	36	8
61	Pesa	1805^{C-F}	1504^{m-z}	1571^{i-o}	1627^{y-G}	6.54	-3.12	32.6	73	48	121	70
62	Raja	1960^{y-B}	1604^{l-x}	854^{J-M}	1473^{G-N}	1.03	7.17	8.8	22	65	87	36
63	Rojo	1280^{RS}	1409^{n-B}	1416^{l-w}	1368^{L-S}	10.63	-1.73	52.7	88	77	165	94
64	Rosenda	1791^{C-G}	1429^{m-B}	668^{M}	1296^{O-V}	0.91	7.28	8.6	20	88	108	59
65	Rozikoko fupi	1615^{I-L}	1209^{y-F}	981^{A-L}	1268^{R-W}	3.66	0.47	18.2	48	91	139	84
66	Ruondera	4548^{d}	2237^{c-f}	1933^{d-g}	2906^{b}	-16.56	-1.38	82.1	93	3	96	47
67	RWR 2154	2642^{n}	2053^{e-i}	1119^{v-K}	1938^{n-r}	-2.50	9.14	15.4	42	28	70	23
68	Selian 05	4831^{b}	1313^{t-D}	1988^{def}	2711^{c}	-23.17	-15.57	115.9	97	7	104	54
69	Selian 06	4785^{bc}	1385^{p-C}	958^{B-M}	2376^{efg}	-28.61	-1.43	141.9	99	13	112	61
70	Selian 10	1763^{C-H}	1639^{k-v}	1070^{y-L}	1491^{F-M}	4.53	5.20	23.1	57	63	120	69
71	Selian 11	2893^{klm}	2144^{c-g}	1543^{j-p}	2193^{hij}	-2.15	4.69	11.6	28	18	46	10
72	Selian 12	1293^{QRS}	1253^{x-F}	901^{G-M}	1149^{VW}	6.71	2.59	33.4	74	97	171	98
73	Selian 13	1669^{F-K}	1249^{x-F}	941^{C-M}	1286^{P-V}	3.03	1.46	15.1	39	89	128	75
74	Selian 14	3429^{f}	2773^{a}	2132^{b-e}	2778^{bc}	-1.43	5.33	8.9	23	5	28	2
75	Selian 15	4678^{c}	2588^{ab}	1993^{def}	3086^{a}	-16.02	2.63	79.5	92	2	94	42
76	Selian 9	2775^{lm}	1782^{h-m}	1844^{e-i}	2134^{i-m}	-0.67	-4.07	5.3	8	21	29	3
77	Selian 94	1520^{L-O}	1258^{x-F}	1430^{k-u}	1403^{K-S}	7.58	-4.40	37.8	81	72	153	88
78	Selian 97	1766^{C-H}	1460^{m-A}	818^{KLM}	1348^{M-S}	2.20	5.87	12.4	30	83	113	63
79	Selundo	2259^{tuv}	1672^{k-t}	2066^{cde}	1999^{l-o}	5.55	-7.68	28.6	67	24	91	39
80	Sinon	1760^{C-H}	1637^{k-v}	1265^{o-B}	1554^{D-K}	5.73	2.71	28.5	66	58	124	72
81	SMC 17	1514^{L-O}	1366^{p-C}	1176^{s-H}	1352^{M-S}	6.57	0.36	32.6	72	82	154	89
82	SMC 18	1982^{yzA}	1155^{y-F}	946^{C-M}	1361^{L-S}	-0.59	-0.39	2.9	5	80	85	34
83	Soya	1857^{A-D}	1309^{t-D}	932^{D-M}	1366^{L-S}	1.28	2.15	6.7	12	78	90	38
84	Soya Mbeya	4343^{e}	2081^{d-h}	1614^{h-n}	2680^{c}	-17.04	0.75	84.5	94	8	102	51
85	SUA 90	1278^{RS}	1333^{t-D}	945^{C-M}	1185^{T-W}	7.48	3.17	37.2	79	95	174	99
86	Tema	2245^{tuv}	1512^{m-y}	802^{LM}	1520^{E-L}	-2.64	6.09	14.4	37	60	97	50
87	Tikiumba Nyama	2060^{xyz}	1671^{k-t}	1489^{j-r}	1740^{t-B}	4.12	-0.09	20.4	50	40	90	37
88	Urafiki	1393^{O-R}	975^{DEF}	969^{A-M}	1112^{W}	4.89	-2.37	24.3	61	99	160	91
89	Uyole 03	2575^{nop}	1500^{m-z}	1432^{k-u}	1836^{p-v}	-2.31	-2.56	11.7	29	34	63	18
90	Uyole 04	2201^{uvw}	1135^{z-F}	1322^{n-y}	1553^{D-K}	-0.67	-5.76	6.7	11	59	70	24
91	Uyole 16	2087^{wxy}	1500^{m-z}	1480^{j-s}	1689^{v-D}	3.04	-2.44	15.3	41	42	83	32
92	Uyole 18	1581^{J-N}	1220^{y-F}	2090^{b-e}	1630^{y-G}	10.77	-13.38	55.1	89	47	136	82
93	Uyole 84	5116^{a}	1736^{h-p}	1313^{n-y}	2722^{c}	-28.37	-1.44	140.7	98	6	104	53
94	Uyole 94	1787^{C-G}	1291^{u-E}	1071^{y-L}	1383^{L-S}	2.78	0.23	13.8	33	74	107	57
95	Uyole 96	2296^{stu}	1634^{l-w}	1001^{z-L}	1644^{y-F}	-1.44	5.23	8.9	24	45	69	22
96	Uyole 98	2124^{vwx}	1323^{t-D}	929^{E-M}	1458^{H-O}	-1.44	1.99	7.4	16	66	82	31
97	Wanja	1663^{G-K}	1351^{r-C}	1185^{r-H}	1400^{K-S}	5.01	-0.18	24.9	63	73	136	83
98	Wifi Nyegela	2211^{uvw}	2391^{bcd}	1363^{m-y}	1988^{m-p}	4.91	11.47	26.9	65	26	91	40
99	Zawadi	1252^{S}	1650^{k-v}	1385^{m-x}	1429^{J-R}	11.78	2.12	58.5	90	69	159	90

