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Evaluation of garlic genotypes for yield performance and stability using GGE biplot analysis and genotype by environment interaction

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Abstract

In Ethiopia, the low productivity of garlic is largely due to a shortage of high yielding and stable varieties. To address this issue, thirteen garlic genotypes were evaluated for yield stability and performance across six different environments in central and southeast Ethiopia. The genotypes were analysed using Additive Main effects and Multiplicative Interaction (AMMI) and genotype-by-environment interaction (G × E) methods. Results showed that the genotypes differed significantly for bulb yield performance and morphological traits, with G-020/03 and G-054/03 producing the highest bulb yield with 25.39% and 18.39% yield advantages over the check variety, Kuriftu, respectively. Furthermore, G-020/03 demonstrated better yield stability across most environments, while G-054/03 exhibited specific adaptability. GGE biplot analysis confirmed that these two genotypes were among the three winning genotypes in terms of yield performance and relative stability. Therefore, G-020/03 and G-054/03 have been selected as candidate varieties for release, potentially improving garlic productivity in Ethiopia.

Introduction

Garlic (*Allium sativum* L. 2n = 16) is an important species belonging to the Allium genus of the Alliaceae family, and widely cultivated worldwide. It is the second most widely distributed and important species after onion (Kamenetsky *et al*., 2007; Gurpree *et al*., 2013). Asia is the centre of origin and the primary area of production, with China and India as the major producers (Haiping *et al*., 2014). Garlic is used as a spice, flavouring agent, and has medicinal properties against plant, animal and human diseases (Dugan *et al*., 2011; Kamkar *et al*., 2011; Haiping *et al*., 2014).

In Ethiopia, garlic is a widely cultivated bulb crop with a wide range of climatic and soil adaptation (Zeleke and Derso, 2015). It is produced by small and commercial growers for various purposes, such as herbal medicine and flavouring traditional cuisines, and serving as a source of income for many smallholders. However, the quality and yield of garlic in Ethiopia are generally low due to biotic and abiotic stresses and management practices under field and storage conditions (Tabor and Zelleke, 2000; Shiferaw, 2016). Garlic is cultivated on 18,345 hectares of land, and 152.5 thousand tons of yields were harvested in the rainy season, with Arsi and East Shewa zones of Oromia region being the major producers (CSA, 2018). More than 37 thousand farmers were involved in garlic production in these two zones alone (CSA, 2018).

Despite being reproduced asexually, garlic cultivars showed inconsistent yield performance, and phenotypic traits across various locations (Bradley *et al*., 1996; Islam *et al*., 2004; Baghalian *et al*., 2005; Haiping *et al*., 2014; Yeshiwas *et al*., 2018; Getahun and Getaneh, 2019; Atinafu *et al*., 2021; Tesfaye, 2021). Evaluation of diversity in garlic is therefore important for selection and breeding purposes to improve yield and quality (Baghalian *et al*., 2005; Haiping *et al*., 2014).

An effective improvement programme in garlic, often based on clonal selection, depends on the availability of sufficient genetic variability in a collection (Gurpree *et al*., 2013; Kumar *et al*., 2019). In Ethiopia, various diversity studies involving germplasm collection, characterization, and evaluation have resulted in the release of eight improved varieties (EAA, 2021). However, the shortage of high yielding and stable varieties remains a major constraint for the low productivity and production of garlic in the country (Belay *et al*., 2020). To address this issue, it is crucial to select high yielding and stable genotypes under variable environments prior to release, which is the primary step for plant breeding. However, little has been reported on genotype by environment interaction (G × E) and stability analyses in garlic in Ethiopia,

Table 1. Summary of site descriptions for the three testing locations in Ethiopia

Testing location	Latitude	Longitude	Soil pH	Soil type	Rainfall [mm]	Altitude [m.a.s.l]	Annual average [T°C]	
							Minimum	Maximum
Debre Zeit	8°44'N	38°58'E	6.9	Vertisol	851	1860	8.9	28.3
Chefe Donsa	8°57' N	39° 06' E	7.8	Vertisol	776	2450	8.8	25. 5
Kulumsa	8°1'7"N	39°9'35"E	6	Luvisol	832	2200	10	22

which are vital for breeders to rank genotypes and/or ideal environments for selection. Therefore, the present study assessed the performance of advanced garlic genotypes for different traits and tested their stability in variable environments for bulb yield.

