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Article

Genotype-by-Environment Interaction and Stability Analysis in Durum Wheat (*Triticum durum* L.)

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Abstract: Information on genotypes, which can be adapted to a wide range of environments, is one of the most important goals of plant breeders in a crop improvement program to set appropriate breeding strategies and improve wheat production. So, the objectives of this study were to (i) estimate the effect of the environment on yield and yield-contributing characters, (ii) determine desired genotypes with high yield and stability by estimating stability via different stability analysis techniques. Forty-nine wheat genotypes were evaluated in a 7 x 7 lattice design with two replications three locations. Based on the combined analysis of variance results, the majority of the traits had a significant difference ($p<0.01$) within location, genotype, and GEI. The observed significance differences among genotypes for the traits under study generally indicated the presence of genetic variations among the genotypes, and genotypes react differently depending on the tested environmental conditions. According to AMMI analysis, genotypes, environments, and their interactions have a considerable impact on grain yield. Variety Alemtena, Denbi, Mangudo, and genotypes DWNL19209 show high stability with high seed yield using all stability analyses. The information obtained in the present study could be used to examine stable genotypes for narrow and broad environmental adaptability.

Keywords: AMMI analysis; durum wheat; genotypes; stability analysis

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1. Introduction

Wheat is the most adaptable of all cereal crop species, capable of growing in a wide range of environments worldwide. The World's total area covered by wheat (durum wheat and bread) is 220.41Mha with a total production of 798.975 M tons. The top five major wheat-producing countries in the world are China, India, Russia, Australia, and Canada. Africa's major Wheat-producing countries are Egypt, followed by Ethiopia, Morocco, Algeria, and South Africa (FAO, 2023). In Ethiopia, wheat is the third major (1,867,047.71ha) cereals crop grown, next to teff (2,932,670.03ha) and maize (2,563,201.21ha) in terms of area coverage and, second (58,078,220.5 tons) in terms of production among Ethiopia's cereal crops, after maize (107,513,689.44 tons) (CSA, 2022).

The grain of durum wheat is mainly required for the manufacturing of pasta products (macaroni, and spaghetti) for human consumption. Additionally, in Ethiopia wheat grain is used to make a wide range of traditional Ethiopian foods. Given its significant contribution, the prioritization of wheat

production and marketing is essential for the country's agricultural sector. Though durum wheat has increasing demand in domestic industries its production is low. This may be due to low productivity per unit areas raised by abiotic, biotic factors and low-yielding and widely adaptable varieties.
Since a genotype's yield performance is the outcome of interactions between the genotype and environment, GEI research has become extremely important in breeding efforts. Consequently, production stability should result from the release of a genotype that performs consistently across a range of conditions. The effectiveness of a genotype evaluation program depends on a measure of the relative yield stability of the durum wheat genotypes under a wide range of environmental conditions. So, a thorough evaluation of the genetic resources under different environments is paramount to selecting promising genotypes for growing areas is the most important thing. Therefore, several statistical techniques have been created to improve breeders' comprehension of GEI, genotype stability, and their relationships. Both parametric and non-parametric methods were used during this study to estimate stability. So, the objectives of this study were to (i) estimate the effect of the environment on yield and yield-contributing characters, (ii) determine desired genotypes with high yield and stability by estimating stability via different stability analysis techniques.

2. Materials and Methods

2.1. Description of study areas

The experiment was conducted in three locations (Alemtena, Debrezeit, and Minjar) over one season in 2020/21, with varying climates and altitudes. The maximum and minimum monthly temperatures, as well as the monthly rainfall measured in millimeters, were taken into account during the growing periods. Table 1 provides a description of the experimental site.

Table 1. Description of experimental site.

Site	Temperature		Mean annual R.F(mm)	Altitude (masl)	Latitude	Longitude
	Annual min.	Annual max.				
Debrezeit	8.9^{0}C	28.3^{0}C	851	1900	08^0 44'N	38^0 58'E
Minjar	10^{0}C	28^{0}C	867	1810	08^0 55'N	39^0 45'E
Alemtena	12.9^0 c	29.8^{0}C	728	1575	8^0 18' N	38° 57'E

2.2. Experimental materials and Experimental design

The experimental materials consisted of 49 genotypes (16 advanced lines, 16 landraces, and 17 improved durum wheat varieties) (Table 2). The 49 genotypes used as treatments were grown under main season conditions at a normal sowing period in July 2020. The experiment was planted in a 7 X 7 simple lattice design. The unit plot was 3 m² in an area with 6 rows at 20 cm spacing. A seed rate of 125 kg/ha, along with the recommended fertilizer rate of 100 kg NPS and 92 kg N ha^{-1}, was employed.

Table 2. Experimental materials used for the study

Entry No	Genotype	Pedigree	Origin
1	DWNL2	C F4 20 S/4/YAZI-1/AKAKI-4//SOMAT-	CIMMYT
2	Yerer	CHEN/TEZONTLE/3/GUILLEMOT//CANDEAL-II	CIMMYT
3	DWNL39	C0RDEIR0/9/GUAYACAN INIA/GUANY/8/GEDIZ FG0//GTA/3/SRN-1/4/TOTUS/5/ENTE/MEXI-2//i¿½	CIMMYT
4	DWLRC 25	DWLR	Ethiopia
5	DWNL4	AG 1-22/2*ACO89//2*UC1113/3/5*KOF	CIMMYT
6	DWLRC 34	2019/20DW/Landrace cluster plot # 34	Ethiopia
7	Ude	CHEN/ALTAR-84//JORI	CIMMYT
8	DWLRC28	DWLR	Ethiopia
9	DWNE9	Mangudo/Mekuye/DZ 2013 meh DW F1 P#20/DZ 2014 meh DW F2	Ethiopia