Different letters among genotype values = significant differences by Duncan's new multiple range test (DNMRT) ($p \leq 0.05$), GN = Genotype number, IPC1 and IPC2 are interaction principal component 1 and 2 respectively, ASV = AMMI Stability Value, RASV = rank of the genotype across environments based on AMMI Stability Value, YSI = Yield Stability Index, RY = rank of the genotype across environments based on mean yield across environments, RGSI = rank of the genotype based on Yield Stability Index.

angle from the average environmental axis (AEA), is described as more representativeness site for the common bean genotypes seed yield evaluation experiment. E1 (TARI-Selian) with a longer vector from the biplot origin had good discriminating ability compared to the other experimental sites, while E3 (TARI-Uyole) with a shorter vector had poor discriminating ability compared to other experimental sites. E3 (TARI-Uyole) vector had a small angle with the AEA, thus more representative compared to the other sites, whereas E2 (SUA) had a larger angle with the AEA and therefore the least representative site among the experimental sites.

3.5. Association between common bean seed yield and yield components with test locations soil chemical properties

Pearson correlation analysis revealed that there was a strong positive significant ($P \leq 0.001$) relationship between common bean

Table 6. The best 20 common bean genotypes at each experimental site in terms of number of pods per plant and seeds per pod.

Number of pods per plant						Number of seeds per pod					
Genotype	Selian	Genotype	SUA	Genotype	Uyole	Genotype	Selian	Genotype	SUA	Genotype	Uyole
Cheupe	45.9^{a}	Cheupe	25.9^{a}	Wifi Nyegela	35.0^{a}	Malirahinda	7.3^{a}	Kaempu	6.9^{a}	Cheupe	7.1^{a}
Ruondera	40.1^{b}	Jabeyila	25.1^{a}	Kikobe	27.3^{b}	Cheupe	7.3^{a}	Kikobe	6.6^{ab}	Kamosi	7.0^{a}
Kaisho kamugole	37.2^{c}	Mwami Kola	21.8^{b}	DOR 500	26.3^{bc}	Ngoma za bahaya	7.0^{ab}	Kyakaragwe	6.5^{abc}	Kaempu	7.0^{a}
Katuku2	35.5^{d}	Selian 9	20.5^{bc}	Ruondera	23.9^{cd}	Selian 11	7.0^{ab}	Kachele	$6.5^{a\text{-}d}$	Wifi Nyegela	7.0^{a}
Kikobe	35.3^{d}	Kikobe	19.7^{bcd}	Jabeyila	23.0^{de}	Maharage Kamba	6.9^{ab}	Kaisho kamugole	$6.4^{a\text{-}e}$	Kanade	6.3^{b}
Selian 05	34.3^{e}	Ruondera	18.9^{cde}	Kaempu	22.4^{def}	Kachele	6.7^{bc}	Kamoshi	$6.4^{a\text{-}e}$	Maharage Kamba	6.3^{b}
Selian 14	34.2^{e}	Wifi Nyegela	$18.7^{c\text{-}f}$	Soya Mbeya	$21.3^{d\text{-}g}$	Kaempu	6.7^{bc}	Kasukari	$6.3^{a\text{-}f}$	Selian 9	6.3^{b}
Selian 11	32.6^{f}	Bagara Ompigize	$18.1^{c\text{-}g}$	Kachele	$20.8^{d\text{-}h}$	Kamosi	6.7^{bcd}	Malirahinda	$6.2^{b\text{-}f}$	Malirahinda	6.1^{b}
Maharage Kamba	32.3^{f}	Kachele	$18.1^{c\text{-}h}$	Pasi	$20.5^{d\text{-}i}$	Selian 10	6.5^{cde}	Mwami Kola	$6.1^{b\text{-}g}$	Kaisho kamugole	6.1^{bc}
Uyole 84	32.1^{f}	Kamosi	$17.7^{c\text{-}i}$	Nyeupe Kubwa	$20.2^{e\text{-}i}$	Kakaritusi	$6.4^{c\text{-}f}$	Ngoma za bahaya	$6.1^{b\text{-}h}$	DOR 500	6.0^{bcd}
Soya Mbeya	31.7^{f}	Selian 05	$17.5^{d\text{-}i}$	Bagara Ompigize	$20.1^{e\text{-}i}$	Selian 9	$6.4^{c\text{-}f}$	Selian 10	$6.1^{b\text{-}h}$	Jabeyila	6.0^{bcd}
Kachele	30.7^{g}	Nyeupe ndogo	$17.1^{d\text{-}j}$	Selian 11	$19.3^{f\text{-}i}$	DOR 500	$6.3^{c\text{-}g}$	Cheupe	$6.0^{b\text{-}i}$	Kamoshi	6.0^{bcd}
Tema	29.7^{h}	Kaempu	$16.7^{e\text{-}j}$	Kaisho kamugole	$19.0^{f\text{-}j}$	Kamoshi	$6.3^{c\text{-}g}$	Kakaritusi	$6.0^{b\text{-}i}$	Kasukari	$6.0^{b\text{-}e}$
Kamosi	28.7^{i}	Masusu	$16.7^{e\text{-}j}$	Kamosi	$19.0^{f\text{-}j}$	Kasukari	$6.3^{d\text{-}h}$	Chumba Neroza	$5.9^{c\text{-}ij}$	Kitebe	$6.0^{b\text{-}e}$
Masusu	27.8^{j}	Kanade	$16.5^{e\text{-}j}$	Katuku	$18.7^{f\text{-}k}$	Wifi Nyegela	$6.2^{e\text{-}i}$	Uyole 84	$5.9^{c\text{-}j}$	Ngoma za bahaya	$6.0^{b\text{-}e}$
DOR 500	27.5^{j}	CODMLB 033	$16.1^{e\text{-}k}$	Mwami Kola	$18.5^{g\text{-}l}$	Bangaya Akatebe	$6.1^{e\text{-}j}$	Wifi Nyegela	$5.9^{c\text{-}j}$	Ruondera	$6.0^{b\text{-}e}$
Kamoshi	27.4^{j}	Msolini	$16.1^{e\text{-}k}$	Selian 9	$18.3^{g\text{-}l}$	Kikobe	$6.1^{e\text{-}j}$	Kamosi	$5.9^{d\text{-}k}$	Selian 10	$6.0^{b\text{-}e}$
Nyeupe Kubwa	27.3^{jk}	Selian 15	$16.0^{e\text{-}k}$	Kanade	$18.0^{g\text{-}m}$	Kitebe	$6.1^{e\text{-}j}$	Selian 05	$5.8^{e\text{-}l}$	Selian 14	$5.9^{b\text{-}f}$
Selundo	26.4^{kl}	Katuku	$15.9^{f\text{-}k}$	Selian 15	$18.0^{g\text{-}n}$	Selian 06	$6.1^{e\text{-}j}$	Kituntunu	$5.7^{f\text{-}l}$	Chumba Neroza	$5.9^{b\text{-}f}$
Pasi	26.1^{lm}	Uyole 18	$15.9^{f\text{-}k}$	Maharage Kamba	$17.7^{g\text{-}o}$	Nyeupe Kubwa	$6.1^{e\text{-}k}$	Bangaya Akatebe	$5.7^{f\text{-}m}$	ACC 714	$5.9^{b\text{-}f}$