Materials and methods

Experimental materials

The study evaluated thirteen promising garlic genotypes and one check variety, namely G-018/03, G-020/03, G-001/03, G-021/03, G-011/03, G-005/03, G-041/03, G-061/03, G-054/03, G-053/03, G-009/03, G-058/03, G-019/03 and Kuriftu (check variety). These genotypes were primarily collected from different parts of Ethiopia and selected for their bulb yield potential and desirable characteristics from previous evaluations. The study was conducted in six environments of three locations over two years, representing mid and high altitudes with different soil types and rainfall patterns in central and southeast Ethiopia during the main cropping seasons of 2018 and 2019 (Table 1).

Experimental design and agronomic practices

The genotypes were arranged in a field experiment using a Randomized Complete Block Design (RCBD) with three replications. Sprouted cloves from each genotype were planted on a plot size of 4.8 m2 with a spacing of 40 cm between double rows, 20 cm between rows and 10 cm between plants. Fertilizers were applied at the rate of 243 kg ha-1 NPS during planting and 130 kg ha-1 urea in split application once during planting and 45 days after emergence. Pesticides, including Tilt (0.5 l ha^{-1}), Karate (0.3 l ha^{-1}) and Ridomil Gold (2.5 Kg ha^{-1}), were uniformly sprayed on all experimental plots to manage garlic rust, onion thrips and downy mildew, respectively. Other agronomic practices, including cultivation and weeding, were applied as recommended (Tabor *et al.*, 2019).

Data analysis

Plant height (cm), days to maturity, number of cloves per bulb, average clove weight (g), bulb yield per plant (g) and per hectare (kg ha^{-1}) were recorded. The collected data were subjected to analysis of variance (ANOVA) using SAS statistical software (SAS, 2008). When the ANOVA indicated a statistically significant difference ($P < 0.05$), the least significant difference (LSD) test was used to compare treatment means. Additionally, Additive Main Effects and Multiplicative Interaction (AMMI), genotype-by-environment interaction (G × E) and GGE biplot analyses were performed using the GGEBiplotGUI package in R to evaluate the test environments and genotypes for bulb yield stability (R Team, 2018).

Results

Significant differences ($P < 0.05$) in bulb yield were obtained among the garlic genotypes and their combinations, except at Debre Zeit in 2018 (Table 2). Individual ANOVA revealed that genotype G-020/03 (4778.29 kg ha^{-1}), followed by G-005/03 (3526.09 kg ha^{-1}), had the highest bulb yield at Debre Zeit, while G-001/03 (3297.25 kg ha^{-1}) recorded the lowest yield. At Chefe Donsa, genotype G-009/03 (6196.90 kg ha^{-1}), followed by G-001/03 (5251.82 kg ha^{-1}), produced the highest bulb yield, while G-058/03 (3467.38 kg ha^{-1}) had the lowest yield (Table 2). Similarly, at Kulumsa, G-054/03 (11,041.90 kg ha^{-1}) and G-020/03 (10,694.55 kg ha^{-1}) gave the highest bulb yield, while G-011/03 (2013.70 kg ha^{-1}) gave the lowest yield. The combined ANOVA showed that G-020/03 and G-054/03 had the highest bulb yield over locations and years.

In addition to bulb yield, significant variation among the genotypes was obtained for different traits such as plant height, date of maturity, number of cloves per bulb and bulb yield per plant (Table 3). However, a statistically non-significant result was obtained for average clove weight (Table 3). Genotypes G-054/03 (61.35 cm) and G-020/03 (60.42 cm) had the maximum plant height and were also relatively late in maturity. Genotype G-019/03 was the shortest in plant height (56.33 cm) and had a similar date of maturity with other genotypes. Genotype G-009/03 had the highest bulb yield per plant (21.35 g), while the check variety-Kuriftu had the lowest (15.16 g). The average number of cloves/bulb among the genotypes varied in the range of 10.71 to 14.44. Furthermore, the combined mean bulb yield of the genotypes over locations and years was statistically significant ($P < 0.05$) and ranged from 3829.6 kg ha^{-1} (G-011/03) to 6576.2 kg ha^{-1} (G-020/03) (Table 2). Based on the results obtained on bulb yield performance, G-020/03 and G-054/03 had a 25.39% and 18.89% yield advantage over the standard check variety-Kuriftu, respectively (Table 2). Furthermore, the yield performance of the genotypes varied highly between the locations and years owing to the significant effect of genotype by environment interaction ($P < 0.05$) (Table 4). The majority of the variability (81.4%) among the tested genotypes in bulb yield was explained by the first principal component (PCA 1), which was also statistically significant ($P < 0.05$). This variation in yield was evidenced by the results of the overall combined analysis, which showed differences in mean yield performances among the testing locations, with the highest obtained from Kulumsa followed by Chefe Donsa and Debre Zeit, respectively (Tables 2 & 3).