10	Mekuye	STJ3//BICRE/LOUKOS-4/3/TER3	ICARDA
11	DWLRC 39	DWLR	Ethiopia
12	Mangudo	MRF1/STJ2|/3/1718/BT//KARIM, TUN	ICARDA
13	DWNE11	CMH83.2578/4/D88059//WARD/YAV79/3/AC089/5/2*S00TY-	CIMMYT
14	Hitosa	CHEN/ALTAR-84	CIMMYT
15	DWLRC60	2019/20DW/Landrace cluster plot # 60	Ethiopia
16	Tesfaye	ARMENT//SRN-NIGRIS-4/3/CANED-9.1/4/TOSKA-26RASCON-37//SNITSN/5/PLAYERO	CIMMYT
17	DWNL10	MINIMUS/COMB DUCK-2//CHAM-/3/FICHE-	CIMMYT
18	Denbi	AJAIA/BAUSHEN[3589]	CIMMYT
19	DWNE10	KR0N0S/10/K0FA/9/USDA595/3/D67.3/RABI//CRA/4/AL0/5/HUI/YAV-1/6/ARDENT/7/HUI/ï¿½	CIMMYT
20	DWLRC 48	DWLR	Ethiopia
21	DWNL18	JUPARE C 2001* 2/RBC/5/MOHAWK/3/GUANAY//TILD-1LDTUS-	CIMMYT
22	Werer	1346/LAHN//BICRE/LOUKOS-4	ICARDA
23	DWLRC 16	DWLR	Ethiopa
24	Utuba	(=Icajihan42) Omruf1/Stojocri2/3/1718/BeadWheat24//Karim½	ICARDA
25	DWNL9	Mangudo/Mekuye/DZ 2013 meh DW F1 P#20/DZ 2014 meh DW F2 P#19-1	Ethiopia
26	Alemtena	Icasyr-1/3/Gcn//Sti/Mrb3	CIMMYT
27	DWNE8	Mangudo/Bekelcha/DZ 2013 meh DW F1 P#19/DZ 2014 meh DW F2 P#18-6	Ethiopia
28	Fetan	ARMENT//2*SOOTY-9/RASCON-37/4/CNDO/PRIMADUR//HAI-OU-17/3/SNITAN	CIMMYT
29	DWLRC20	DWLR	Ethiopia
30	DWNL11	CMH83.2578/4/D88059//WARD/YAV79/3/AC089/5/2*S00TY-9/RASC0N-37/6/1A.1D5+1-06/ï¿½	CIMMYT
31	D-18	CGS	Italy
32	DWLRC 94	DWLR	Ethiopia
33	Gerardo	VZ 466/61-130xGII' 's'', CM9605	Ethiopia
34	DWNE13	otb4/3/HFN94N-8/Mrb5//Zna-1/4/5+j3//Dra2/Bcr/3/Ter-3	ICARDA
35	Cocorit	RAE/4*TC60//STW63/3/	Mexico
36	DWLRC96	DWLR	Ethiopia
37	Bekelcha	980SNGedirfa/Gwerou #15 patho	CIMMYT
38	DWNE7	Yere/Mova/DZ 2013mehF1 P#9/DZ 2014mehF2 P#9-2	Ethiopia
39	Toltu	4/B/R9096#21001(980SN Patho)	CIMMYT
40	DWLRC92	DWLR	Ethiopia
41	DWLRC79	DWLR	Ethiopia
42	DWNE8	Mangudo/Bekelcha/DZ 2013 meh DW F1 P#19/DZ 2014 meh DW F2 P#18-6	Ethiopia
43	DWLRC84	DWLR	Ethiopia
44	DWLRC85	DWLR	Ethiopia
45	DWNL12	CMH83.2578/4/D88059//WARD/YAV 79/3/ACO89/5/2*SOOTY.9/RASCON-37/6/1A.1D 5+1-6/ï¿½	CIMMYT
46	DWLRC 88	DWLR	Ethiopia
47	DWLRC89	DWLR	Ethiopia
48	DWNL19	YAVA 79/9/ USDA 595/3/D67.3/RABI//CRA/4/ALO/5/HUI/YAV-1/6/ARDENTE /7/HUI/YAV 79/8/T1/2	CIMMYT
49	Filakit	EN-25	CIMMYT

2.3. Data collection

To avoid border effects, the data for all of the parameters considered were taken from the net plot area. All agronomic, yield, and yield-related data were recorded on the middle four rows of each experimental unit. Days to heading, days to 90% maturity, days to grain filling period (GFP, days), plant height (PH), number of tillers per plant, thousand kernel weights (TKW), hectoliter weight (HLW), spike length (SPL), number of seeds per spike (NSP), grain yield (GY, kg/ha), Number of grain per spike (NGS). Biomass yield (BY, kg/ha), harvest index, and grain protein content (GP, %).

2.4. Statistical Analysis

The data were analyzed following procedures appropriate to the lattice design described by Gomez and Gomez (1984). Means of significant treatment effects were separated using Duncan's New Multiple Range Test (DNMRT) at a 5% probability level.

The Additive Main effect and the Multiplicative Interaction effect (AMMI) will be analyzed using Yan's (2011) method. Stability analysis will be conducted using Shukla's (1972) stability variance, AMMI Stability Value (ASV) (Purchase et al. 2000), Wricke's Eco-valence Analysis (W2i) used by Wricks's (1962), Superiority Index (PI) measure as used by Lin and Binns (1988), Stability Analysis According to Eberhart and Russell (1966), the coefficient of variation stability parameter is the conventional linear regression coefficient as suggested by Finlay and Wilkinson (1963).

3. Results and Discussion

3.1. Analysis of variance

Combined analysis of three locations for 14 parameters revealed a significant difference ($p<0.01$) for location and genotype (Table 3). The significant variances observed among the genotypes for the traits under investigation typically suggest the existence of genetic variations among them. Additionally, a notable difference ($p<0.01$) exists in GEI for YLD, DTH, DTM, GFP, PH, BM, HI, HLW, and GPC, while significant differences ($p \leq .05$) are observed for NTP, TKW, and NGS. This indicates that different genotypes exhibit varying responses based on the environmental conditions being tested. Similarly, Alambo et al. (2022); Ebsa et al. (2024); Mullualem et al. (2024) and found significant differences in GEI for the number of tillers per plant, plant height (PH), harvest index (HI), grain yield (GY), and biomass weight (BM). Additionally, Ebsa et al. (2024) found a significant difference in GEI for hectoliter weight (HLW) and days for maturity (DM); Gebrewahid et al. (2021) for thousand seed weight (g); and Gebremariam et al. (2022); Mullualem et al. (2024) for days to heading (DTH) and grain filling period (GFP). Furthermore, Gebrewahid et al. (2021); Shibeshi and Kassa (2021); Alambo et al. (2022); and Ebsa et al. (2024); Mullualem et al. (2024) found significant differences in GEI for seed yield. There is a non-significant difference between NSP and spike length (SPL). Similarly, Alambo et al. (2022) found similar differences in spike length. This indicates the genotype's performance showed close differences.