Different letters among genotype values = significant differences by Duncan's new multiple range test ($p \leq 0.05$).

seed yield (kg/ha) with soil available phosphorus, soil pH, soil exchangeable potassium, sodium, and calcium. A strong negative significant ($P \leq 0.001$) correlation between seed yield and total soil nitrogen and organic carbon was observed. A week positive significant ($P \leq 0.001$) correlation between seed yield and soil exchangeable magnesium was observed. A strong positive significant ($P \leq 0.001$) relationship was obtained between the number of pods/plant and available soil phosphorus, soil pH, exchangeable soil potassium, sodium, and calcium. A moderate negative significant ($P \leq 0.001$) relationship between the number of pods/plant with total soil nitrogen and soil organic carbon was obtained, whereas a weak significant ($P \leq 0.001$) association was observed between the number of pods/plant and soil exchangeable magnesium. A moderate positive significant ($P \leq 0.001$) association was observed between 100 seed weight (g) and available soil phosphorus, soil pH, exchangeable soil potassium, sodium, and calcium, whereas exchangeable magnesium had a weak positive significance ($P \leq 0.001$) influence on 100 seed weight. A negative weak significant ($P \leq 0.001$) association was observed between 100 seed weight with total soil nitrogen and soil organic carbon (Table 11).

Table 7. The best 20 common bean genotypes in terms of 100 seed weight and earliest flowering 20 genotypes at each experimental site.