In addition to ANOVA, the GGE biplot analysis ranked the genotypes for bulb yield performance, with G-020/03 ranking first followed by G-054/03, while G-011/03 ranked last (Fig. 1-left). This analysis also showed the stability of the genotypes for bulb yield across the six environments, with G-020/03 showing better stability in the majority of the environments,

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Table 2. Mean of bulb yield and combined mean (kg/ha) of the 13 promising garlic genotypes evaluated over three locations in two years main cropping season

Genotypes	Debre Zeit			Chefe Donsa			Kulumsa			Combined mean
	2018	2019	Mean	2018	2019	Mean	2018	2019	Mean	
G-018/03	1431.74	4180.5^{bc}	2806.12^{bc}	3347.71^{abc}	6248.4^{b}	4798.06^{bcd}	6319.5^{d}	9167^{def}	7743.25^{fg}	5381.9^{cde}
G-020/03	1845.97	7710.6^{a}	4778.29^{a}	3464.79^{ab}	6158.1^{bc}	4811.45^{bcd}	8611.1^{ab}	12778^{b}	$10{,}694.55^{ab}$	6576.2^{a}
G-001/03	1625.49	4969.0^{bc}	3297.25^{bc}	3661.53^{a}	6842.1^{b}	5251.82^{b}	7222.2^{bcd}	11111^{bcd}	9166.60^{cde}	5905.3^{abc}
G-021/03	1563.33	4491.9^{bc}	3027.62^{bc}	3348.54^{abc}	6390.1^{b}	4869.32^{bc}	7777.8^{abc}	11389^{bc}	9583.40^{bcd}	5780.5^{abc}
G-011/03	1349.31	4736.6^{bc}	3042.96^{bc}	2759.03^{cde}	6494.0^{b}	4626.52^{bcd}	694.4^{e}	3333^{g}	2013.70^{h}	3829.6^{g}
G-005/03	1622.78	5429.4^{bc}	3526.09^{b}	3041.74^{a-d}	5975.7^{bc}	4508.72^{bcd}	7500.0^{bcd}	12222^{bc}	9861.00^{abc}	5939.8^{abc}
G-041/03	1485.76	4323.0^{bc}	2904.38^{bc}	3224.86^{abc}	6782.2^{b}	5003.53^{b}	7208.3^{bcd}	10278^{cde}	8743.15^{c-f}	5529.5^{bcd}
G-061/03	1362.78	3613.8^{bc}	2488.29^{c}	2192.22^{ef}	5848.9^{bc}	4020.56^{de}	7500.0^{bcd}	8889^{ef}	8194.50^{efg}	4530.7^{gf}
G-054/03	1318.75	4666.2^{bc}	2992.48^{bc}	2982.01^{bcd}	5927.6^{bc}	4454.81^{bcd}	6527.8^{cd}	15556^{a}	$11{,}041.90^{a}$	6209.3^{ab}
G-053/03	1769.24	4643.5^{bc}	3206.37^{bc}	3070.35^{a-d}	6695.1^{b}	4882.73^{bc}	6805.6^{cd}	10556^{cde}	8680.80^{c-f}	5636.2^{bcd}
G-009/03	1321.32	5183.5^{bc}	3252.41^{bc}	3473.19^{ab}	8920.6^{a}	6196.90^{a}	9166.7^{a}	8611^{ef}	8888.85^{c-f}	5846.5^{abc}
G-058/03	1018.96	3905.0^{bc}	2461.98^{c}	2051.46^{f}	4883.3^{c}	3467.38^{e}	6388.9^{cd}	10278^{cde}	8333.45^{efg}	4707.9^{ef}
G-019/03	1755.35	3270.1^{c}	2512.7^{bc}	3050.69^{a-d}	7020.3^{b}	5035.50^{b}	7638.9^{bcd}	7222^{f}	7430.45^{g}	4830.9^{def}
Kuriftu	1487.64	3914.0^{bc}	2700.82^{bc}	$2468.40d^{ef}$	5679.5^{bc}	4073.95^{cde}	6666.7^{cd}	10278^{cde}	8472.35^{d-g}	5244.4^{c-f}
Minimum value	1018.96	3270.1	2461.98	2051.46	4883.3	3467.38	694.4	7222	7430.45	3829.6
Maximum value	1845.97	7710.6	4778.29	3661.53	8920.6	6196.90	9166.7	15,556	11,041.90	6576.2
Range unit	827.01	4440.5	2316.31	1610.07	4037.3	2729.52	8472.3	8334	3611.45	2746.6
Mean	1497.03	4645.48	3071.26	3009.75	6418.99	4714.37	6859.13	10,119.05	8489.09	5424.91
CV (%)	24.49	24.96	19.76	12.57	12.49	10.42	12.59	13.05	8.54	22.62
LSD (5%)	NS	1946.3	1018.5	634.81	1346.4	824.36	1450.1	2216.3	1216.7	807.97

