

Stability Analysis and Genotype-by-Environment Interaction of Onion (*Allium Cepa* L.) Genotypes across Diverse Agro-Ecologies of Ethiopia

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Research Article

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Abstract

Onion (*Allium cepa* L.) is one of the most economically vital vegetable crops in Ethiopia, yet its production is heavily constrained by environmental variability across diverse agroecological zones. This study evaluated the yield performance, stability, and genotypes-by-environment interaction (GEI) of seven experimental onion genotypes along with two commercial check varieties (NAFIS and NASIK) across ten testing environments (five locations across two consecutive seasons, 2025 and 2026) in Ethiopia. The experiment was laid out using a randomized complete block design with three replications. The combined analysis of variance revealed highly significant ($P < 0.001$) main effects of environment and genotype, as well as significant GEI ($P < 0.05$) for marketable bulb yield. Environmental variation accounted for the largest proportion of the total variation (22.40%), followed by genotype (13.00%) and GEI (8.65%). The first two interaction principal component axes (IPCA1 and IPCA2) of the AMMI model captured 37.77% of the total GEI variation, while the GGE biplot explained 80.83% of the total G + GE sum of squares. Mean marketable bulb yield ranged from 18.38 t ha⁻¹ NF × AFD to 26.15 t ha⁻¹ (NAFIS). Based on AMMI Stability Value (ASV) and GGE biplot ranking relative to the ideal genotype, BY × AFD achieved a high mean marketable yield (25.15 t ha⁻¹) and total yield (29.39 t ha⁻¹) performing on par with the standard checks NAFIS (26.15 t ha⁻¹) and NASIK (25.78 t ha⁻¹), while demonstrating strong stability and broad adaptability. The GGE biplot polygon and AEA view confirmed crossover interaction, identifying KARC 2026 and MARC 2026 as the most representative and discriminating environments for genotype evaluation. Among the experimental genotypes, BY × AFD demonstrated superior agronomic productivity, low bolting frequency, and high stability. Consequently, BY × AFD is recommended for further verification and pre-release evaluation across onion-growing agro-ecologies of Ethiopia.

1. Introduction

Onion (*Allium cepa* L.) is one of the most widely cultivated and economically important vegetable crops worldwide, ranking second only to tomato in terms of production and consumption [1, 2]. It is valued for its nutritional, culinary, and medicinal properties and serves as an important source of vitamins, minerals, dietary fiber, flavonoids, anthocyanins, fructose oligosaccharides, and organosulfur compounds, which are associated with antioxidant, antimicrobial, and health-promoting effects [3, 4, 5, 6]. In Ethiopia, onion is an important cash and food security crop cultivated under both irrigated and rain-fed production systems [7, 8]. The crop contributes substantially to farmers' incomes and plays a significant role in supplying domestic and export markets [9, 10]. However, onion productivity remains below its genetic potential because of several production constraints, including limited access to quality seed, poor nutrient management, pests and diseases, inadequate irrigation management [2, 10, 11, 12]. In addition, postharvest losses and variations in environmental conditions further reduce productivity and marketable yield [13, 14, 15, 16]. Among these constraints, genotype × environment interaction (GEI) is particularly important because it influences the adaptation, productivity, and stability of onion genotypes across different production environments [17].

Genotype $\times$ environment interaction (GEI) occurs when genotypes respond differently to changes in environmental conditions, resulting in variations in their relative performance across locations and seasons [18]. Consequently, genotypes that perform well in one environment may not necessarily exhibit superior performance in another. Such interactions complicate the selection of superior cultivars because genotype rankings often change across environments [19, 20]. Therefore, evaluating genotypes under diverse environmental conditions is essential for identifying cultivars with either broad or specific adaptation.

Multi-environment trials (METs) are widely used in plant breeding to evaluate genotype performance, stability, and adaptability across contrasting environments. These trials provide reliable information on the magnitude of genotype, environment, and genotype $\times$ environment interaction effects, thereby facilitating the identification of stable and high-yielding cultivars suitable for target production areas [20, 21, 22]. Reliable evaluation of GEI enables breeders to recommend genotypes with consistent performance across a wide range of environments or with specific adaptation to particular agroecological conditions.

Several statistical methods have been developed to evaluate genotype performance in multi-environment trials. Among these, the Additive Main Effects and Multiplicative Interaction (AMMI) model and the Genotype plus Genotype $\times$ Environment (GGE) biplot are the most widely used analytical approaches. The AMMI model combines analysis of variance with principal component analysis to partition and explain genotype $\times$ environment interaction, thereby improving the interpretation of genotype stability and environmental responses [23, 24, 25]. Likewise, the GGE biplot graphically illustrates genotype performance, stability, mega-environment patterns, and the discriminating ability of testing environments, making it an effective tool for identifying superior genotypes and representative testing locations [26]. Recent advances in plant breeding have also introduced multivariate selection approaches, including the Multi-trait Genotype-Ideotype Distance Index (MGIDI), which simultaneously considers yield performance, stability, and multiple agronomic traits to facilitate the identification of superior genotypes [27, 28]. These complementary approaches enhance breeding efficiency by integrating productivity, adaptability, and stability into genotype selection.

Several studies have reported significant genotype $\times$ environment interaction for onion and other vegetable crops, demonstrating that genotype performance varies considerably across locations and seasons. Such findings highlight the importance of conducting multi-environment evaluations before recommending varieties for commercial production [21, 29]. Although onion improvement programs in Ethiopia have developed several promising breeding lines and released varieties, comprehensive information on the stability and adaptability of advanced onion genotypes across the major onion-growing agro-ecologies of the country remains limited. Therefore, this study was conducted to evaluate the yield performance and stability of onion genotypes across diverse environments using AMMI and GGE biplot analyses and identify stable, high-yielding genotypes for growing areas in Ethiopia.

2. Materials and methods

2.1. Experimental Sites and Plant Materials

The field experiment was conducted during the 2025 and 2026 production seasons at five major onion-growing locations in the mid-altitude agro-ecologies of Ethiopia: Melkassa Agricultural Research Center (MARC), Bishoftu Agricultural Research Center (BARC), Kulumsa Agricultural Research Center (KARC), Fogera Agricultural Research Center (FOG), and Wonji Sugar Estate (WONJI). Evaluation across five locations over two years generated ten testing environments, each defined by a unique location × year combination. The geographical characteristics of the experimental sites are presented in Table 1. Seven onion genotypes, including two released varieties (NAFIS and NASIK) used as standard checks, were evaluated (Table 2). The experimental genotypes were developed through hybridization of adapted onion varieties at Melkassa Agricultural Research Center (MARC) and were selected based on their performance in preliminary yield trials before evaluation under multi-environment conditions.