Weight (g) of 100 seeds						Days to 75% flowering					
Genotype	Selian	Genotype	SUA	Genotype	Uyole	Genotype	Selian	Genotype	SUA	Genotype	Uyole
Lyamungo 90	66.0^{a}	Lyamungo 90	44.9^{a}	Selian 15	50.1^{a}	Jesca	34.3^{a}	Pesa	33.0^{a}	Calima Uyole	36.0^{a}
CAL 96	65.0^{b}	Msolini	44.5^{ab}	Msolini	47.0^{b}	Kigoma	35.0^{b}	Rojo	33.0^{ab}	Kigoma	36.0^{a}
Msolini	64.0^{c}	Selian 15	44.2^{ab}	Uyole 94	$46.7b^{c}$	Selian 12	35.0^{b}	Zawadi	33.3^{abc}	Kituntunu	36.0^{ab}
Selian 15	63.7^{c}	Lyamungo 85	43.6^{bc}	Rosenda	$46.6b^{c}$	CAL 96	35.3^{b}	SUA 90	$33.7^{a\text{-}d}$	Selian 05	36.0^{abc}
Bilfa Uyole	62.0^{d}	Rosenda	43.1^{c}	Masusu	46.0^{cd}	Soya	35.3^{b}	Buji	$34.0^{a\text{-}e}$	Wifi Nyegela	$36.0^{a\text{-}d}$
Fibea	62.0^{d}	Buji	41.8^{d}	Lyamungo 90	45.9^{cd}	Kilindi	36.0^{c}	Selian 13	$34.0^{a\text{-}e}$	Kabumburi	$37.0^{a\text{-}e}$
Lyamungo 85	62.0^{d}	Bilfa Uyole	41.2^{d}	Wanja	45.3^{de}	Kisapuri	36.0^{c}	Uyole 16	$34.0^{a\text{-}f}$	Maharage Mbeya	$37.0^{a\text{-}f}$
Uyole 03	62.0^{d}	Fibea	41.2^{d}	Fibea	45.0^{e}	Masusu	36.0^{c}	Kilindi	$34.3^{c\text{-}g}$	Msolini	$37.0^{a\text{-}g}$
Calima Uyole	61.3^{d}	Selian 14	41.2^{d}	CAL 96	44.0^{f}	Mshindi	36.0^{c}	Selian 12	$34.7^{d\text{-}g}$	Uyole 18	$37.0^{a\text{-}h}$
Wanja	59.3^{e}	Uyole 96	41.2^{d}	Meupe Uyole	43.4^{fg}	Pesa	36.0^{c}	Kibugu	35.0^{egh}	Jesca	$38.0^{e\text{-}i}$
Selian 14	59.0^{ef}	Masusu	40.7^{d}	Ngwakungwaku	43.2^{g}	SUA 90	36.0^{cd}	Kigoma	$35.0^{e\text{-}h}$	KAB o6F2-8-35	$38.0^{e\text{-}i}$
Uyole 94	58.3^{fg}	Kipapi	40.7^{d}	Tikiumba Nyama	43.0^{gh}	Buji	36.3^{cde}	Kipapi	$35.0^{e\text{-}h}$	Kaisho kamugole	$38.0^{e\text{-}i}$
Uyole 96	58.0^{g}	Ngwakungwaku	39.5^{e}	Selian 14	43.0^{gh}	Kabumburi	$36.3^{c\text{-}f}$	Njano fupi	$35.0^{e\text{-}i}$	Kashule	$38.0^{e\text{-}i}$
Meupe Uyole	57.7^{g}	Sinon	38.7^{ef}	Uyole 96	42.3^{hi}	Ngwakungwaku	$36.3^{c\text{-}g}$	Tikiumba Nyama	$35.0^{e\text{-}j}$	Kipapi	$38.0^{e\text{-}i}$
Buji	56.3^{h}	Njano fupi	38.7^{ef}	Lyamungo 85	41.8^{ij}	Njano fupi	$36.3^{c\text{-}h}$	Wanja	$35.0^{e\text{-}j}$	Mwami Kola	$38.0^{e\text{-}i}$
Masusu	56.0^{h}	Wanja	38.6^{ef}	Ruondera	41.8^{ijk}	Urafiki	$36.3^{c\text{-}i}$	Jesca	36.0^{hk}	Nyeupe ndogo	$38.0^{e\text{-}i}$
Ngwakungwaku	56.0^{h}	CODMLB 033	38.4^{fg}	CODMLB 033	$41.8^{i\text{-}l}$	Wanja	$36.3^{c\text{-}j}$	Kitebe	$36.0^{h\text{-}l}$	Selian 13	$38.0^{e\text{-}i}$
Sinon	56.0^{h}	Meupe Uyole	38.3^{fg}	Uyole 18	$41.3^{j\text{-}m}$	Zawadi	$36.3^{c\text{-}k}$	Mshindi	36.3^{klm}	Selian 97	$38.0^{e\text{-}i}$
Rosenda	55.0^{i}	Uyole 16	37.7^{fgh}	Kipapi	41.0^{jlm}	Kinyobya	$36.7^{c\text{-}l}$	Selian 9	36.3^{klm}	Soya	$38.0^{e\text{-}i}$
Uyole 16	55.0^{i}	CAL 96	37.7^{fgh}	Selundo	$41.0^{j\text{-}m}$	Bangaya Akatebe	37.0^{lm}	CAL 96	$37.0^{k\text{-}n}$	SUA 90	$38.0^{e\text{-}i}$

Different letters among genotype values = significant differences by Duncan's new multiple range test ($p \leq 0.05$).

Table 8. AMMI analyses of variance for seed yield of common bean genotypes across sites.

Source of Variation	DF	SS	MS	F	P-value.	%TSS	%GEISS
Total	890	506262438	568834				
Treatments	296	493659622	1667769	82.8	<0.001	97.5	
Genotypes	98	199047377	2031096	100.84	<0.001	39.3	
Environments	2	158873571	79436785	627.26	<0.001	31.4	
Block	6	759843	126640	6.29	<0.001	0.2	
Interactions	196	135738674	692544	34.38	<0.001	26.8	
IPCA	99	112960007	1141010	56.65	<0.001		83.2
IPCA	97	22778667	234832	11.66	<0.001		16.8
Error	588	11842974	20141				

DF = degree of freedom, SS = sum of square, MS = mean sum square, F = F value, P-value. = F probability, %TSS = percentage of total sum square and %GEISS = percentage of genotype by environment interaction sum square.

Table 9. AMMI analyses of variance for days to 75% flowering and number of pods/plant of common bean genotypes across sites.

Source of Variation	DF	Days to 75% flowering						Number of pods per plant					
		SS	MS	F	P-value	%TSS	%GEISS	SS	MS	F	P-value	%TSS	%GEISS
Total	890	6851	7.7					44930	50.5				
Treatments	296	6696	22.6	89.5	<0.001	97.7		43574	147.2	68.9	<0.001	97.0	
Genotypes	98	3804	38.8	153.6	<0.001	55.5		22094	225.5	105.5	<0.001	49.2	
Environments	2	376	188.1	167.2	<0.001	5.5		11660	5829.8	350.4	<0.001	26.0	
Block	6	7	1.1	4.5	<0.001	0.1		100	16.6	7.8	<0.001	0.2	
Interactions	196	2516	12.8	50.8	<0.001	36.7		9820	50.1	23.4	<0.001	21.9	
IPCA	99	1707	17.3	68.3	<0.001		67.8	7324	74	34.6	<0.001		74.6
IPCA	97	808	8.3	33.0	<0.001		32.1	2495	25.7	12.0	<0.001		25.4
Error	588	149	0.3					1257	2.1				

DF = degree of freedom, SS = sum of square, MS = mean sum square, F = F value, P-value. = F probability, %TSS = percentage of total sum square and %GEISS = percentage of genotype by environment interaction sum square.

