International Journal of Bio-resource and Stress Management https://ojs.pphouse.org/index.php/IJBSM

Crossref

IJBSM March 2025, 16(3): 01-11

Article AR5918

Research Article

Natural Resource Management

DOI: HTTPS://DOI.ORG/10.23910/1.2025.5918

BLUP and Stability Analysis of Multi-environment Trials in Bread Wheat (*Triticum aestivum* L.) Genotypes under High Rainfall Conditions of Ethiopia

Alemu Dabi[1], Ruth Duga[1], Berhanu Sime[1], Gadisa Alemu[1], Demeke Zewdu[1], Negash Geleta[1], Tafesse Solomon[1], Abebe Delessa[1], Habtemariam Zegaye[1], Dawit Asnake[1], Bayisa Asefa[1], Abebe Getamesay[1], Tilahun Bayisa[2], Endashaw Girma[3], Ayele Badebo[4] and Bekele Abeyo[4]

[1]Ethiopian Institute of Agricultural Research, Kulumsa Agricultural Research Center, Asella, Ethiopia
[2]Oromia Agricultural Research Institute, Sinana Agricultural Research Center, Bale-Robe, Ethiopia
[3]Ethiopian Institute of Agricultural Research, Holeta Agricultural Research Center, Holeta, Ethiopia
[4]CIMMYT Ethiopia office, Addis Ababa, Ethiopia

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Corresponding alemudabi2009@gmail.com

0009-0006-1676-8294

ABSTRACT

The experiment was conducted from June, 2020 to December, 2022 at Bekoji, Chefe Donsa, Debre Markos, Enewari, Gonder, Holeta, Kofele, Kulumsa, Robe Arsi and Sinana in Ethiopia to identify stable and high-yielding wheat genotypes resistant to stem and yellow rust disease. The study evaluated the performance of bread wheat genotypes across 21 high land environments in Ethiopia. Agronomic and quality traits, including days to heading, maturity, plant height, grain yield, hectoliter weight, thousand kernel weight, and disease resistance (stem rust and yellow rust), were recorded for each genotype in all environments. The results showed that the genotypes EBW182767 and EBW192345 were the top-yielding and stable genotypes across the 21 environments. These genotypes not only yielded significantly more than the standard checks, Boru and Danda'a but also demonstrated strong resistance to yellow and stem rust. EBW182767 outperformed the standard check Boru and Danda'a in terms of yield by 30.5% and 58.1%, respectively. Similarly, the second genotype EBW192345 was also produced a 25.4% and 51.9% yield advantage over the standard check (Boru) and (Danda'a), respectively. Because of their great performance and disease resistance, EBW182767 (named "Melka") and EBW192345 (named "Gutu") were released as new commercial varieties in 2024. These varieties can be used to create even better wheat varieties in the future and are also suitable for large-scale wheat farming in highland areas of Ethiopia.

KEYWORDS: Genotype×environment interaction, stability, *Triticum aestivum*, highland

***Citation* (VANCOUVER):** Dabi et al., BLUP and Stability Analysis of Multi-environment Trials in Bread Wheat (*Triticum aestivum* L.) Genotypes under High Rainfall Conditions of Ethiopia. *International Journal of Bio-resource and Stress Management,* 2025; 16(3), 01-11. HTTPS://DOI.ORG/10.23910/1.2025.5918.

Data Availability Statement: Legal restrictions are imposed on the public sharing of raw data. However, authors have full right to transfer or share the data in raw form upon request subject to either meeting the conditions of the original consents and the original research study. Further, access of data needs to meet whether the user complies with the ethical and legal obligations as data controllers to allow for secondary use of the data outside of the original study.

Conflict of interests: The authors have declared that no conflict of interest exists.

RECEIVED on 07th November 2024 RECEIVED in revised form on 19th February 2025 ACCEPTED in final form on 02nd March 2025 PUBLISHED on 10th March 2025

1. INTRODUCTION

Wheat (*Triticum* spp L.) is the most important cereal crop cultivated worldwide. In Ethiopia, wheat is the top priority food, cultivated on 2.6 million ha of land under rain-fed and irrigated systems, and with an annual total production of 8.2 mt in 2022. Ethiopia achieved 100% wheat self-sufficiency with a surplus of more than 1 mt for export, indicating that the new irrigated wheat initiative was found to be transformational and a game changer (Anonymous, 2021; Effa et al., 2023; Silva et al., 2023). Wheat production increasing, on average, by 6.2% per annum in Ethiopia (Alemu, 2024). Rosegrant and Agcaoili (2010) reported that the demand for wheat in the developing world is projected to increase by 60% by 2050. The Ethiopian government is attempting to enhance production through land expansion, agro-clustering of wheat farmers, and expansion of irrigation to lowlands areas of Ethiopia (Tadesse et al., 2022; Senbeta and Worku, 2023).