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Table 3 combined analysis of variance for 14 traits with in three location

Traits	LOC (2)	Genotype (48)	Loc:Genotype (96)	Loc:Rep (3)	Loc:Rep:Block (36)	Residuals (108)	cv	mean	range
DTH	441.84**	71.71**	5.33**	14.48**	3.62	3.29	2.9	61.5	55.6-61.5
DTM	1717.24**	85.85**	25.58**	8.06	8.82	7.75	2.98	93.2	87.33-102.17
GFP	951.53**	26.34**	23.52**	11.37	10.13	8.32	9.08	31.7	25.67-33.66
PH	1644.74**	644.31**	40.34**	74.78**	21.07	14.84	4.64	82.9	68.23-108.13
NTP	56.792**	1.598**	0.692*	2.299**	0.681**	0.439	17.07	3.88	3.0-5.23
NSP	74.616**	6.928**	1.4	27.867**	2.028	1.38	6.8	17.2	
SPL	2.447**	8.49**	0.2	4.2621**	0.266	0.24	10.6849	42.8	
NGS	353.94**	607.95**	28.96*	16.19	42.2**	20.9	10.68	42.8	24.43 to 61.5
BMY	311688835**	2441842**	2290329**	12218871**	1994711**	1E+06	15.95	6531	4977.67 -79.17
HI	1834.34**	151.19**	30.13***	4.86	25.54**	16.2	12.42081	32.4	22.68-41.08
HLW	419.91**	51.67**	11.97***	0.36	3.37	3.95	2.65	74.9	67.97-78.92
TKW	1429.24**	112.77**	14.2*	24.24	10.16	9.79	9.86	31.7	23.67-39.00
GPC	132.072**	4.77**	1.88**	15.736**	1.015**	0.564*	5.7	13.1	11.60- 15.80
YLD	59133463**	1778508**	268289**	549274**	94891**	1E+05	2.49	2567	1234.17- 34.50

, * significant at p<0.01, and p<0.05 respectively. Days to heading(DTH), Days to 90% maturity(DTM), Days to grain filling period (GFP), Plant height (PHT), Number of tillers per plant(NTP), thousand kernel weights (TKW), Hectoliter weight (HLW), spike length(SPL), number of seed per spike(NSP), Grain yield (GY, kg/ha), NGS. Biomass yield (BY, kg/ha), Harvest index, Grain protein content (GP, %)

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3.2. *Mean Performance Evaluation of Seed Yield and yield related Traits*

The mean values of 49 wheat genotypes from combined analysis for seed yield and yield-related traits are listed in Table 4.

3.2.1. Days to heading and Days to maturity

The days to heading exhibited significant variability, ranging from 55.6 days for Filakit to 69 days for DWLRC192079, resulting in a mean value of 61.5 days. Days to maturity showed a wide range of variability, with a range of 102.17 for Werer and 87.33 for genotype DWLRC192084, with an average mean of 93.2. Genotypes with fewer days to maturity could be considered during selection for early-maturing types. Gebremariam et al. (2022) found that the average number of days to heading varied from 57 to 84, with an average of 67.95, while the average number of days to maturity ranged from 95 to 136, with a mean of 112.39.

3.2.2. Grain filling period (GFP) and plant height (PH)

The grain filling period showed a mean value ranging from 25.67 for genotype DWNE192013 to 36.33 for genotype DWLRC192020, with an average mean of 31.7. The mean value for a plant height ranged from 68.23 to 108.13, with an average mean of 82.9. The highest plant height was recorded for genotype DWLRC192016, and the lowest was recorded for genotype DWNL192019. Plant height for wheat genotypes ranged from 74.8 cm to 94.0 cm, according to Shibeshi and Kassa (2021), and from 59.6 cm to 96.5 cm, according to Khan et al. (2020). Plant height is an important agronomic trait in wheat breeding because it commonly impacts grain yield (GY) due to lodging risk and affects productive tillers and the number of kernels per spike.

3.2.3. Number of grains per spike (NGS) and Number of tillers per plant

The mean number of grains per spike ranged from 24.43 to 61.5, with an average value of 42.8. The highest number of grains per spike was recorded for genotype DWNL192018, followed by genotypes Tesfaye, DWNE192011, and DWNE19209, with no significant difference between them. The genotype DWLRC192089 had the fewest NGS reported compared to the other eight genotypes, with no significant difference. Khan *et al*. (2020) found that a variety's average number of grains per spike ranged from 40.9 to 20.4. There was significant variation in the number of tillers per plant, ranging from 3.00 for DWNL192012 to 5.23 for DWLRC192094, with a mean value of 3.88. Gebremariam *et al*. (2022) found that the average total number of productive tillers varied between 1.5 and 7.2.

3.2.4. Biomass yield and harvest index

The mean values for biomass yield range from 4977.67 to 7909.17 kg/ha, with a 6531 kg ha^{-1} average mean. Four genotypes: DWLRC192020, Hitosa. DWLRC192039 and DWLRC192025 had the maximum biomass yield with no significance between them. The lowest biomass yield was observed for DWLRC192088 and the other 21 genotypes, with no significance among them. Denbi has the highest harvest index, with a range of 22.68-41.08% mean value and a 32.4 average mean, followed by nine genotypes with no significant difference between them. Genotype DWLRC192094 and 14 genotypes had the lowest harvest index. Shibeshi and Kassa (2021) reported mean values for biomass yield from 5,300 to 10,050 kg ha^{-1}.

Hectoliter weight and thousand grain weight

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The mean hectoliter weight values ranged from 67.97 to 78.92, with an average of 74.9. Denbi had the highest mean value of thousand seed weight, followed by twenty-one genotypes with no significant differences. The hectoliter weight was determined for genotype DWLRC192079 (67.97), followed by DWLRC192084 and DWLRC192088 genotypes, with no significant difference between them. The mean values for thousand seed weights were 23.67 to 39.00 with 31.7 average mean values. The highest mean value of thousand kernel weight was found for genotype DWNL192011, followed by five genotypes with no significant difference between them. The lowest thousand-seed weight was found for genotype DWLRC192079, followed by eight genotypes with no significant difference. Similarly, Ebsa *et al*. (2024) found 79.4 kg/hL and 39.6 g average mean values for hectoliter weight and thousand kernel weights, respectively.

3.2.5. Grain protein content (GPC) and Seed yield

The study found that the average grain protein content ranged between 11.60 and 15.80, and the average combined mean is 13.1. DWLRC192094 (15.80%) had the highest mean value, followed by genotypes DWLRC192092 and DWLRC192088 with a non-significant difference between them. The lowest mean values were found for genotype DWNE19208, followed by eighteen genotypes with a non-significant difference between them. The mean values for seed yield ranged from 1234.167 to 3417.500 kg/ha, with 2567 combined average value. The genotype Mangudo had the highest seed yield (3417.500), followed by genotypes DWNE19209 Denbi, Fetan, and DWNL19209, Utuba, Toltu, Hitosa, Werer, Bekelcha, DWNE192011, DWNL19208, and Alemtena, with no significant difference between them. With no significant difference between them, genotype DWLRC192079 (1234.167) had the lowest mean value, followed by genotypes DWLRC192088, DWLRC192094, and DWLRC192089 with a non-significant difference among them. Shibeshi and Kassa (2021) reported seed yield with a mean value ranging from 4446.3 kg ha^{-1} to 3634.8 kg ha^{-1}.