Pearson correlation analysis for common bean seed yield and yield components (Table 12) showed that there was a strong positive significant ($P \leq 0.001$) relationship between seed yield and number of pods/plant. The number of seeds/pod exhibited a weak positive significant ($P \leq 0.001$) relationship with seed yield, whereas a moderate positive significant ($P \leq 0.001$) association was observed between 100 seed weight and seed yield. No significance ($P \leq 0.001$) relationship was observed between days to 75% flowering and seed yield and 100 seed weight with the number of pods/plant. Moderate negative significant ($P \leq 0.001$) associations were observed between 100 seed weight with days to 75% flowering and the number of seeds/pod.

4. Discussion

Yield and yield components of common bean genotypes were strongly influenced by the genetic makeup of bean genotypes, environmental conditions of the sites, and their interactions. in common bean, the influence of genotype, environment, and genotype by environment interaction has been reported [31]. Common bean genotypes particularly the landraces which were high yielding in specific sites can be used for improving varieties specific for locations where they have performed better. The highest seed yield was recorded at TARI-Selian followed by TARI-Uyole and lastly SUA-Morogoro, this may have been caused by

Table 10. AMMI analyses of variance for number of seed/pod and 100 seed weight of common bean genotypes across sites.

Source of Variation	DF	Number of seeds per pod						100 seed weight (g)					
		SS	MS	F	P-value	%TSS	%GEISS	SS	MS	F	P-value	%TSS	%GEISS
Total	890	933.4	1.1					119863	135				
Treatments	296	881.1	3.0	34.5	<0.001	94.4		119705	404	1532.7	<0.001	99.9	
Genotypes	98	684.5	7.0	80.9	<0.001	73.3		85390	871	3302.4	<0.001	71.2	
Environments	2	22.3	11.2	45.7	<0.001	2.4		27393	13696	34089.6	<0.001	22.9	
Block	6	1.5	0.2	2.8	0.01	0.2		2	0	1.5	0.168	0.0	
Interactions	196	174.3	0.9	10.3	<0.001	18.7		6922	35	133.9	<0.001	5.8	
IPCA	99	100.2	1.0	11.7	<0.001		57.5	5819	59	222.8	<0.001		84.1
IPCA	97	74.1	0.8	8.8	<0.001		42.5	1103	11	43.1	<0.001		15.9
Error	588	50.8	0.1					155	0				

DF = degree of freedom, SS = sum of square, MS = mean sum square, F = F value, P-value = F probability, %TSS = percentage of total sum square and %GEISS = percentage of genotype by environment interaction sum square.

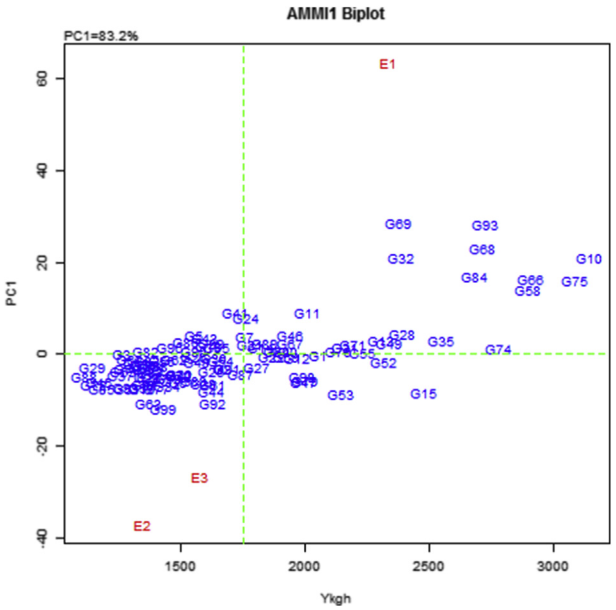

Figure 3. AMMI-1 model biplot for seed yield (kg/ha) presenting the means of ninety nine genotypes (G) and three environments (E) against their corresponding IPCA-1 scores.

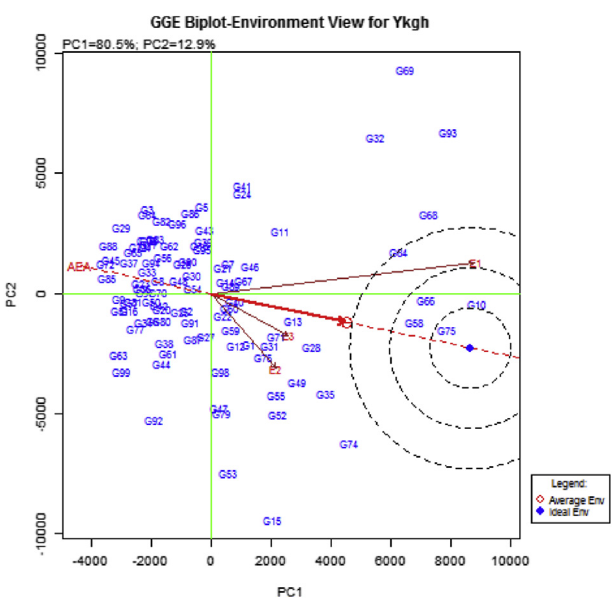

Figure 4. GGE biplot showing experimental sites discriminating power and representativeness on common bean genotypes seed yield.

well-distributed rainfall and soil properties. The high variations of common bean genotypes within location form the basis for selection on the respective bean traits [16].