Table 1
Geographical coordinates and soil type across testing location

Environment code	Location	Year	Av. Annual Rainfall(mm)	Soil type	Altitude (m.a.s.l.)	Latitude	Longitude
MARC_2025	Melkassa	2025	827	Andosol	1550	08.24 N	39.21 E
MARC_2026	Melkassa	2026	846				
BARC_2025	Bishoftu	2025	851	Vertisol	1876	08.46 N	39.00 E
BARC_2026	Bishoftu	2026	866				
KARC_2025	Kulumsa	2025	840	Vertisol	2181	08.01 N	39.09 E
KARC_2026	Kulumsa	2026	840				
FOG_2025	Fogera	2025	1280	Eutric Vertisols	1815	11.58 N	37.41 E
FOG_2026	Fogera	2026	1580				
WONJI_2025	Wonji	2025	830	Alluvial-colluvial	1550	08.45 N	39.43 E
WONJI_2026	Wonji	2026	846				

Source: National Metrology: EIAR/MARC agroecology and experimental site records, 2025, while the 2026 Average Annual Rainfall(mm) was on up to the date.

Table 2
Description of onion genotypes used for the evaluation in 2025 and 2026

Genotype	Pedigree	Bulb shape	Skin color	Bulb flesh color
NF × TX	Nafis x Tropix	Globe	yellow-brown	white
BY × AFD	Bombey Red x Nafid	Flat globe	Red	Reddish white
NR × NF	Nasik red x Nafis	Oblong	Brown-yellow	Reddish white
NF × AFD	Nafis x Nafid	Globe	Light red	Reddish white
C4 MIDEL	Breeding line	Obovate	Brown-yellow	White
NAFIS	<i>Franciscana</i> selection	globose-flat	Deep red	Reddish white
NASIK	Niphad-53	flattish-round	Dark red	Light red to white
Note: C4- Advanced breeding line, NAFIS and NASIK were included as released commercial check varieties.				

2.2. Experimental design and procedures

The experiment was laid out in a randomized complete block design (RCBD) with three replications at each testing environment. Seedlings were raised in nursery beds following standard nursery management practices and transplanted to the field at the recommended growth stage. Each experimental plot measured 2.4 m × 3.0 m and consisted of four double rows. Plants were spaced 40 cm between double rows, 20 cm between rows, and 5 cm between plants in accordance with the recommended agronomic practices for irrigated onion production in Ethiopia (EIAR, 2024). The spacing between adjacent plots and replications was 0.5 m and 1.5 m, respectively. All experimental sites received uniform crop management practices, including irrigation scheduling, fertilizer application, weed control, and other cultural operations according to the national onion production recommendations [30, 31].

2.3. Data collection and analysis

Phenological, growth, yield, and yield-related data were collected following the Descriptors for *Allium* (*Allium* spp.) developed by the International Plant Genetic Resources Institute (IPGRI et al., 2001). Data for most traits were recorded from five randomly selected plants within the central rows of each plot, whereas days to maturity and marketable bulb yield were determined from all plants harvested from the net plot area. Prior to combined analysis, the assumptions of normality and homogeneity of error variance were evaluated using the Shapiro–Wilk and Bartlett's tests, respectively. Combined analysis of variance (ANOVA) across environments was performed using R statistical software version 4.5.2 [33]. Mean comparisons were conducted using Duncan's Multiple Range Test (DMRT) at the 5% probability level.

Genotype × environment interaction and yield stability were further investigated using the Additive Main Effects and Multiplicative Interaction (AMMI) model and the Genotype plus Genotype × Environment

Interaction (GGE) biplot methodology. The AMMI model partitions genotype $\times$ environment interaction into interaction principal component axes (IPCA), whereas the GGE biplot simultaneously evaluates genotype performance, stability, discriminating ability of environments, representativeness of testing locations, and mega-environment patterns [26, 34, 35].

3. Result and Discussion

3.1. Combined Analysis of Variance in different environments

The combined analysis of variance confirmed that genetic and environmental parameters significantly influenced onion yield potential. The environmental effect accounted for the largest share of variation and highly significant differences ($P < 0.001$) for almost all traits (Table 3). The main effect was highly significant for the yield variable, which provided substantial genetic variance among the genotypes. However, there was no significant difference between the genotypes in days to maturity, foliage length, and average bulb weight. There are due to the high $G \times E$ interaction against which genotypes were tested (Table 3). Different authors also observed the performance and variability of different onion and garlic genotypes for yield-related traits in Ethiopia [36, 37, 38]. Similar findings have been reported in onion multi-environment studies, reported significantly affected genotype performance [39, 40]. The presence of statically significant differences between the environments across all traits indicates variability in the growing environments, and the environment was the most influential factor for yield-related traits of onion in Ethiopia.

Genotype effects were significant for the number of bolters, leaf number, marketable yield, total yield, and total soluble solids, demonstrating the existence of substantial genetic variability among the tested onion genotypes. The significant variation observed for marketable and total bulb yields suggested that selection for yield improvement is feasible within the evaluated germplasm. Likewise, the significant differences in bolting tendency and bulb quality traits indicate opportunities for identifying genotypes with desirable agronomic characteristics. Similar levels of genetic variation for yield and yield related traits have been reported in onion breeding programs aimed at developing high yielding and well-adapted cultivars [40]. The genotype $\times$ environment interaction ($G \times E$) effect was highly significant for the number of bolters and marketable yield and significant for plant height, indicating that genotype performance for these traits varied across environments. This suggests that some genotypes responded differently to changes in environmental conditions, resulting in differences in ranking among locations and years. The presence of significant $G \times E$ interaction for marketable yield highlights the importance of evaluating genotypes across multiple environments before making variety recommendations. Similar results have been reported in stability studies where environmental variation significantly influenced onion genotype performance and adaptation [26, 41]. In contrast, non-significant $G \times E$ interaction for days to maturity, foliage length, leaf number, total yield, total soluble solids, and average bulb weight indicates relatively consistent genotype performance for these traits across environments. Overall, the combined ANOVA

results demonstrate that both genotype and environment contributed significantly to trait variation, while the observed G×E interaction for key traits such as marketable yield emphasizes the need for stability analysis and multi-environment testing to identify broadly adapted onion genotypes