Means followed by the same letter within a column are not significantly different at 5% level of probability CV, coefficient of variation; LSD, least significant different; NS, non-significant.

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Table 3. Mean of yield related traits for promising garlic genotypes for three locations in 2019

	Debre Zeit					Chefe Donsa					Kulumsa					Combined mean				
Genotypes	PH	DM	NCB	WC	BYPP	PH	DM	NCB	WC	BYPP	PH	DM	NCB	WC	BYPP	PH	DM	NCB	WC	BYPP
G-018/03	56.93^{abc}	107.33^{def}	8.33^{f}	3.62^{bcd}	13.54	57.93	138.00	14.00	4.61	19.58^{bc}	62.40^{bcd}	117.33^{a}	9.80^{e}	2.01^{a}	19.63	59.08^{a-d}	120.88^{a-d}	10.71^{d}	3.42	17.58^{bc}
G-020/03	56.47^{abc}	113.00^{a}	9.87^{c-f}	3.46^{cd}	25.54	58.80	140.33	13.20	4.19	19.74^{bc}	66.00^{ab}	113.33^{bcd}	13.93^{a-d}	1.24^{bcd}	17.31	60.42^{ab}	122.22^{a}	12.33^{bcd}	2.96	20.86^{ab}
G-001/03	60.60^{a}	111.00^{abc}	10.47^{b-e}	3.23^{cde}	16.06	55.33	138.33	14.27	3.58	21.51^{b}	65.46^{abc}	113.33^{bcd}	11.53^{de}	1.42^{bc}	16.46	60.46^{ab}	120.88^{a-d}	12.09^{bcd}	2.76	18.01^{abc}
G-021/03	54.53^{bc}	105.66^{ef}	9.20^{ef}	3.52^{bcd}	15.83	55.40	137.33	13.80	4.77	20.38^{b}	66.33^{ab}	112.66^{cde}	11.00^{de}	1.51^{bc}	16.50	58.75^{a-e}	118.55^{cde}	11.33^{cd}	3.27	17.57^{bc}
G-011/03	57.73^{abc}	108.66^{b-e}	8.40^{f}	4.67^{a}	16.35	58.27	136.66	12.93	4.39	20.94^{b}	57.73^{e}	112.33^{cde}	11.93^{cde}	2.00^{a}	25.48	57.91^{b-e}	119.22^{b-e}	11.09^{d}	3.69	20.92^{ab}
G-005/03	57.80^{abc}	107.33^{def}	11.60^{abc}	3.38^{cd}	17.89	57.27	136.00	15.67	4.36	18.94^{bc}	62.86^{a-d}	109.33^{e}	13.33^{bcd}	1.09^{cd}	14.29	59.31^{abc}	117.55^{e}	13.53^{ab}	2.94	17.04^{c}
G-041/03	56.47^{abc}	107.66^{c-f}	8.20^{f}	4.37^{ab}	15.38	59.93	137.33	14.67	4.61	21.98^{b}	64.26^{abc}	109.66^{de}	10.87^{de}	1.41^{bc}	15.34	60.22^{ab}	118.22^{de}	11.24^{d}	3.46	17.57^{bc}
G-061/03	53.87^{bcd}	106.66^{ef}	9.80^{c-f}	3.21^{cde}	12.27	56.07	138.33	16.67	4.34	18.37^{bc}	59.66^{de}	113.00^{b-e}	16.87^{a}	0.93^{d}	15.62	56.53^{de}	119.33^{b-e}	14.44^{a}	2.83	15.42^{c}
G-054/03	58.47^{ab}	110.66^{a-d}	12.80^{ab}	2.78^{de}	16.05	58.73	138.66	15.73	4.48	19.42^{bc}	66.86^{a}	109.66^{de}	11.40^{de}	1.59^{ab}	17.59	61.35^{a}	119.66^{a-e}	13.04^{abc}	2.95	17.69^{abc}