AMMI analysis revealed that common bean seed yield was largely influenced by the genotype main effect (39.3%) compared to the environmental main effect (31.4). This indicated that the genotypes and experimental sites used were diverse and good for specific and general genotype adaptability studies. Similarly [32] determined a large contribution of cowpeas genotypes (38.0%) in seed yield compared to environmental effects (5.0%), and [26] reported 41.3 % genotype main effect on rice seed yield compared to the environmental main effect (31.9%). In contrast to this study [33], reported a larger contribution of environmental effect (78.2%) compared to the genotype main effect (6.5%). The difference in genotype main effect reported by this study may be due to a difference in the number of common bean genotypes and location used, whereby the current study used 99 diverse bean genotypes while [33] used 14 all white bean genotypes. Due to nearly equal environmental influence and genotype main effect on seed yield, this trait selection needs to be done in several environments to have a genotype that can be grown across several agro-ecological zones and perform more or less the same. From this preliminary one year result, days to 75% flowering, number of pods/plant, number of seeds/pod, and 100 seed weight were observed to be largely influenced by genotypes than environment and genotype by environment interaction, thus these traits are easy to select and breed for compared to seed yield. To confirm the results, the experiment needs to be repeated in other more sites and years.

There are several adaptabilities and stability analysis procedures that are used by plant breeders in the selection of plant genotypes that performs more or less similar across environments [31, 32]. Additive main effects and multiplicative interaction (AMMI) stability value (ASV) is one of the modern methods used for the identification and selection of plant genotypes that are stable across environments. Plant genotypes with low ASV closer to zero are thought to be more stable whereas those with great values are influenced by environmental effects [32]. Some of the bean genotypes that were ranked as stable by ASV had very low yield, this is because stability doesn't care about high or low yielding genotypes [35]. Thus yield stability index (YSI) was used to identify high seed yielding and stable bean genotypes, as it combines both stability and high yielding traits into a single index, that is used in the selection of genotypes [29, 34]. Genotypes with lower YSI are more useful as they have high mean yield and stability traits [28]. Thirty high seed yield and stable common bean genotypes were identified in this study based on YSI.

The concentric circles help in the visualization of the ideal experimental site, which has both high discriminating ability of superior genotypes and representativeness of the experimental sites [37]. Experimental site E1 (TARI-Selian), has both the high discriminating ability of superior common bean genotypes and representativeness of other experimental sites, thus it is an ideal site for a selection of the widely adapted common bean genotypes, as this site provided more information on seed yield performance of the tested genotypes. The

Table 11. Association of common bean seed yield and yield components with soil properties.

Soil Property	Seed yield (kg/ha)	Days to 75% flowering	Number of pods/plant	Number of seeds/plant	100 seed weight (g)
Soil N	-0.54***	0.03ns	-0.47***	-0.12***	-0.29***
Soil P	0.71***	-0.15***	0.64***	0.15***	0.45***
Soil OC	-0.52***	0.02ns	-0.45***	-0.12***	-0.28***
Soil K	0.68***	-0.21***	0.63***	0.15***	0.48***
Soil Mg	0.13***	-0.19***	0.15***	0.02ns	0.18***
Soil Na	0.69***	-0.20***	0.64***	0.15***	0.48***
Soil Ca	0.65***	-0.22***	0.61***	0.14***	0.47***
Soil pH	0.62***	-0.23***	0.58***	0.13***	0.46***

*** = significant at $P \leq 0.001$, and ns = not significant ($P > 0.05$).

Table 12. Association of common bean seed yield and yield components.

Yield component	Days to 75% flowering	Number of pods/plant	Number of seeds/pod	100 seed weight	Seed yield (kg/ha)
Days to 75% flowering	1.00	0.12***	0.27***	-0.34***	-0.003ns
Number of pods/plant	0.12**	1.00	0.43***	0.06ns	0.79***
Number of seeds/pod	0.27***	0.43***	1.00	-0.48***	0.27***
100 seed weight	-0.34***	0.06ns	-0.48***	1.00	0.33***
Seed yield (kg/ha)	-0.003ns	0.79***	0.27***	0.33***	1.00

*** = significant at $P \leq 0.001$, and ns = not significant ($P > 0.05$).

experiment can be further conducted into other sites to provide more information on this, as this was a one-season field experiment, [38] used GGE biplot to determine the discriminating power and representativeness of the experimental sites on sorghum genotypes yield.

The influence of individual soil properties on common bean performance indicated a strong positive effect of available soil phosphorus on seed yield and number of pods per plant also moderate 100 seed weight. Thus available soil phosphorus was the most important soil-plant nutrient to increase bean productivity and therefore needs to be considered carefully when growing beans. TARI-Selian which had optimum available soil phosphorus level had higher seed yield compared to TARI-Uyole and SUA which had low soil available phosphorus. The phosphorus influence and limiting factor for common bean seed yield was also been reported [39].