Table 3

Mean squares of yield and yield-related traits from combined ANOVA and Bartlett test of homogeneity of error variance

Traits	Mean squares				
	Environment	Genotype	G×E	Residuals	CV (%)
	DF (9)	DF (6)	DF (54)	DF (138)	
DM	1785.01 ^{***}	28.27 ^{ns}	17.84 ^{ns}	27.11	4.45
FL	2979.18 ^{***}	12.84 ^{ns}	16.67 ^{ns}	13.44	8.73
PH	1210.34 ^{***}	15.49 ^{ns}	27.50 [*]	18.60	7.62
NB	3643.71 ^{***}	13.70 ^{***}	175.69 ^{***}	63.55	35.02
LN	105.58 ^{***}	6.38 [*]	2.98 ^{ns}	2.46	13.14
MY	528.92 ^{***}	269.79 ^{***}	40.19 ^{**}	23.01	21.11
TY	775.75 ^{***}	101.76 ^{**}	29.34 ^{ns}	21.60	17.20
TS	10.39 ^{***}	5.40 [*]	1.92 ^{ns}	2.24	10.23
Abwt	3824.84 ^{***}	188.03 ^{ns}	160.41 ^{ns}	136.49	12.07
DF=Degree of freedom, DM=Days to maturity, FL= Foliage length(cm), PH= Plant height (cm), NB = Number of bolter, LN= Leaf number, MY = Marketable bulb yield ton per hectare, TY = Total yield ton per hectare; ABWt = Average bulb weight, *** = very highly significant (P < 0.001), ** = highly significant (P < 0.01), * = significant (P < 0.05) and ns = non-significant (P > 0.05)					

3.2. Genotype performance across Environments

The combined analysis of variance across locations and years revealed significant differences ($p < 0.05$) among the tested onion genotypes for marketable bulb yield, total bulb yield, leaf number, and bolting number (Table 4). This indicates substantial genetic variability for key agronomic and economically important traits within the evaluated germplasm. Conversely, non-significant variations were observed among genotypes for days to maturity, plant height, foliage length, and total soluble solids (TSS), reflecting relatively uniform baseline performance for these traits across the test environments. Similar findings highlighting variable genotypic responses across multi-environment onion trials have been documented previously [20, 42].

Among the evaluated genotypes, BY×AFD achieved a mean marketable yield of 25.15 t ha⁻¹ and a total bulb yield of 29.39 t ha⁻¹. These yields were statistically on par with the standard commercial check varieties NAFIS (26.15 t ha⁻¹ marketable yield; 29.47 t ha⁻¹ total yield) and NASIK (25.78 t ha⁻¹ marketable yield; 27.84 t ha⁻¹ total yield). The high yield capacity of BY×AFD, comparable to established commercial benchmarks, underscores its agronomic potential as a candidate for prospective release. Significant differences were observed for bolting incidence across genotypes. C4MIDEL exhibited the highest bolting frequency, whereas NF×AFD recorded the lowest incidence. Premature bolting redirects photosynthetic assimilates away from bulb tissue toward reproductive development, thereby compromising both total bulb weight and market quality [43]. This physiological sink shifts likely accounts for the lower marketable yield observed in C4MIDEL, despite its vigorous early vegetative establishment. Variable genotypic susceptibility to premature bolting under field conditions aligns with previous observations by Singh et al. [44].

Leaf number per plant also varied significantly among genotypes, with NF×AFD producing the dense foliage canopy. However, despite its higher leaf production, NF×AFD yielded the lowest marketable bulb weight. This inverse relationship highlights that canopy volume alone is an unreliable predictor of yield; rather, sink strength and the efficiency of photoassimilate partitioning from source leaves to developing bulb tissues remain the primary drivers of commercial productivity [45, 46]. Overall, BY×AFD demonstrated high yield potential and marketability, performing competitively against the standard reference cultivars NAFIS and NASIK across environments. Given its favorable agronomic profile, BY×AFD warrants further multi-location validation for potential integration into Ethiopian onion production systems.

Table 4

The combined mean performance of onion genotypes for different traits evaluated across locations over years.

Genotypes	DM	FL	PH	NB	LN	MY	TY	TS
BY×AFD	115.47	42.27	55.95	21.55bc	12.27ab	25.15a	29.39a	14.19
C4MIDEL	117.47	41.14	56.72	31.67a	12.27ab	21.61b	25.64bc	14.89
NAFIS	117.63	42.61	56.26	25.22b	11.91abc	26.15a	29.47a	14.19
NASIK	117.33	41.36	57.25	24.99b	11.6bc	25.78a	27.84ab	14.62
NF×AFD	118.07	41.45	57.55	15.33d	12.63a	18.38c	25.56bc	15.38
NF×TX	116.9	42.71	56.88	17.57cd	11.36c	21.69b	25.91bc	14.4
NR×NF	115.8	42.4	55.53	23b	11.59bc	20.32bc	25.34c	14.77
Mean	116.95	41.99	56.59	22.76	11.95	22.73	27.02	14.63
CV (%)	4.45	8.73	7.62	35.02	13.14	21.11	17.20	10.23
LSD (5%)	2.66ns	1.87ns	2.20ns	4.07**	0.80*	2.45**	2.37**	0.76ns
DM, days to maturity; FL, Foliage length, PH: plant height, NB, number of bolters; LN, leaf number; MY, marketable bulb yield; MY, Marketable bulb Yield (t/ha); TY, Total bulb Yield (t/ha); TS, total soluble solid (%); ** = highly significant at $P \leq 0.05$, and Least Significant Difference (LSD)								

3.2. Variability in genotypes across the environments

Strong genotype × environment interaction (GEI) was evident from the heatmap analysis (Fig. 1), which revealed substantial variation in marketable and total bulb yields of onion genotypes across testing environments. The differences in color intensity and changes in genotype ranking among environments indicate that genotype performance varied depending on environmental conditions, reflecting differential adaptation of the tested genotypes. Similar patterns have been widely reported in multi-environment onion trials [26, 47]. The heatmap also showed differences between marketable and total bulb yield responses across environments, indicating that high total yield did not always correspond to high marketable yield. This suggests that environmental conditions influenced both productivity and marketable bulb production. Among the environments, KARC 2026 generally produced the highest marketable yields for most genotypes, particularly BY × AFD and the standard check NAFIS, whereas FOG 2025 consistently recorded lower yields across genotypes. The changes in genotype ranking across environments indicate the occurrence of crossover GEI, emphasizing the importance of multi-environment testing for identifying genotypes with stable and wide adaptation.