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Table 4 combined mean analysis for 49 durum wheat genotype

Genotype	DTM	DTH	GFP	PH	NTP	NGS	BMY	HI	HLW	TKW	GPC	YLD
Mangudo	92.33^{i-n}	58.67^{opq}	33.67 $^{a-f}$	76.40^{f-n}	3.77 $^{c-j}$	48.50^{d-i}	6960.42^{a-i}	39.54^{abc}	78.70^{a}	36.3^{a-d}	12.67^{i-p}	3417.50^{a}
DWNE19209	95.83^{d-i}	62.50^{g-l}	33.33^{a-h}	83.0^{fgh}	4.10^{b-i}	56.77^{abc}	7236.42^{a-f}	40.82^{ab}	76.43^{a-f}	38.33^{ab}	12.37^{k-q}	3320.00^{ab}
Denbi	90.12^{mno}	58.33^{o-r}	31.83^{b-i}	77.07^{i-m}	3.57^{e-j}	54.03bcd	6533.17^{a-j}	41.08 a	78.92 a	28.67^{i-p}	12.0^{m-q}	3218.33^{abc}
Fetan	91.0^{k-o}	61.3^{k-n}	29.66 $^{f-i}$	77.66^{h-m}	3.50^{e-j}	50.63^{c-f}	6974.0^{a-i}	38.27^{a-e}	78.83^{a}	29.66^{i-o}	12.35^{k-q}	3193.33^{a-d}
DWNL19209	92.33^{i-n}	60.67^{k-p}	31.67^{c-i}	71.53^{n-r}	4.30^{b-g}	44.10^{g-j}	7273.95^{a-f}	36.46^{a-g}	78.00^{abc}	35.00^{a-f}	12.27^{k-q}	3191.66^{a-d}
Utuba	92.0^{i-n}	60.33^{k-p}	31.67 $^{c-i}$	82.20^{ghi}	3.50^{e-j}	45.77^{f-j}	6625.25^{a-j}	38.35^{a-e}	77.6^{a-d}	38.0^{ab}	12.30^{k-q}	3178.3^{a-e}
Toltu	92.50^{i-n}	58.17^{pqr}	34.3^{a-d}	72.37^{m-r}	3.47^{e-j}	49.90^{d-g}	6858.17^{a-j}	38.27 $^{a-e}$	77.40^{a-d}	30.00^{h-n}	12.97^{f-o}	3135.83^{a-f}
Hitosa	91.00^{k-o}	58.3^{o-r}	32.67^{a-h}	79.07^{h-k}	3.63^{e-j}	53.93^{bcd}	7640.37^{ab}	35.08 $^{c-h}$	78.77^{a}	30.67^{g-n}	12.28^{k-q}	3111.7^{a-g}
Werer	102.17^{a}	66.33^{b-e}	35.83^{ab}	78.27^{h-k}	3.93^{b-j}	43.97^{g-k}	6843.75^{a-j}	38.29^{a-e}	76.30^{a-g}	38.67^{a}	12.52 $^{j-q}$	3108.33^{a-g}
Bekelcha	91.67^{j-n}	57.67^{qrs}	34.00^{a-e}	79.33^{h-k}	4.27^{b-g}	42.30^{i-l}	6961.7^{a-i}	36.46^{a-g}	77.97^{abc}	37.33^{ab}	13.88^{c-g}	3105.0^{a-g}
DWNE192011	92.00^{i-n}	58.67^{opq}	33.33^{a-h}	72.83^{l-r}	3.43^{f-j}	56.80^{abc}	6813.58^{a-j}	37.41^{a-f}	77.03^{a-d}	32.33c-j	13.07^{f-m}	3098.33^{a-g}
DWNL19208	93.50^{h-m}	60.00 $^{l-q}$	33.5^{a-g}	78.73^{h-k}	3.83c-j	48.77^{d-h}	6249.91^{b-k}	36.59^{a-g}	76.73^{a-e}	36.00^{a-d}	11.88^{pq}	3024.2^{a-h}
Alemtena	91.0^{k-o}	57.50^{qrs}	33.50^{a-g}	76.23^{j-n}	3.83^{c-j}	51.20^{b-f}	6436.50^{a-k}	37.22^{a-g}	78.433^{ab}	32.67^{c-i}	12.22^{k-q}	3017.50^{a-h}
DWNL192011	90.50^{l-o}	57.67^{qrs}	32.83^{a-h}	78.53^{h-k}	3.73^{d-j}	42.30^{i-l}	6439.83^{a-k}	34.97^{c-h}	77.13^{a-d}	39.00a	12.93^{f-p}	3017.50^{a-h}
DWNL19202	96.50^{c-h}	65.50^{def}	31.0^{c-i}	75.27 $^{j-p}$	3.47^{e-j}	54.17^{bcd}	7109.33^{a-g}	36.55^{a-g}	76.57^{a-e}	30.33^{h-n}	14.25^{bcd}	2995.8^{a-i}
D18	92.50^{i-n}	60.33^{k-p}	32.17^{b-i}	69.73^{qr}	3.57^{e-j}	48.00^{d-i}	5643.08^{g-k}	35.98^{a-h}	77.67^{a-d}	35.33^{a-e}	12.63^{i-q}	2973.3^{a-i}
Ude	89.17^{n-p}	57.67^{qrs}	31.50^{c-i}	80.57^{hij}	3.37^{g-j}	51.73^{b-f}	7280.45^{a-f}	38.56^{a-d}	77.43^{a-d}	38.33^{ab}	12.10 $^{l-q}$	2935.83^{bj}
DWNE19208	89.00^{n-p}	59.00^{n-q}	30.00^{e-i}	77.90^{h-l}	3.50^{e-j}	47.43^{e-i}	6322.25^{b-k}	33.65^{d-j}	77.17^{a-d}	36.68^{abc}	11.60^{q}	2918.33^{b-j}
DWNE192013	99.0^{a-d}	62.67^{g-k}	36.33^{a}	76.30^{j-n}	3.47^{e-j}	50.90c-f	6748.67^{a-j}	33.44^{d-k}	76.85^{a-e}	32.00^{d-k}	12.85^{g-p}	2790.00^{c-k}
DWNL9	95.33^{d-j}	61.83^{ijkl}	33.50^{a-g}	79.97^{h-k}	3.27^{hij}	48.20^{d-i}	6808.33^{a-j}	32.61^{e-l}	76.90^{a-e}	36.00^{a-d}	11.90^{opq}	2746.7^{d-l}
Cocorit	93.5^{h-m}	61.83^{i-l}	31.67^{c-i}	75.77^{j-o}	4.37^{a-f}	43.67 $^{h-k}$	7324.83^{a-e}	31.6^{g-m}	76.80^{a-e}	34.00^{b-h}	13.81^{c-h}	2740.8^{e-l}
Mekuye	90.5^{l-o}	58.50^{opq}	32.00^{b-i}	76.13^{j-n}	3.43^{f-j}	37.90^{k-n}	6039.8^{c-k}	35.2^{b-h}	75.2^{c-i}	36.33^{a-d}	12.90^{f-p}	2726.7^{f-m}
DWNE192010	94.5^{g-k}	61.50^{j-m}	33.00^{a-h}	71.23^{n-r}	3.23^{ij}	51.10^{b-f}	6081.67^{c-k}	35.51^{a-h}	76.30^{a-g}	27.67^{k-q}	13.00^{f-n}	2700^{f-m}
Filakit	90.17^{mno}	55.66^{s}	34.5^{a-d}	78.16^{h-k}	3.43^{f-j}	43.53^{h-k}	6111.0^{c-k}	34.81^{c-h}	76.87^{a-e}	34.67^{a-g}	12.97^{f-o}	2664.17^{g-n}
DWNL19204	90.33^{mno}	58.83^{opq}	31.50^{c-i}	78.57^{h-k}	3.47^{e-j}	53.33^{b-e}	5877.25^{e-k}	34.28^{c-i}	76.90^{a-e}	31.00^{f-m}	13.67^{c-i}	2626.67^{h-o}
Tesfaye	92.5^{i-n}	60.83^{k-o}	31.67^{c-i}	74.73^{k-q}	3.27^{hij}	57.20^{ab}	6969.0^{a-i}	30.53^{h-n}	72.80^{h-l}	27.33^{l-q}	13.1^{e-m}	2619.17^{h-o}
DWNL192018	94.67^{g-k}	62.33^{h-l}	32.33^{a-i}	76.47^{j-n}	3.90^{b-j}	61.50^{a}	6388.00^{b-k}	34.11^{c-i}	74.23^{e-j}	25.33^{opq}	13.05^{f-m}	2615.0^{h-o}