Total soil nitrogen and soil organic carbon influenced common bean seed yield negatively compared to the study [13], where soil organic carbon and nitrogen influenced seed yield in common bean positively. The negative influence of total soil nitrogen on common bean yield and its components may be due to low rainfall at SUA which recorded higher total soil nitrogen compared to other sites. [40] reported that, total soil nitrogen availability is positively influenced by precipitation, thus the availability of the measured total high soil nitrogen at SUA prior–planting may have been decreased by low rainfall during bean growing season. In all sites, soil organic carbon was optimum, therefore its influence on bean seed yield maybe it is the function of other soil and weather parameters. In all experimental sites, soil exchangeable potassium, magnesium, and sodium were adequate for common bean growth, and the highest levels of these were recorded at TARI-Selian, whereas soil exchangeable calcium was adequate and highest at TARI-Selian and low in other sites. All the measured exchangeable bases were positively and strongly correlated with seed yield.

5. Conclusion

All the common bean traits under this study were significantly influenced by genotype by environment interaction, thus a need to plant multilocation trials when selecting for these traits. Days to 75% flowering, number of pods/plant, number of seeds/plant, and 100 seed weight are largely influenced by genotype main effect, while seed yield is almost equally influenced by genotype and environmental main effects. Among 20 identified high seed yielding and stable common bean genotypes across sites, 17 had larger seed yield mean than grand mean, these genotypes includes ACC 714, Selian 14, Selian 9, Katuku, Msolini, CODMLB 033, Nyeupe ndogo, Pasi, Kaempu, Selian 11, Kikobe, Kitebe, Ngwakungwaku, Masusu, Fibea, Uyole 03 and Kichele. These genotypes can further be tested into other several bean-growing areas involving farmers and other common bean stakeholders for participatory variety selection, recommendation, and release. The genotypes can also be used for different breeding purposes in different agroecologies of Tanzania. The number of pods/plant can be used in the selection of high seed yielding common bean genotypes, as among the yield component traits, it was observed to associate strongly and positively with seed yield and was less influenced by environmental effect compared to seed yield.

Declarations

Author contribution statement

Mashamba Philipo: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Patrick Alois Ndakidemi: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Ernest Rashid Mbega: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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References

[1] M. Singh, I.S. Bisht, M. Dutta, Broadening the Genetic Base of Grain Legumes, Springer India, 2014.
[2] J.A. Acosta-Gallegos, J.D. Kelly, P. Gepts, Prebreeding in common bean and use of genetic diversity from wild germplasm, Crop Sci. 47 (2007) 44–59.
[3] E. Ossom, S. Zwane, R. Rhykerd, Plant population effects on ecological characteristics of field bean (Phaseolus vulgaris L.) in Swaziland, Trans. Ill State Acad. Sci. 99 (2006) 1–15. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Plant+Population+Effects+on+Ecological+Characteristics+of+Field+Bean+(+Phaseolus+vulgaris+L+.)+in+Swaziland#0%5Cnhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Plant+population+e.
[4] J.M. Salcedo, Regeneration Guidelines: Common Bean, CGIAR System-wide Genetic Resource Programme, Rome, Italy, 2008.
[5] J.J. Musimu, Economics of Small Holder Common Beans Production in Mbeya, Tanzania, Sokoine University of Agriculture, 2018.
[6] Ministry of Agriculture, Agriculture Basic Data, 2010. http://www.kilimo.go.tz/index.php/en/resources/view/agriculture-basic-data-2005-2006-2009-2010. (Accessed 5 December 2018).
[7] FAOSTAT, crops. http://www.fao.org/faostat/en/#data/QC, 2016. (Accessed 7 December 2018).
[8] N. Ntukamazina, R.N. Onwonga, R. Sommer, C.M. Mukankusi, J. Mburu, J.C. Rubyogo, Effect of excessive and minimal soil moisture stress on agronomic performance of bush and climbing bean (Phaseolus vulgaris L.), Cogent Food Agric. 3 (2017).