Although the heatmap suggested consistently high mean yields for the standard check varieties NAFIS and NASIK, visual assessment alone cannot determine stability. The AMMI stability analysis (Table 8) confirmed that NAFIS combined high yield with relatively good stability, whereas NASIK, despite its high mean yield, exhibited larger interaction effects and lower stability. BY × AFD combined high marketable

yield with good stability, while NF × TX showed the greatest stability based on the AMMI Stability Value (ASV), although with a lower mean yield than NAFIS and BY × AFD. Overall, the heatmap analysis demonstrated substantial environmental influence on genotype performance and highlighted NAFIS and BY × AFD as high-performing genotypes, while NF × TX exhibited the greatest stability across environments. These findings justify further stability analysis using the AMMI model.

3.3. AMMI analysis for marketable bulb yield

The AMMI analysis revealed that environmental effects accounted for the largest proportion of the total variation in marketable bulb yield (22.40%), followed by genotype effects (13.00%) and genotype × environment interaction (GEI) effects (8.65%) (Table 7). The predominance of environmental variation indicates that differences among testing environments had a greater influence on bulb yield than genetic differences among genotypes. Similar findings have been reported in recent multi-environment evaluations of onion and other vegetable crops [21, 48, 49].

The significant genotype effect indicates the existence of sufficient genetic variability for marketable bulb yield, while the significant GEI demonstrates that genotype performance differed across environments. Partitioning of the interaction sum of squares showed that IPCA1 and IPCA2 explained 23.78% and 13.99% of the GEI variation, respectively, accounting for 37.77% of the total interaction. These results indicate that a considerable proportion of the interaction pattern was captured by the first two principal components and justify the use of AMMI biplots to investigate genotype adaptation and stability. The AMMI1 biplot (Fig. 2a) showed that NAFIS and NASIK had above-average marketable bulb yields, whereas BY × AFD combined relatively high yield with a comparatively small interaction score, indicating good adaptation across environments. Genotypes located close to the origin, such as BY × AFD and NF × TX, exhibited lower interaction effects and therefore greater stability, while NASIK, C4 MIDEI, and NF × AFD showed stronger interactions with specific environments [50].

The AMMI2 biplot (Fig. 2b) further illustrated specific genotype adaptation. NASIK was positively associated with BARC 2025, KARC 2025, and FOG 2025, whereas C4 MIDEI and NF × AFD were more closely associated with WONJI 2026. The long vectors observed for WONJI 2026, BARC 2026, and MARC 2026 indicate that these environments were highly discriminating and effective for differentiating genotype performance [26]. Overall, the AMMI analysis confirmed the presence of substantial GEI and demonstrated that no single genotype performed best across all environments. BY × AFD combined high yield with good stability, whereas NF × TX exhibited the greatest stability despite a lower mean yield. NAFIS maintained superior yield with relatively good stability, while NASIK displayed high productivity but stronger environmental responsiveness. These results demonstrate the importance of considering both yield performance and stability when selecting onion genotypes for recommendation.

Table 7
AMMI Analysis of variance for marketable bulb yield across
the testing Environments

Source	Df	SS	MS	% SS Explained
ENV	4	2789.6	697.4	22.4
REP(ENV)	10	593.4	59.3	4.77
GEN	6	1618.7	269.8	13.0
GEN: ENV	24	1076.5	44.9	8.65
PC1	9	256.0	28.4	23.78 GEI*
PC2	7	150.6	21.5	13.99 GEI*
PC3	5	95.0	19.0	8.82 GEI*
PC4	3	36.6	12.2	3.40 GEI*
Residuals	165	5835.9	35.4	
Total	233	12452.4	53.4	
* = significant ($P < 0.05$)				

3.4. AMMI stability

The AMMI stability analysis revealed substantial genotype $\times$ environment interaction (GEI) for marketable bulb yield, indicating differential responses of onion genotypes across the testing environments (Table 8). The first two interaction principal component axes (IPCA1 and IPCA2) together explained 37.77% of the GEI, demonstrating that the AMMI model effectively captured the interaction pattern and provided reliable information for assessing genotype stability. Based on the AMMI Stability Value (ASV), NF $\times$ TX was identified as the most stable genotype (ASV = 0.9226), followed by BY $\times$ AFD (ASV = 1.3317) and the standard check NAFIS (ASV = 1.4349). Although NF $\times$ TX exhibited the greatest stability, its mean marketable bulb yield (21.69 t ha⁻¹) was lower than those of BY $\times$ AFD (25.15 t ha⁻¹) and NAFIS (26.15 t ha⁻¹). Among the experimental genotypes, BY $\times$ AFD combined high marketable bulb yield with good stability, indicating broad adaptation across the testing environments.

In contrast, NASIK, NF $\times$ AFD, and NR $\times$ NF exhibited relatively high ASV values and larger IPCA scores, indicating greater sensitivity to environmental variation and lower yield stability. Despite its high mean yield, NASIK showed stronger genotype $\times$ environment interaction, suggesting specific adaptation to favorable environments rather than consistent performance across all testing locations. Similar relationships between high yield potential and reduced stability have been reported in multi-environment trials of onion and other crops [26, 51]. Overall, the AMMI stability analysis identified BY $\times$ AFD as the most promising candidate genotype because it combined high marketable bulb yield with good stability across environments, whereas NAFIS served as a high-yielding and relatively stable standard check.

These findings demonstrate the importance of jointly considering yield performance and stability when selecting onion genotypes for broad adaptation and future variety development.