G-053/03	49.60^{d}	114.00^{a}	10.00^{c-f}	3.56^{bcd}	15.40	52.33	137.00	14.93	4.03	22.12^{b}	63.66^{a-d}	111.66^{cde}	12.33^{cde}	1.27^{bcd}	15.63	59.11^{a-d}	118.77^{cde}	12.42^{bcd}	2.95	17.72^{abc}
G-009/03	57.33^{abc}	112.00^{ab}	8.20^{f}	4.02^{abc}	16.92	58.80	139.00	12.33	4.39	27.82^{a}	66.33^{ab}	114.66^{abc}	13.73^{a-d}	1.41^{bc}	19.31	57.33^{cde}	121.88^{ab}	11.42^{cd}	3.27	21.35^{a}
G-058/03	54.13^{bcd}	105.00^{f}	11.47^{a-d}	2.80^{de}	12.89	53.13	133.66	13.40	3.56	15.72^{c}	61.20^{cde}	113.66^{abc}	15.27^{abc}	1.28^{bcd}	18.79	58.88^{a-e}	121.55^{ab}	13.38^{ab}	2.45	15.80^{c}
G-019/03	53.33^{cd}	110.66^{a-d}	12.80^{a}	2.51^{de}	10.66	55.53	139.00	13.60	4.33	22.36^{b}	66.26^{ab}	116.66^{ab}	13.33^{bcd}	1.17^{bcd}	15.53	56.33^{e}	118.44^{cde}	13.04^{abc}	2.67	16.18^{c}
Kuriftu	56.67^{abc}	106.33^{ef}	9.67^{def}	3.08^{de}	13.94	59.53	138.33	13.33	3.26	18.37^{bc}	64.80^{abc}	113.66^{abc}	16.73^{ab}	0.81^{d}	13.17	59.22^{a-d}	121.11^{abc}	13.24^{ab}	2.48	15.16^{c}
Minimum value	49.60	105.00	8.20	2.51	10.66	52.33	133.66	12.33	3.26	18.37	57.73	109.33	9.80	0.81	13.17	56.33	117.55	10.71	2.45	15.16
Maximum value	60.60	114.00	12.80	4.67	25.54	59.53	140.00	16.67	4.77	27.82	66.86	117.33	16.87	2.01	25.48	61.35	122.22	14.44	3.69	21.35
Range unit	11.00	9.00	4.60	2.16	14.88	7.20	6.34	4.34	1.51	9.45	9.13	8.00	7.07	1.20	12.31	5.02	4.67	3.73	1.24	6.19
Mean	55.99	109	10.00	3.45	15.62	56.93	137.71	14.18	4.21	20.52	63.85	112.93	13.00	1.37	17.19	58.92	119.88	12.39	3.01	17.78
CV (%)	4.94	1.95	11.40	14.77	26.58	5.91	2.78	15.12	16.04	12.21	4.01	2.1	15.96	20.59	28.94	4.92	2.41	14.73	17.18	22.43
LSD (5%)	6.07	3.57	1.91	0.85	NS	NS	NS	NS	NS	4.20	4.3	3.98	3.48	0.47	NS	2.72	2.71	1.71	NS	3.74

Means followed by the same letter within a column are not significantly different at 5% level of probability CV, coefficient of variation; LSD, least significant different; NS, non significant, plant height, date of maturity, number of cloves per bulb, weight of clove and bulb yield per plant. PH, plant height; DM, dry matter; NCB, number of cloves per bulb; WC, weight of clove; BYPP, bulb yield per plant.