[9] L.M. Diaz, J. Ricaurte, E. Tovar, C. Cajiao, H. Terán, M. Grajales, J. Polanía, I. Rao, S. Beebe, B. Raatz, QTL analyses for tolerance to abiotic stresses in a common bean (Phaseolus vulgaris L.) population, PloS One 13 (2018) 1–26.
[10] S.E. Beebe, I.M. Rao, M.W. Blair, J.A. Acosta-Gallegos, Phenotyping common beans for adaptation to drought, Front. Physiol. 4 (2013).
[11] R.C. De la Peña, A.W. Ebert, P.A. Gniffke, P. Hanson, R.C. Symonds, Genetic Adjustment to Changing Climates: Vegetables, 2011.
[12] A.M. De Ron, A.P. Rodiño, M. Santalla, A.M. González, M.J. Lema, I. Martín, J. Kigel, Seedling emergence and phenotypic response of common bean germplasm to different temperatures under controlled conditions and in open field, Front. Plant Sci. 7 (2016) 1–12.
[13] V. Chekanai, R. Chikowo, B. Vanlauwe, Response of common bean (Phaseolus vulgaris L.) to nitrogen, phosphorus and rhizobia inoculation across variable soils in Zimbabwe, Agric. Ecosyst. Environ. 266 (2018) 167–173.
[14] M. Namugwanya, J.S. Tenywa, E. Otabbong, D.N. Mubiru, T.A. Masamba, Development of common bean (phaseolus vulgaris L.) production under low soil phosphorus and drought in sub-saharan Africa: a review, J. Sustain. Dev. 7 (2014) 128–139.
[15] H. Williams, Soil Factors Affecting Plant Performance of Climbing Beans (Phaseolus vulgaris L) in South Western Kenya, Swedish University of Agricultural Sciences, 2016.
[16] G. Acquaah, Principles of Plant Genetics and Breeding, second ed., 2013. Malden, USA.
[17] R.C. PLC, Morogoro Region Socio-Economic Profile, 1997. http://www.tzonline.org/pdf/Morogoro.pdf.
[18] F.C. Kahimba, S. Mbaga, B. Mkoko, E. Swai, A.A. Kimaro, A. Liingilie, Analysing the Current Situation Regarding Biophysical Conditions and Rainfed Crop - , Livestock - and Agroforestry Systems, A Baseline Report; 031A249A, Trans-SEC Consortium: Müncheberg, Germany, 2015.
[19] R.C. PLC, Mbeya Region Socio-Economic Profile, 1977. http://www.tzonline.org/pdf/Mbeyareg.pdf.
[20] A.A. Chuwa, United Republic of Tanzania National sample census of agriculture, Natl. Bur. Stat. III (2012) 41–44. www.nbs.org.
[21] R.C. PLC, Kagera Region Socio-Economic Profile, 1998. http://www.tzonline.org/pdf/kagera.pdf.
[22] R.J. Okalebo, K.W. Gathua, W. Paul L, Laboratory Methods of Soil and Plant Analysis : A Working Manual, second ed., Sacred Africa, Nairobi, 2002.
[23] J. Estefan, R. Sommer, John Ryan, Methods of Soil, Plant, and Water Analysis: A Manual for the West Asia and North Africa Region, Third Edit, ICARDA, Beirut, Lebanon, 2013. http://infosiap.siap.gob.mx/aagricola_siap_gb/icultivo/index.jsp.
[24] P.L. va Reeuwijk, Procedures for Soil Analysis, Sixth Edit, ISRIC, Wageningen, Netherlands, 2002.
[25] Ministry of Agriculture Food Security and Cooperatives, The United Republic of Tanzania Agriculture Climate Resilience Plan, 2014. http://extwprlegs1.fao.org/docs/pdf/tan152483.pdf.
[26] D. Balakrishnan, D. Subrahmanyam, J. Badri, A.K. Raju, Genotype × environment interactions of yield traits in backcross introgression lines derived from Oryza sativa cv . Swarna/Oryza nivara, Front. Plant Sci. 7 (2016) 1–19.
[27] J.L. Purchase, H. Hatting, C.S. Van Deventer, Genotype × environment interaction of winter wheat (Triticum aestivum L .) in South Africa : II . Stability analysis of yield performance, S. Afr. J. Plant Soil 17 (2000) 101–107.
[28] L.K. Bose, N.N. Jambhulkar, K. Pande, O.N. Singh, Use of AMMI and other stability statistics in the simultaneous selection of rice genotypes for yield and stability under direct-seeded conditions, Chil. J. Agric. Res. 74 (2014) 3–9.
[29] J. Adjebeng-danquah, J. Manu-aduening, V.E. Gracen, I.K. Asante, S.K. Offei, AMMI stability analysis and estimation of genetic parameters for growth and yield components in cassava in the forest and Guinea savannah ecologies of Ghana, Int. J. Agron. 2017 (2017).
[30] H.G. Gauch, H. Piepho, P. Annicchiarico, Statistical Analysis of Yield Trials by AMMI and GGE : Further Considerations, 2008.
[31] L.D. Barili, N. Martins, A. Lelis, J. Eustáquio, D.S. Carneiro, Genotype-environment interaction in common bean cultivars with carioca grain cultivated in Brazil in the last 40 years, Crop Breed, Appl. Biotechnol. 15 (2015) 244–250.
[32] L. Horn, H. Shimelis, F. Sarsu, L. Mwadzingeni, M.D. Laing, ScienceDirect Genotype-by-environment interaction for grain yield among novel cowpea (Vigna unguiculata L .) selections derived by gamma irradiation ☆, Crop J 6 (2017) 306–313.
[33] T. Tadesse, A. Tekalign, B. Mulugeta, G. Sefera, Evaluation of the effect of genotype , environment and genotype X environment interaction on white common bean varieties using additive main effect and multiplicative interaction (AMMI) analysis in the mid- altitude of Bale zone, Southeastern Ethiopia 13 (2018) 338–344.
[34] A.S. Milioli, A.D. Zdziarski, L.G. Woyann, R. Santos, A.C. Rosa, A. Madureira, Yield stability and relationships among stability parameters in soybean genotypes across years, Chil. J. Agric. Res. 78 (2018) 299–309.
[35] J.K. Rono, E.K. Cheruiyot, J.O. Othira, V.W. Njuguna, J.K. Macharia, J. Owuoche, M. Oyier, A.M. Kange, Adaptability and stability study of selected sweet sorghum genotypes for ethanol production under different environments using AMMI analysis and GGE biplots, Sci. World J. 2016 (2016) 1–23.
[37] E. Tena, F. Goshu, H. Mohamad, M. Tesfa, A. Seife, Genotype × environment interaction by AMMI and GGE-biplot analysis for sugar yield in three crop cycles of sugarcane (Saccharum officinirum L .) clones in Ethiopia Genotype × environment interaction by AMMI and GGE-biplot analysis for sugar yield in thre, Cogent Food Agric. 5 (2019) 1–14.
[38] M. Mare, P. Manjeru, B. Ncube, G. Sisito, GGE biplot analysis of genotypes by environment interaction on Sorghum bicolor L . (Moench) in Zimbabwe, Afr. J. Plant Sci. 11 (2017) 308–319.
[39] S.K. Mourice, G.M. Tryphone, Evaluation of common bean (phaseolus vulgaris L .) genotypes for adaptation to low phosphorus, ISRN Agron 2012 (2012) 9.
[40] X. Nie, F. Xiong, L. Yang, C. Li, G. Zhou, Soil nitrogen storage , distribution , and associated controlling factors in the Northeast Tibetan plateau shrublands, Forests 8 (2017) 1–13.