Table 8
AMMI Stability Value (ASV), IPCA Scores, and Ranking of Onion Genotypes for Marketable Bulb Yield (t/ha)

Genotype	Marketable Bulb Yield(t/ha)	IPCA 1	IPCA 2	ASV	Rank
NF × TX	21.69	0.5048	0.4736	0.9226	1
BY × AFD	25.15	0.6776	0.8025	1.3317	2
NAFIS	26.15	-0.7975	0.7032	1.4349	3
C4 MIDE L	21.61	1.699	-1.0898	2.8789	4
NASIK	25.78	-1.3551	2.281	3.1177	5
NF × AFD	18.38	1.9914	-0.8286	3.2314	6
NR × NF	20.32	-2.7203	-2.3419	4.8669	7

3.5. GGE biplot analysis of marketable bulb yield

The GGE biplot showed substantial genotype × environment interaction for marketable bulb yield, with PC1 and PC2 explaining 57.09% and 23.74% of the GGE variation, respectively (a cumulative of 80.83%) (Fig. 3). This level of explanation was adequate to visualize the major patterns of genotype adaptation across the ten environments. The which-won-where polygon further indicated clear crossover interaction and differentiated the test environments into distinct response patterns, demonstrating that genotype performance was strongly environment-dependent. Similar findings have recently been reported in onion, where GGE biplot analysis effectively identified genotype adaptation, mega-environments, and high-yielding and stable genotypes across contrasting environments [5, 20, 40, 52].

The polygon identified NR × NF, NF × AFD, C4 MIDE L, BY × AFD, and NAFIS as important vertex genotypes, indicating specific adaptation to different environmental groups. NR × NF was associated mainly with FOG_2026, whereas NF × AFD and C4 MIDE L were associated with the low-performing WONJI_2026 environment. In contrast, BY × AFD was positioned in the sector containing the 2026 environments MARC_2026, KARC_2026, and BARC_2026, indicating its specific adaptation to these environments. The 2025 environments, including MARC_2025, KARC_2025, FOG_2025, WONJI_2025, and BARC_2025, were largely located toward the NAFIS sector, suggesting comparatively broad adaptation of this standard check under the 2025 conditions.

Among the standard checks, NAFIS (25.51 t ha⁻¹) and NASIK (24.39 t ha⁻¹) showed strong overall performance, with NAFIS having the higher mean marketable yield. However, the polygon indicates that NAFIS had broader winning adaptation than NASIK, while NASIK was located within the polygon rather

than at a vertex. BY × AFD (24.02 t ha⁻¹) was the most promising new genotype based on mean yield and showed particular adaptation to several 2026 environments, although its environmental specificity suggests that additional testing is needed before considering it for broad recommendation. Overall, the results emphasize the value of combining high mean yield, stability, and specific adaptation when selecting onion genotypes for diverse production environments. Recent onion studies similarly demonstrated that GGE analysis can distinguish broadly adapted genotypes from specifically adapted materials and identify appropriate testing environments for cultivar selection [5, 20].

3.6. Discriminativeness and representativeness analysis of testing Environments

The GGE biplot analysis identified clear differences among testing environments in their ability to discriminate genotypes and represent the target production region (Fig. 4). For marketable bulb yield, BARC 2026, MARC 2026, and WONJI 2026 exhibited long vectors, indicating strong discriminating ability, whereas WONJI 2025 and FOG 2025 showed short vectors and lower capacity to differentiate genotypes. Among the environments, KARC 2026 had the smallest angle with the Average Environment Axis (AEA), making it the most representative environment for evaluating marketable bulb yield. A test environment showing a smaller angle with the AEC abscissa is more representative than other test environments. Environments with long vectors and small angles with AEC are ideal environments for selecting superior genotypes. However, environments with long vectors and large angles with AEC abscissa are useful environments for culling unstable genotypes [53].

Similarly, for total bulb yield, KARC 2026 and WONJI 2026 were highly discriminative environments due to their long vectors, while MARC 2025 and WONJI 2025 were less discriminative. MARC 2026 and KARC 2026 were the most representative environments, as they were closely aligned with the AEA, indicating that genotype performance in these locations closely reflected the overall target environment. Considering both discriminativeness and representativeness, KARC 2026 and MARC 2026 were identified as ideal testing environments for onion genotype evaluation. In contrast, WONJI 2026 and BARC 2026 were useful for identifying specifically adapted genotypes, whereas FOG 2026 and WONJI 2025 contributed less information for genotype selection. Therefore, KARC 2026 and MARC 2026 can be recommended as the most suitable environments for future onion breeding and multi-environment evaluation programs [26].

3.6. Ranking of genotypes Relative to the Ideal Genotype

The GGE biplot analysis explained 80.83 of the total G + GE variation (PC1 = 57.09% and PC2 = 23.74%), indicating that the biplot reliably represented genotype performance and stability across environments. In the ranking views, genotypes located closer to the ideal genotype are considered more desirable because they combine high mean yield with greater stability across environments [26]. Among the evaluated genotypes, the check variety NAFIS was the closest to the ideal genotype, indicating superior yield performance combined with broad adaptation and stability across environments. NASIK ranked

second, exhibiting very high yield potential but relatively greater interaction with environments, suggesting specific adaptation to favourable conditions. BY×AFD ranked third and showed above-average yield performance with acceptable stability, making it a promising genotype for wider cultivation. In contrast, NF×TX exhibited good stability but relatively lower yield performance, while NF×AFD and NR×NF were the least desirable genotypes due to their lower yield and higher instability across environments (Fig. 5). Overall, the GGE biplot identified NAFIS as the most desirable genotype, followed by NASIK and BY×AFD, suggesting that these genotypes have the greatest potential for cultivation and recommendation in the target onion-growing environments.

4. Conclusion

The multi-environment evaluation demonstrated significant effects of environment, genotype, and genotype × environment interaction (GEI) on onion marketable bulb yield, with environment accounting for the largest proportion of the total variation (22.40%). This highlights the strong influence of agro-ecological conditions on yield expression and the importance of evaluating genotypes across diverse production environments. AMMI and GGE biplot analyses further confirmed substantial differences in genotype performance and adaptation across environments. Among the evaluated genotypes, BY × AFD showed a favorable combination of high yield and stability, producing 25.15 t ha⁻¹ marketable bulb yield and 29.39 t ha⁻¹ total bulb yield, comparable with the standard checks NAFIS and NASIK. Its relatively low AMMI stability value (ASV = 1.3317) further indicated good stability across environments, suggesting broad adaptation and competitive yield potential under the tested production conditions. GGE biplot analysis identified KARC_2026 and MARC_2026 as favorable testing environments, combining high discriminating ability with good representativeness of the target production environments. These locations may therefore be useful for future multi-environment onion breeding and variety evaluation. Overall, BY × AFD demonstrated relatively high, stable yield performance and favorable and adaptation across the tested environments. Based on its consistent performance relative to the standard checks, BY × AFD is recommended for national variety verification trials for further validate its agronomic performance, stability, and suitability for potential release in onion-growing areas of Ethiopia.