Table 4. Analysis of variance of main effects and multiple interactions for bulb yield of garlic genotypes

Source of variation	Per cent explained	Degrees of freedom	Mean squares	*F* value	Pr(>*F*)
Genotype (G)	-	13	9,750,620	6.53	0.0000***
Environment (E)	-	5	394,370,268	125.9	0.0000***
Rep (Env)	-	12	3,132,058	2.10	0.01994*
G × E	-	65	4,763,713	3.19	0.0000***
PCA 1	81.4	17	14,824,736	9.93	0.0000***
PCA 2	10.5	15	2,158,188	1.45	0.1308
PCA 3	4.1	13	976,934.7	0.65	0.8085
PCA 4	3.5	11	992,750.6	0.66	0.7744
PCA 5	0.5	9	180,846.6	0.12	0.9992
Error	-	156	1,493,506	-	-

PCA, principal component analysis, *, **, and *** denote significant effects at $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively.

while G-011/03 was the least stable genotype. Although G-054/03 was the second high yielder, it was found to be unstable in the majority of the environments, but showed specific stability at Kulumsa than the rest of the genotypes. Furthermore, the GGE biplot analysis identified three winning genotypes (G-009/03, G-020/03 and G-054/03), among which the two high yielders were situated on the vertex of the polygon (Fig. 1-right). G-020/03 did well in the majority of the environments, while the second high yielder (G-054/03) did well only at KU-19.

The analysis identified that the majority of the environments (DZ-18, DZ-19, CD-18, CD-19 and KU-18) were ideal for genotype G-020/03, while KU19 was ideal only for G-054/03. The two high-yielder genotypes were further examined in the GGE biplots, which showed their relative stability in the six environments. G-020/03 (Fig. 2-left) was closer to the five environments (DZ-18, DZ-19, CD-18, CD-19 and KU-18), which depicted its wider stability and adaptability, while G-054/03 (Fig. 2-right) was closer to KU-19 than any of the environments, affirming its specific stability and adaptation.

Discussion

The results of the current study revealed significant variability in bulb yield and bulb-related traits among garlic genotypes, influenced by genetic factors and environmental conditions. Nevertheless high yield difference between the two testing years (2018 and 2019) for each genotype across the environments was experienced due to the difference in weather conditions, particularly the availability and distribution of rainfall. The improved rainfall conditions in 2019 likely created a more favourable environment for garlic cultivation, leading to higher yields compared to 2018.

Genotype by environment interaction plays a crucial role, necessitating the evaluation of genotypes across diverse environments to identify those with stable and high yield potential. Developing garlic cultivars with broad adaptation and stable performance is essential for enhancing productivity and profitability. Variability in bulb yield and bulb-related traits among garlic genotypes has been widely reported in numerous studies conducted