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Gerardo	100.67^{ab}	65.83^{c-f}	34.83^{abc}	80.60^{hij}	3.37^{g-j}	43.50^{h-k}	6462.83^{a-j}	30.40^{h-n}	75.87^{b-g}	37.33^{ab}	13.13^{e-l}	2567.5^{i-o}
DWNL192010	85.83^{p}	56.00^{rs}	29.83^{e-i}	72.77 $^{l-r}$	3.47^{e-j}	40.57 $^{j-m}$	6220.61^{b-k}	31.70^{f-m}	75.37^{c-h}	32.67^{c-i}	11.93^{n-q}	2513.33^{j-p}
DWNE19207	95.17^{e-j}	61.33^{k-n}	33.83^{a-e}	94.80^{de}	3.83^{c-j}	37.20^{lmn}	5894.29^{e-k}	33.15^{d-k}	76.90^{a-e}	36.00^{a-d}	13.13^{e-l}	2510.8^{j-p}
DWLRC192025	92.83^{h-n}	62.17^{i-l}	30.67^{d-i}	97.67^{b-e}	4.83ab	32.97 $^{n-r}$	7504.83^{a-d}	28.91^{i-o}	72.06^{jkl}	28.67^{i-p}	12.95^{f-p}	2470.0^{k-p}
Yerer	100.17^{abc}	67.17^{a-d}	33.00^{a-h}	70.13^{pqr}	3.93^{b-j}	50.43^{def}	5585.0^{h-k}	33.82^{d-i}	73.78^{f-k}	36.00^{a-d}	13.90^{c-g}	2466.66^{k-p}
DWNL192012	91.83^{j-n}	59.2^{m-q}	32.67^{a-h}	70.67^{o-r}	3.00^{j}	48.30^{d-i}	6155.83^{b-k}	32.18^{f-l}	74.90^{d-i}	29.33^{i-o}	13.01^{f-m}	2376.66^{k-q}
DWLRC192048	87.17^{op}	57.50^{qrs}	29.67^{f-i}	101.13^{b}	4.70^{abc}	33.77^{n-q}	7013.29^{a-h}	27.99^{k-p}	71.75^{jkl}	32.0^{d-k}	13.53^{c-j}	2326.67^{l-q}
DWNL192019	89.16^{nop}	58.66^{opq}	30.50^{d-i}	68.23^{r}	3.30^{hij}	51.83^{b-f}	5529.91^{h-k}	30.70^{h-n}	72.98^{h-l}	26.7^{m-q}	13.58^{c-j}	2292.5^{m-r}
DWLRC1920 34	92.50^{i-n}	62.83^{g-k}	29.67^{f-i}	94.90^{cde}	4.00^{b-i}	30.57^{o-t}	6620.29^{a-j}	30.51^{h-n}	71.10^{kl}	29.33^{i-o}	12.97^{f-o}	2245.83^{n-r}
DWLRC192085	94.67^{g-k}	63.83^{f-j}	30.83^{c-i}	96.93^{b-e}	4.63^{a-d}	30.60^{o-t}	6000.50^{d-k}	26.4^{m-p}	72.07^{jkl}	31.33^{e-l}	13.93^{c-f}	2202.50^{o-r}
DWLRC1920 84	87.33^{op}	59.0^{n-q}	28.33^{ij}	92.70^{e}	4.67^{a-d}	29.20^{p-t}	6515.83^{a-j}	28.13^{j-p}	70.33^{lm}	28.00^{j-p}	13.80^{c-h}	2120.0^{p-s}
DWLRC192020	87.17^{op}	61.50^{j-m}	25.67^{j}	97.30^{b-e}	4.27^{b-g}	29.70^{p-t}	7909.17^{a}	27.58^{l-p}	72.6^{i-l}	27.00^{l-q}	14.35^{bc}	2089.17^{p-s}
DWLRC192060	95.0^{f-j}	65.83^{c-f}	29.17^{hij}	95.50^{cde}	4.40^{a-e}	33.93^{n-q}	6596.25^{a-j}	26.3^{m-p}	73.65^{g-k}	28.67^{i-p}	13.28^{d-k}	2075.83^{p-s}
DWLRC192039	90.5^{l-o}	61.33^{k-n}	29.17^{hij}	100.03^{bc}	3.73^{d-j}	29.20^{p-t}	7518.17^{abc}	25.6^{nop}	70.67^{l}	27.33^{l-q}	13.55^{c-j}	2012.50^{qrs}
DWLRC192092	98.83^{a-e}	64.83^{d-g}	34.00^{a-e}	96.37^{b-e}	4.80^{ab}	27.80^{q-t}	6727.50^{a-j}	26.4^{m-p}	71.47^{jkl}	28.33^{i-p}	15.08^{ab}	1975.00^{q-t}
DWLRC192016	97.5^{b-g}	68.00^{abc}	29.50^{f-i}	108.13^{a}	4.16^{b-i}	36.43^{l-o}	6898.75^{a-i}	26.03^{nop}	71.48^{jkl}	28.00^{j-p}	12.43^{k-q}	1943.33^{q-t}
DWLRC192028	94.33^{g-l}	64.67^{e-h}	29.67^{f-i}	99.30^{bcd}	4.27^{b-g}	30.80^{o-s}	6423.17^{a-k}	24.82^{op}	72.80^{h-l}	29.67^{i-o}	12.77^{h-p}	1869.17^{rst}
DWLRC192096	98.83^{a-e}	68.50^{ab}	30.33^{d-i}	86.53^{fg}	4.70^{abc}	29.53^{p-t}	5482.67^{ijk}	25.93^{nop}	71.63^{jkl}	31.33^{e-l}	12.42^{k-q}	1770.83st
DWLRC192094	94.67^{g-k}	64.00^{e-i}	30.67^{d-i}	92.60^{e}	5.23^{a}	27.53^{rst}	6276.67^{b-k}	22.68^{p}	72.02^{jkl}	24.67^{pq}	15.80^{a}	1592.50^{tu}
DWLRC192089	98.83^{a-e}	68.00^{abc}	30.83^{c-i}	86.67^{fg}	4.20^{b-h}	24.43^{t}	5809.0^{f-k}	24.796^{op}	72.63^{i-l}	26.33^{n-q}	14.13^{cde}	1583.33^{tu}
DWLRC192088	91.67^{j-n}	62.33^{h-l}	29.33^{g-j}	98.1^{bcd}	4.33^{b-f}	34.97^{m-p}	4977.67^{k}	25.10^{nop}	68.13^{m}	24.67^{pq}	15.12^{ab}	1336.67^{u}
DWLRC192079	98.50^{a-f}	69.0^{a}	29.50^{f-i}	87.23^{f}	3.63^{e-j}	24.80st	5356.08^{ijk}	24.056^{op}	67.97^{m}	23.67^{q}	12.38^{k-q}	1234.17^{u}