Declarations

Ethical approval

This study did not involve human participants or animals. All experimental procedures complied with institutional, national, and international guidelines for field trials and plant breeding research. Not applicable, as the study did not involve human participants.

Consent to participate

Not applicable.

Consent to publish

All authors consent to the publication of this manuscript and confirm that the data and results presented are original and have not been published elsewhere.

Author Contribution

All authors contributed to the study conception, methodology, data collection, analysis, and interpretation of results. The manuscript was drafted, reviewed, and approved by all authors.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

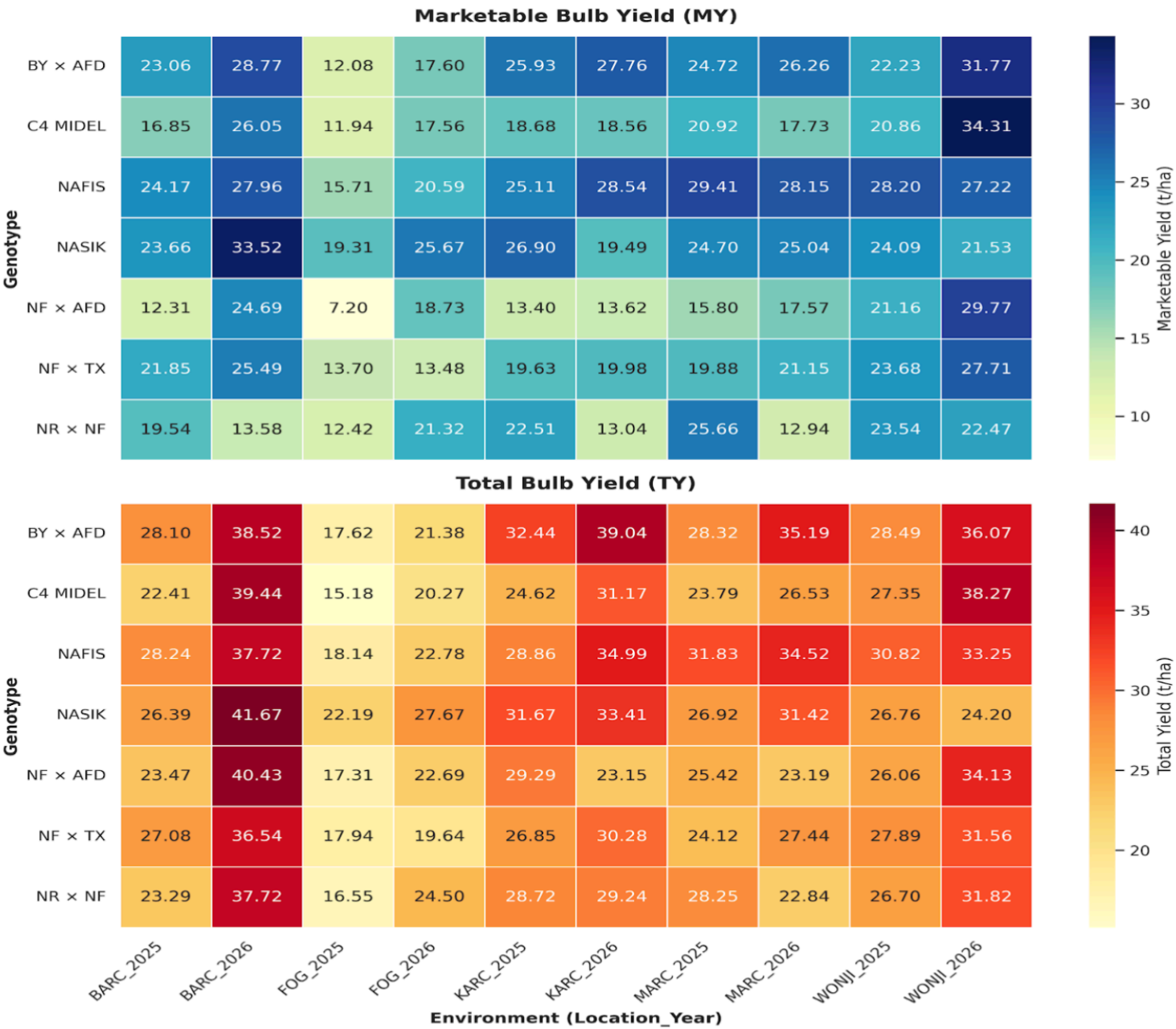


Figure 1

Heat plotting performance across environments for marketable and total bulb yield