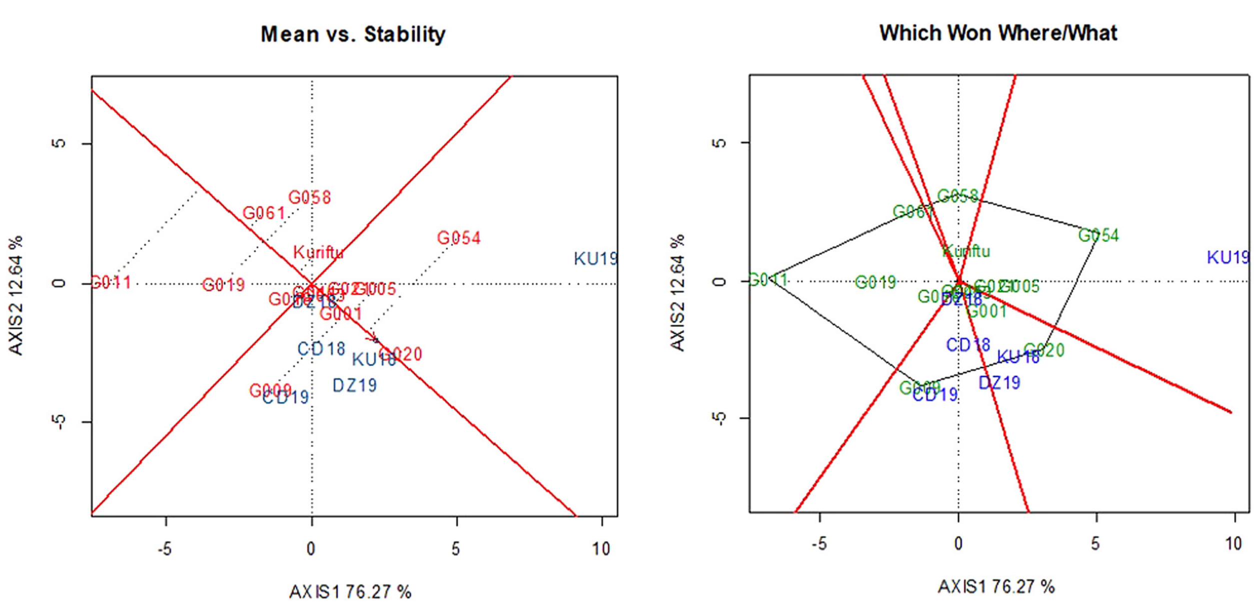

Figure 1. GGE biplots ranking garlic genotypes based on bulb yield performance in the six environments DZ 18, DZ 19, CD 18, CD 19, KU 18 and KU 19 (left) and the which-won-where view of the GGE biplot depicting the winning genotypes on the vertex of the polygon(right).

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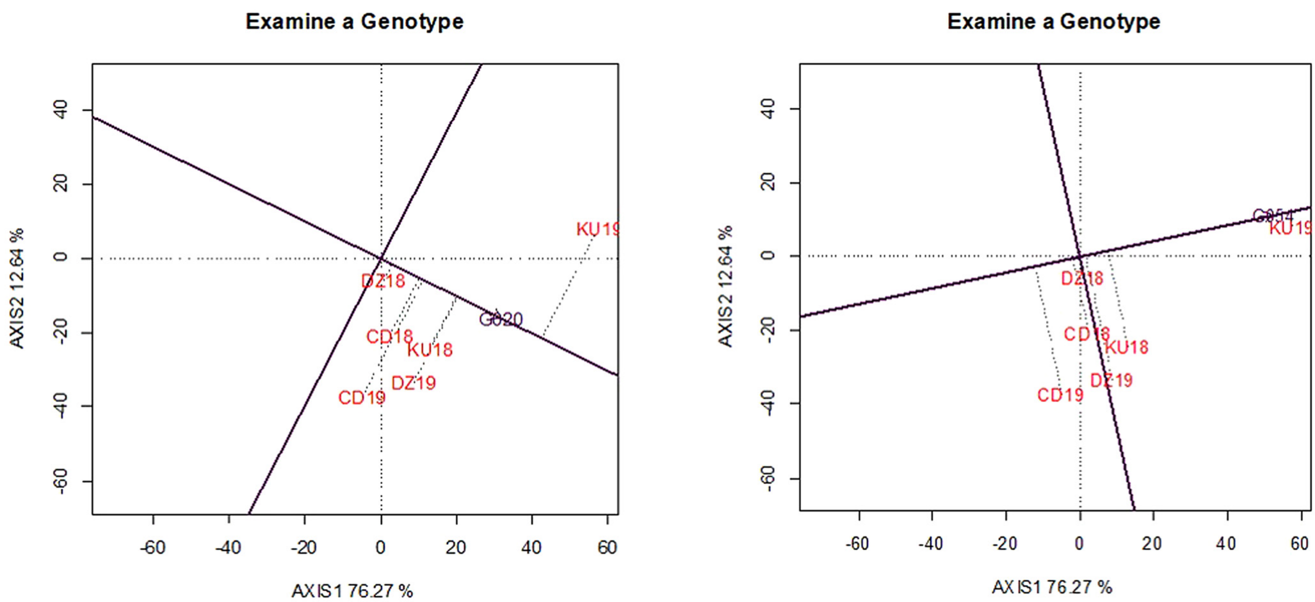