Mean values followed by similar letter(s) in each column are not significantly different each other using DMRT (5%) = Duncan's New Multiple Range Test at P< 0.05.Days to heading(DTH), Days to 90% maturity(DTM), Days to grain filling period (GFP), Plant height (PHT), Number of tillers per plant(NTP), thousand kernel weights (TKW), Hectoliter weight (HLW), Grain yield (GY, kg/ha), Number of grain per spike (NGS). Biomass yield (BY, kg/ha), Harvest index (HI, %), Grain protein content (GP, %)

3.3. AMMI Analysis

AMMI analysis revealed highly significant effects of environments, genotypes, and their interactions on grain yield ($P < 0.001$). Similarly, Mullualem et al. (2024) reported significant affected effects of environment, genotype, and Genotype × Environment interaction on bread wheat grain yield. The environment accounted for the largest amount of the total sum of squares (43.5%), followed by genotype (31.4%) and GEI (9.1%). Similarly, as found by Mohammadi et al. (2018), the environment contributes the most variance to total variation in durum wheat tested genotypes, followed by genotype and GE interaction. Genotypic main effect accounted for 1.4% and the residual variance. Considering the multiplicative component of AMMI, the sum of squares due to the GEI is further separated into two significant Interaction Principal Components (PC-1 and PC-2), as shown in Table 4. The first IPCAs accounted for the largest proportion of 59.8 of % interaction sum of squares, while the other IPCAs accounted for 40.2%.

AMMI 2 biplot indicated that G2, G32, G8, G44, and G48 (figure 1) were located closest to the origin. Those genotypes that are clustered closer to the center are non-sensitive to environmental interactive forces and tend to be stable. AMMI 2 biplot indicated that G29, G46, G34, and G35 were located farthest from the origin of the biplot which indicated the most responsive (interactive) genotypes and most sensitive to the environment, contributed the highest interaction effects and unstable in yield (Alemu et al., 2021). Some studies have been undertaken in order to evaluate wheat genotypes using AMMI biplot for different agro ecological environments (Singh et al., 2019; Alemu et al., 2021; Gupta et al., 2022; Megerssa et al., 2024).

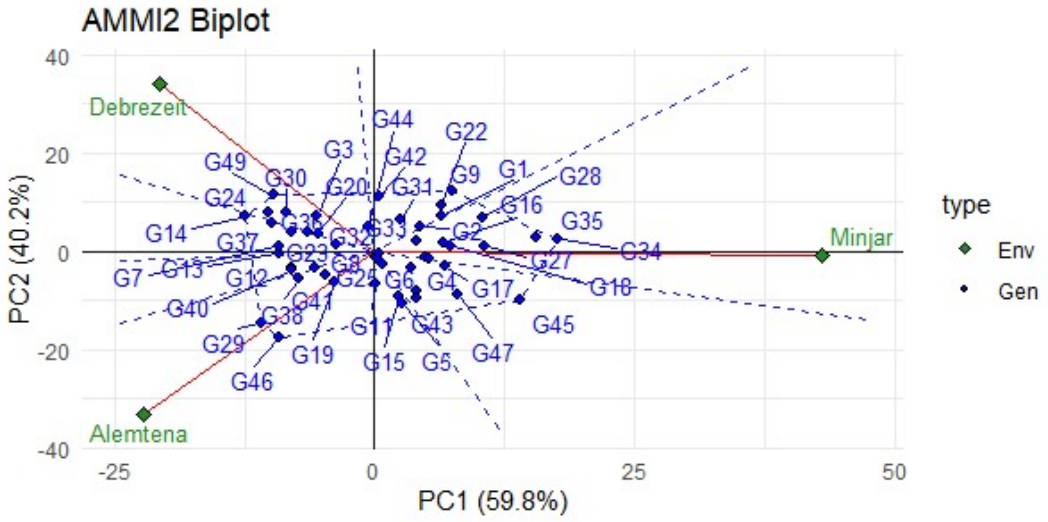

Figure 1 AMMI-biplot of 49 durum wheat genotypes

Table 4. Additive Main effect and Multiplicative Interaction (AMMI) analysis of variance over the environments.