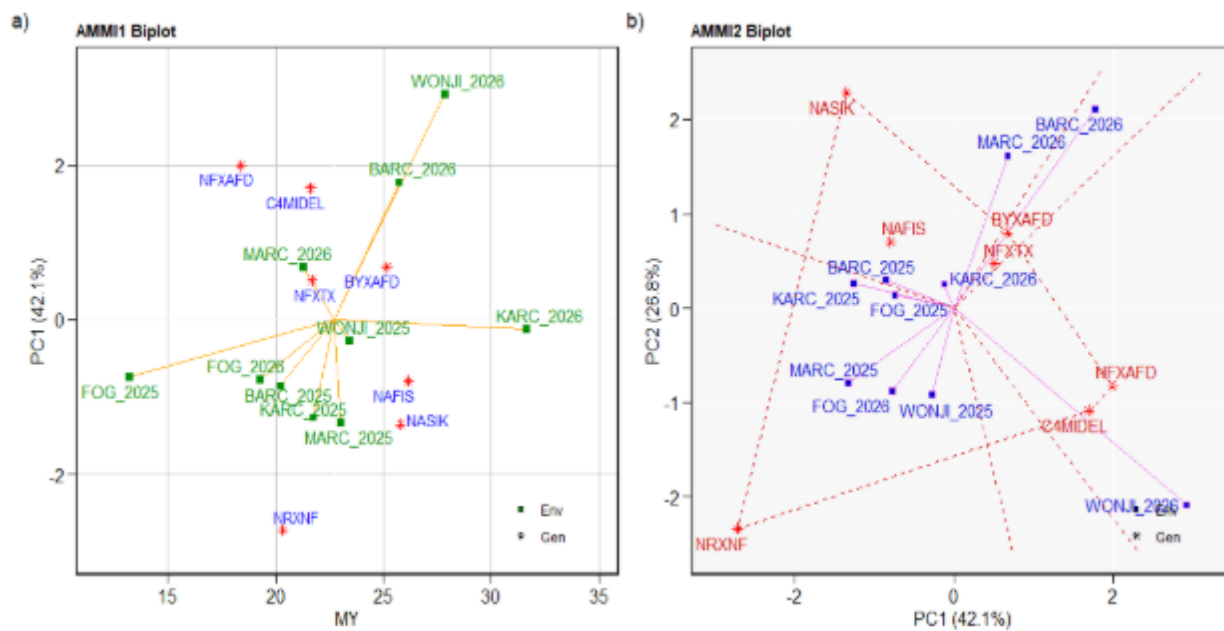


Figure 2

a(left) AMMI 1 Biplot of IPCA 1 vs. IPCA 2 for marketable bulb yield, b (right)AMMI 2 biplot of marketable bulb yield of genotypes with IPCA 1 scores of environments

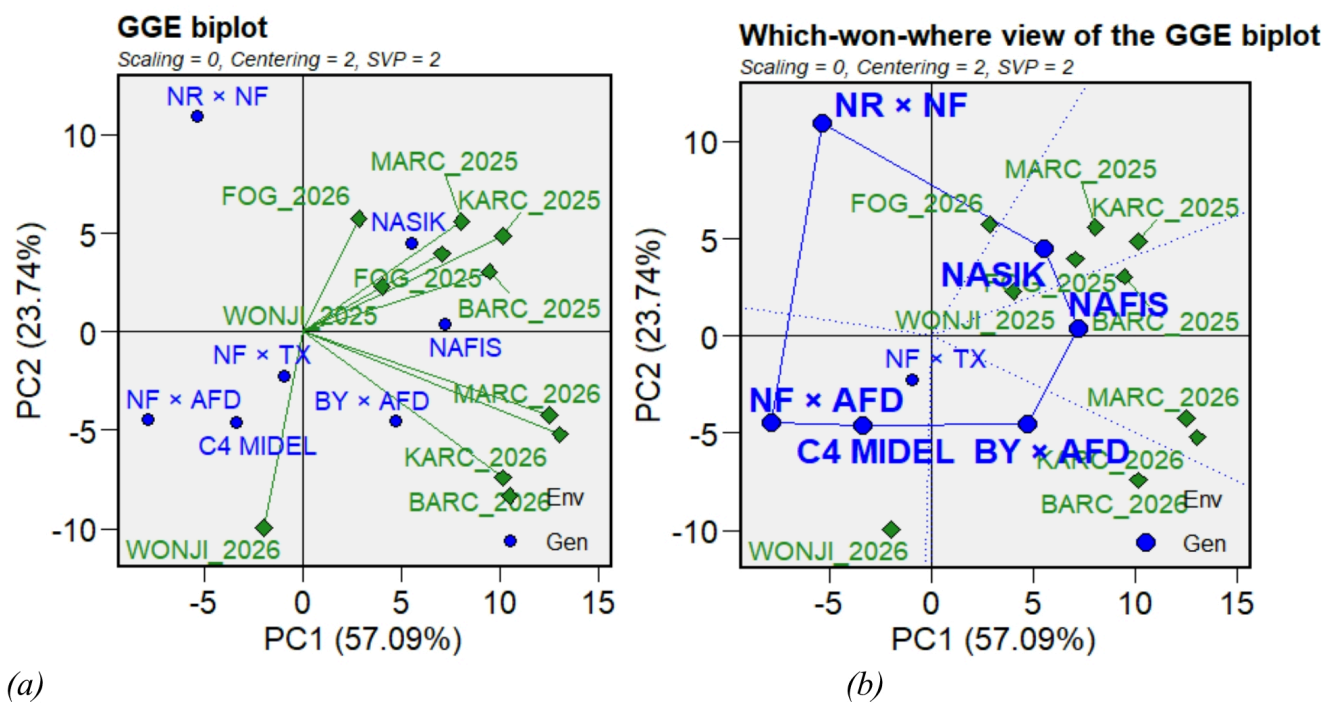


Figure 3

GGE biplot (a), and Which-won-where view of the GGE biplot (b) of marketable onion genotypes tested at different environments