Figure 2. GGE biplots examining each of two selected garlic genotypes: G-020/03 (left) and G-054/03 (right) in relation to the seven environments (DZ 18, DZ19, CD 18, CD 19, KU18 and KU19).

in Ethiopia and other countries. For instance, Ayalew *et al.* (2015) and Getahun and Getaneh (2019) observed significant variations in the performance of garlic cultivars from different locations in Gonder, Northern Ethiopia. Similarly, Belay *et al.* (2020) found substantial differences in bulb yield and yield-related traits among garlic genotypes across different locations, indicating the influence of both genetic and environmental factors. These findings align with the study by Bezu *et al.* (2014), which demonstrated the effects of environmental factors on the performance of garlic genotypes.

Furthermore, the influence of various factors, such as cultivar, location, soil type, agricultural methods and harvest date, on garlic yield and quality has been extensively documented. Raslan *et al.* (2015) emphasized the significant impact of these factors on garlic production outcomes. Studies conducted in India, such as Gurpree *et al.* (2013) and Nandini *et al.* (2018), also reported geographically diverse garlic genotypes exhibiting variations in bulb and bulb-related traits, including yield ranges of 2180 to 6290 kg ha^{-1} (Islam *et al.*, 2004), 551.3 to 1402.7 kg ha^{-1} (Aslam *et al.*, 2016) and 2003 to 7328 kg ha^{-1} (Atinafu *et al.*, 2021). Additionally, Verma and Thakre (2018) highlighted the influence of different agro-climatic conditions on the growth and quality of garlic varieties.

In Ethiopia, similar studies have identified significant variation in agro-morphological traits among evaluated garlic genotypes. For instance, Atinafu *et al.* (2021) observed variations in plant height, maturity and average clove weight, while Yeshiwas *et al.* (2018) and Teshale and Tekeste (2021) reported differences in plant height, maturity and bulb yield per plant. These findings highlight the genetic diversity present within garlic genotypes and the potential for selecting superior varieties with desirable traits.

Moreover, studies conducted in Ethiopia, such as those by Bezu *et al.* (2014) and Belay *et al.* (2020), demonstrated the influence of genotype by environment interaction on garlic performance. This interaction effect can complicate breeding programmes aimed at yield enhancement, leading to inconsistent genotype performance across different environments. To overcome this challenge, it is crucial to evaluate genotypes under diverse environmental conditions and select those with stable and high yield potential across locations and years. This approach, as suggested by Singh *et al.* (2016) and Belay *et al.* (2020), allows for the development of garlic cultivars adapted to various agro-ecologies, ultimately improving productivity and profitability in the garlic industry.

In conclusion, the studies reviewed in this discussion highlight the significant variability in bulb yield and bulb-related traits among garlic genotypes, both within Ethiopia and in other countries. The influence of genetic factors, environmental conditions, and their interaction necessitates the evaluation of genotypes across diverse environments to identify those with stable and high yield potential. Such evaluations are critical for developing improved garlic varieties that can thrive in different agro-ecologies, contributing to enhanced productivity and profitability in garlic production.

In summary, a study was conducted to evaluate the performance of thirteen garlic genotypes and one check variety for bulb yield and different morphological traits in six environments in central and southeast Ethiopia. The genotypes differed significantly for bulb yield and morphological traits, except for average clove weight. Two genotypes (G-020/03 and G-054/03) showed the highest bulb yield and had significant yield advantages over Kuriftu. AMMI analysis also resulted in significant results of genotype, environment and genotype × environment interactions for bulb yield. G-020/03 showed better stability in most of the environments tested, while G-054/03 had specific adaptability and stability. GGE biplot analysis identified three winning genotypes, among which only G-20/03 and G-054/03 were identified as promising genotypes for yield performance and relative stability. Therefore, G-020/03 and G-054/03 were selected as candidate varieties for release in the central and southeast garlic growing areas of Ethiopia. The study highlights the importance of evaluating the performance of genotypes under different environments and selecting those with stable and high yield potential across locations and years for developing new varieties that are adapted to different agro-ecologies, contributing to improving the productivity and profitability of the garlic industry.

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