Source	Df	Sum Square	Mean Square	Explained %
ENV	2	1.18E+08	59133463**	
REP(ENV)	3	1647823	549274.3**	
GEN	48	85368391	1778508**	
GEN:ENV	96	25755775	268289.3**	
PC1	49	15405844	314405**	59.8

PC2	47	10349931	220211.3**	40.2
Residuals	144	14530052	100903.1	

** is 0.01 levels of probability

3.4. Stability analysis

3.4.1. AMMI Stability Value

This stability measure indicates that the genotype with the lowest ASV score is the most stable, whereas the genotype with the highest ASV and rank indicates unstable yield in various circumstances. Table 5 shows the AMMI model IPCA1 and IPCA2 grain yield scores for each durum wheat Genotypes, as well as the related AMMI stability value (ASV).Low AMMI stability values were obtained for the Alemtena, Denbi, and Mangudo genotypes, as well as DWNL19209. This result revealed that they were the most stable and high-yield varieties. Genotype DWNL19208 had a high seed yield with moderate satiability. And high ASV was recorded for genotype Cocorit, DWLRC192085, DWNE192011, DWNL192011. This suggests that those varieties were unstable. Delesa et al. (2022); Bayissa et al. (2023); Mullualem et al. (2024) used the AMMI stability value to assess wheat genotype stability across various agro-ecological conditions.

3.4.2. Shukla's Stability Variance

Mangudo, Denbi, Alemtena, and DWNL19209 table 5 genotypes had a high yield, with the lowest ssiShukaVar making them the best overall. The presence of ssiShukaVar indicates the maximum stability over time and the least genotype-environment interaction. DWLRC192088 and DWNE192013 were the most unstable genotypes. Genotype DWNE19209 has the greatest mean but the least stability, therefore it may be a good choice if stability isn't important and the genotype is chosen for a certain environmental condition. Shukla's stability variance is also used in Wardofa and Ararsa's (2020) study to assess wheat genotype stability in various agro ecological conditions.

3.4.3. Wricke's Eco-valence Analysis (W2i)

Lower values of W2i indicate smaller variations in different situations, while higher values of W2i indicate more instability and fluctuation. Stability analysis in the performance of genotypes across environments using Wricke's ecovalence (Wi) showed that DWNL19209, Mangudo, Alemtena, and Denbi were more stable in grain yield and had the least contributions to the GXE interaction sum of squares (Table 5). Fetan, DWNE19209, and Werer had high seed yield with moderate stability. In this study, DWLRC192020, DWLRC192079, DWLRC192088, DWLRC192089, DWLRC192092, DWLRC192094, and DWLRC192096 had high Wi ecovalance. This suggests that there were unstable genotypes that contributed high GEI to the sum of squares based on the eco-valence method. Some studies have been undertaken to evaluate bread wheat genotypes' stability across different agroecological environments using Wricke's Eco-valence Analysis (Wardofa and Ararsa, 2020).

3.4.4. Lin and Binns Superiority Measure

Stable genotypes are those with the lowest Pi value. The genotypes Mangudo, followed by DWNL19209, Alemtena, and Denbi, had lower Lin and Binns' genotype performance measures, indicating that they were stable and performed well. Genotypes DWLRC192079 and DWLRC192088 were higher than Lin and Binns's, and this suggested the most unstable genotype coupled with the lowest grain yield. Similarly, Wardofa and Ararsa (2020) studied bread wheat genotype stability across diverse agroecological conditions using the Lin and Binns Superiority Measure.

3.4.5. Coefficient of Variation Stability Parameter

In this study, genotypes DWNE192011, DWNL19209, Alemtena, denbi, and Mangudo had the lowest CV with the highest mean grain yield. According to this stability parameter, this indicates that they have low variability across the locations, the most stable, widely adapted genotypes with the most overall seed yield performance. Furthermore, genotypes DWLRC192020 and DWLRC192088 are stable, with yields lower than the average grain yield. However, the genotypes DWLRC192089,

DWLRC192094, and DWNE192013 had more coefficient of variability and narrowly adapted genotypes. Wardofa and Ararsa (2020) studied wheat genotype stability across different agroecological environments using the coefficient of variation stability parameter.

3.4.5. Stability Analysis According to Eberhart and Russell (1966)

The regression-based stability parameters for analyzing genotypes across environments revealed that regression coefficients (bi values) range from 0.126 to 1.637. The varieties, viz. Mangudo, Alemtena, DWNE2011, DWNL19209, and denbi have a regression coefficient lower than 1 and a higher grain yield than the grand mean, are stable, and have good overall performance. In addition, varieties Mangudo, followed by Alemtena, have the most consistent performance due to low RMSE, and it is the most stable, indicating they are adapted well to all environments (wider adaptation over different environments). Also, genotype DWNL19209, Mekuye, had a regression coefficient lower than 1, a higher grain yield than the grand mean, and moderate stability across environments. Genotypes DWNL19208 and Fetan have a regression coefficient greater than 1 and a higher grain yield than the grand mean, and they are unstable and adapted to narrow environments. In the same way, Gupta et al. (2022); Delesa et al. (2022) evaluate wheat genotypes across agro-ecological environments to study genotype stability using regression-based stability parameters.