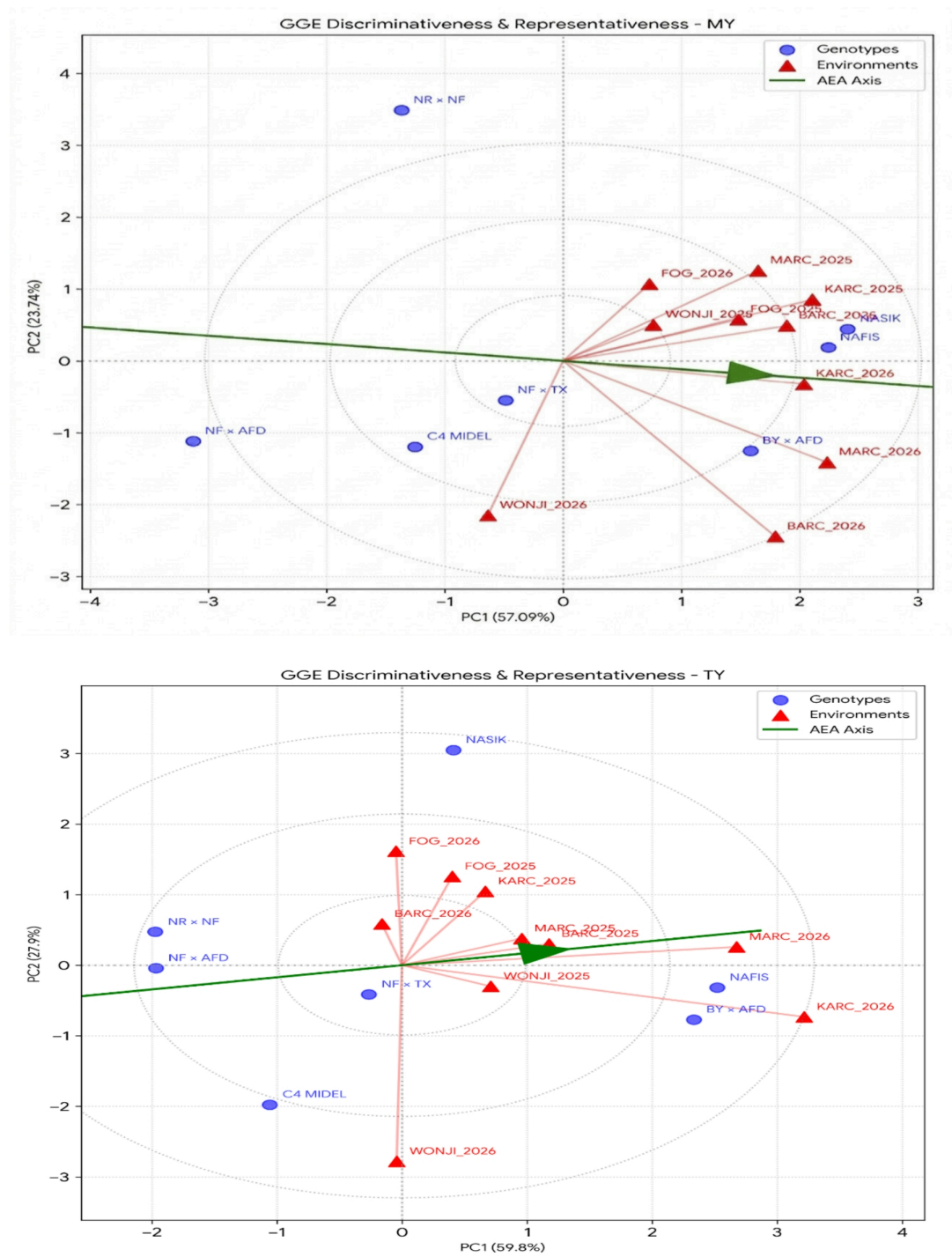


Figure 4

Discriminativeness and representativeness view of GGE biplots under the effects of GEI: (a) Marketable tuber yield (MY), and (b) Total tuber yield (TY)

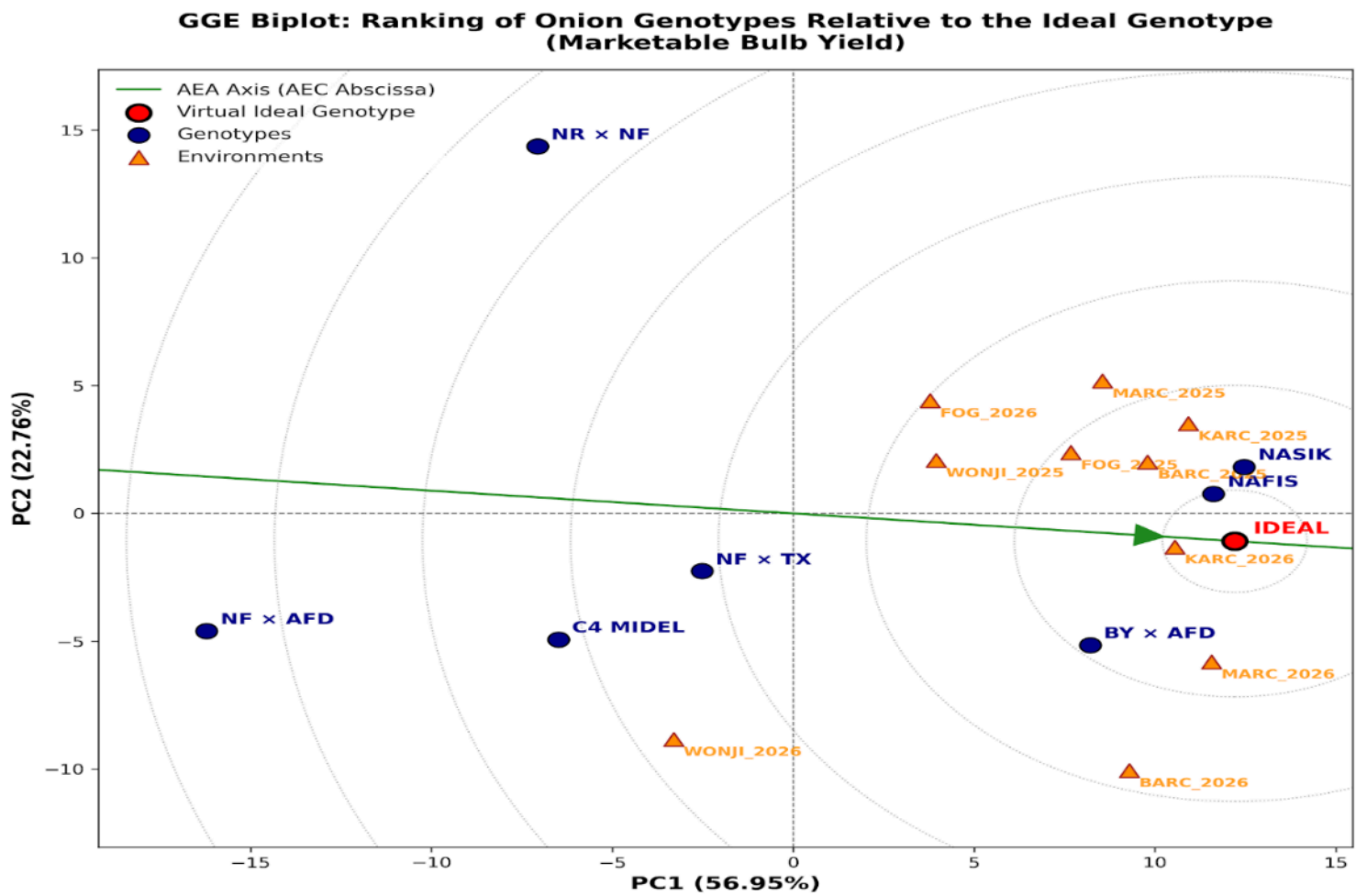


Figure 5

Ranking of genotypes relative to the ideal genotype