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Entry№	GEN	Yield(kg/ha	PC1	PC2	CV	Shukla	Wi_g	Ecoval	ASV	Pi_a
1	Alemtena	3017.5	6.37	7.28	25.6	27561.3	102.7	116695.92	6.127	221427.1
2	Bekelcha	3105	4.97	-1.21	27.1	176935	95.13	689804.59	15.8	210271.9
3	Cocorit	2740.8	0.08	-6.55	45.5	351896	67.17	1361082.31	23.18	554543.8
4	D18	2973.3	-7.99	-3.25	34	56110.5	105	226231.80	7.486	263905.2
5	Denbi	3218.3	-9.12	-0.37	30.4	76788.2	114	305566.50	1.602	132055.2
6	DWLRC1920 34	2245.8	-12.43	7.2	32.9	101.35	81.64	11339.46	11.22	1009090
7	DWLRC1920 84	2120	2.28	-9.2	31.2	127771	66.03	501172.96	9.294	1235680
8	DWLRC192016	1943.3	6.66	1.94	29.5	59750.4	69.25	240197.11	21.76	1498043
9	DWLRC192020	2089.2	6.7	-3.07	7.65	419424	45.48	1620168.03	10.08	1363615
10	DWLRC192025	2470	7.36	1.07	27.8	98598.7	79.17	389247.45	5.635	747219.8
11	DWLRC192028	1869.2	-3.86	-6.16	40.6	19150.7	53.69	84426.70	6.551	1619442
12	DWLRC192039	2012.5	4.33	5.07	30.1	48029.8	71.66	195228.06	8.887	1380558
13	DWLRC192048	2326.7	-5.46	3.59	34.5	55577.8	75.84	224187.93	9.801	913321.9
14	DWLRC192060	2075.8	0.8	-2.53	29.5	104935	67.15	413559.35	8.528	1296502
15	DWLRC192079	1234.2	6.41	9.36	44.4	56754.7	31.43	228703.23	5.119	2970265
16	DWLRC192085	2202.5	-5.81	-3.41	41.4	27755.8	62.12	117442.35	22.13	1082708
17	DWLRC192088	1336.7	-10.13	8.03	7.83	478777	29.4	1847890.99	14.83	2852139
18	DWLRC192089	1583.3	0.03	-1.21	50.8	182880	31.55	712614.46	12.4	2230211
19	DWLRC192092	1975	3.46	-3.33	27.3	105008	65.82	413838.27	0.706	1456714
20	DWLRC192094	1592.5	10.55	1.03	48.5	-2425.3	34.79	1645.41	10.32	2150015
21	DWLRC192096	1770.8	10.32	6.97	45.7	75574.8	42	300910.88	8.43	1818094
22	DWNE192010	2700	-10.86	14.56	19.4	63781.1	83.66	255661.73	13.58	482461.5
23	DWNE192011	3098.3	-5.51	7.37	20.7	117700	91.32	462535.37	26.28	192980.2
24	DWNE192013	2790	-8.54	7.77	46.8	451223	65.09	1742173.98	12.08	543511.5
25	DWNE19207	2510.8	2.52	6.48	19.6	108298	76.18	426462.42	15.74	695068.8
26	DWNE19208	2918.3	0.37	-0.44	36.6	159521	92.22	622990.48	16.44	340146.9
27	DWNE19209	3320	4.03	2.29	38.3	252756	104.2	980707.65	10.43	153071.9
28	DWNL192010	2513.3	17.58	2.46	34.6	73201	81.97	291803.23	14.9	692536.5

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29	DWNL192011	3017.5	15.47	2.7	30.4	174362	95.06	679933.16	22.95	264364.6
30	DWNL192012	2376.7	-6.36	4.09	42	392679	58.17	1517556.29	2.79	963909.4
31	DWNL192018	2615	-9.92	5.62	27.7	5628.97	95.46	32547.45	7.949	554734.4
32	DWNL192019	2292.5	-7.24	-5.45	37.5	39757.2	72.12	163488.27	11.95	960306.3
33	DWNL19202	2995.8	-7.99	4.13	37.2	118702	97.19	466380.27	11.45	271852.1
34	DWNL19204	2626.7	4	-8.12	22.8	144067	77.53	563698.64	11.11	584517.7
35	DWNL19208	3024.2	-7.95	-3.73	36.9	143253	96.96	560573.64	11.02	258420.8
36	DWNL19209	3191.7	-4.75	-4.77	29	105432	107	415466.50	1.211	146676
37	DWNL9	2746.7	0.49	11.09	27.1	-1115.8	100.4	6669.56	11	422903.1
38	Fetan	3193.3	3.98	-9.53	37.6	208688	101.5	811630.78	16.86	190630.2
39	Filakit	2664.2	-0.63	5.03	39	290192	73.16	1124339.97	18.48	593679.2
40	Gerardo	2567.5	13.93	-9.84	36.1	26846.4	85.61	113953.06	6.418	617177.1
41	Hitosa	3111.7	-9.17	17.42	28.7	282019	90.3	1092982.31	19.85	238980.2
42	Mangudo	3417.5	7.98	-8.88	16.2	102138	94.63	402828.06	12.34	57354.17
43	Mekuye	2726.7	5.23	-1.59	31.6	34606	96.32	143724.66	7.494	456626
44	Tesfaye	2619.2	-9.73	11.47	37.5	65681.1	83.22	262951.70	10.09	575997.9
45	Toltu	135.8	2.7	-10.73	25.5	109730	99.35	431953.74	12.59	172743.8
46	Ude	2935.8	0.27	-1.55	23.6	119888	89.73	470928.74	13.67	299768.8
47	Utuba	3178.3	-9.15	1.15	29	221999	97.06	862700.17	17.08	187180.2
48	Werer	3108.3	-3.64	1.54	37.7	160367	99.4	626237.42	13.36	217096.9
49	Yerer	2466.7	7.41	12.19	40.9	54731.8	71.48	220942.01	8.2	743411.5

90

4. Conclusion

In general, the current scientific studies conducted at Alemtena, Debrezeit, and Minjar can lead to the following conclusions:

1) Combined analysis of three locations for 14 parameters revealed that significant difference ($p<0.01$) for location and genotype GEI for most of the traits. The observed significance differences among genotypes for the traits under study generally indicated the presence of genetic variations among the genotypes, and genotypes react differently depending on the tested environmental conditions.

2) From the combined analysis, Mangudo, DWNE19209 Denbi, Fetan, and DWNL19209 give high seed yield with no significance among. The highest mean value of oil content was observed for accession 28326 (53.5%). Genotypes DWLRC192094, DWLRC192092, and DWLRC192088 had the highest mean value of grain protein content.2) AMMI analysis revealed highly significant effects of environments, genotypes, and their interactions on grain yield. Only two Principal Components (PC-1 to PC-2) IPCAs interaction significantly contribute to the total sum of the squares. AMMI 2 biplot indicated that G2, G32, and G8 were non-sensitive to environmental interactive forces and tend to be stable.

3) Variety Alemtena, Denbi, Mangudo, and genotypes, DWNL19209, show high stability with high seed yield using all stability analyses conducted in this study. So, variety should be considered for selection for wide or broad adaptability.

Overall, this study provides foundations for additional studies in the future. Because yield is a polygenic trait influenced by a variety of environmental conditions, future research could focus on the current outcome to validate and generalize the study's findings.

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Competing Interest

The authors declare that they have no known competing financial interests.

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