Wheat productivity is affected by complex and interwoven biophysical and socio-economic challenges (Nigus et al., 2022; Semahegn et al., 2021; Alemayehu et al., 2024). Wheat productivity has consistently remained low, and food production has lagged behind population growth for a long time (Reynolds and Braun, 2022; Hodson et al., 2020; Shiferaw et al., 2014). According to numerous studies (Tadesse et al., 2022; Negash et al., 2022; Badebo et al., 2008), the productivity of wheat in Ethiopia is significantly impacted by both biotic and abiotic factors. Wheat diseases, including rusts (YR, and SR), Septoria tritici blotch (Sep) and Fusarium head blight (FHB), are significant contributors to yield losses in wheat production. Globally, all three wheat rusts i.e., stripe rust (leaf rust, stem rust, and other foliar diseases, affect wheat production (Shafi et al., 2022). Approximately 8.5% to 19.8% of the global wheat yield is compromised annually due to prevalent diseases, including stripe rust, leaf rust, stem rust, and powdery mildew (Chai et al., 2022; Savary et al., 2019). Yellow Rust can lead to yield losses ranging from 10% to 60%, depending on the wheat variety and environmental factors (Xinli et al., 2021; Chen et al., 2020; Wellings, 2011). In severe cases, both stem and yellow rusts losses can reach 100% on susceptible wheat cultivars (Ali et al., 2014; Prank et al., 2019). The prevalence of yellow and stem rusts in East Africa, especially Ethiopia, poses a significant risk to wheat yields. These diseases can cause up to 100% yield loss if not controlled effectively. The rapid emergence of new pathogen races has compromised the durability of many high-yielding, disease-resistant varieties (e.g. Kubsa, Digelu, Ogolcho). This poses a significant challenge to breeding programs aimed at developing stable, high yielding, and disease-resistant wheat varieties (Meyer et al., 2021). Therefore, major research efforts are required to safeguard wheat production against biotic and abiotic stresses.

Ethiopia's wheat breeding program aims to develop new technologies to enhance production and productivity. As a result during the last 70 years more than 120 bread wheat varieties were released/registered. The wider adaptation of varieties for national release across a range of eco-geographical environments is confirmed by multi-location evaluation which involved a number of federal and regional research centers and higher learning institutions (Negash et al., 2022) Evaluation of different genotypes in multi-environments is important to identify the adapted and stable genotypes under target environments (Yan, 2001; Yan and Kang, 2003). A genotype is considered stable if it is adapted for a trait of economic importance across diverse environments. The objective of this study was to evaluate genotypes, and their (G×E) interaction and identify stable genotypes for grain yields in the test environments of Ethiopia.

2. MATERIALS AND METHODS

2.1. *Experimental sites description*

The experiment was conducted at 11 locations for three years from June, 2020 to December, 2022 and the trials were planted at, Bekoji, Chefe Donsa, Debre Markos, Enewari, Gonder, Holeta, Kofele, Kulumsa, Robe Arsi and Sinana Agricultural research sites in Ethiopia. A description of the study sites, number of test genotypes, and environments are given below.

Table 1: List of testing locations and their descriptions

Site	Altitude (m.a.s.l)	Latitude	Longitude
Bekoji	2780	07°32'37"N	39o15'21"E
Chefe Donsa	2444	8°57'60"N	39°06'28"E
Debre Markos	2450	10° 19'59"N	37°44'53"E
Enewari	2650	9°53'0.0"N	39°09'00.0"E
Holeta	2400	09°03'41"N	38°30'44"E
Kofele	2695	7°00'N	38°45"E
Kulumsa	2200	08°01'10"N	39°09'11"E
Robe Arsi	2420	07°53'02"N	39°37'40"E
Sinana	2450	7°7'N	39°49'E

2.2. *Experimental design and field management*

A study was done using bread wheat genotypes to assess how the interaction between genetic factors and environmental conditions influences the grain yield of bread wheat varieties. Twelve promising bread wheat breeding genotypes and standard check varieties were tested across three growing

Table 2: List of test genotypes

Genotype	Pedigree	Source
EBW192345	KENYA SUNBIRD/2*KACHU/3/SWSR22T.B./2*BLOUK #1//WBLL1*2/KURUKU	CIM-MYT
EBW182767	MANKU/3/MUU/FRNCLN//FRANCOLIN #1	CIM-MYT
EBW192022	W15.92/4/PASTOR//HXL7573/2*BAU/3/WBLL1	CIM-MYT
EBW192387	KACHU/DANPHE/3/KACHU//KIRITATI/2*TRCH	CIM-MYT
EBW182981	SUP152/BAJ #1//KFA/2*KACHU	CIM-MYT
EBW192874	MUTUS/AKURI//SUP152/BAJ #1	CIM-MYT
Boru	SAUAL/MUTUS/6/CNO79//PF70354/MUS/3/PASTOR/4/BAV92*2/5/FH6-1-7/7/CNO79//PF70354/MUS/3/PASTOR/4/BAV92*2/5/FH6-1-7	Released Variety
EBW192873	MUTUS/ROLF07//MUCUY	CIM-MYT
EBW192140	SAUAL/3/ACHTAR*3//KANZ/KS85-8-4/4/SAUAL*2/5/MUTUS/ROLF07	CIM-MYT
EBW183001	CHIPAK*2//KFA/2*KACHU	CIM-MYT
EBW182999	CHIPAK*2/3/KSW/SAUAL//SAUAL	CIM-MYT
Danda'a	KIRITATI//2*PBW65/2*SERI.1B	Released Variety

seasons (2020, 2021, and 2022) at various locations, resulting in a total of 21 experimental environments. The trials were designed using partially replicated designs with 1.5 replication for OVT and randomized complete block designs with 2 and 3 replications for PVT and NVT respectively. To account for field trends, the trials were laid out in a rectangular (square) array of plots, arranged in rows and columns for all environments, and data were sorted accordingly. The phenotypic data of test genotypes were derived from Observation Variety Trials (OVT), Preliminary Variety Trials (PVT), and National Variety Trials (NVT) conducted in consecutive years at potential environments. Each experimental unit consisted of a 3 m^2 (with 1.2 m width×2.5 m length) plot size and 1.5 m alleys between reps. Non-experimental variables such as fertilizer rates and other crop management practices were done as per the recommendations of each test location uniformly. A seed rate of 125 kg ha^{-1} was used at all locations.

2.3. Statistical analyses

The R software was used to analyze the phenotypic data. A linear mixed model analysis that integrates spatial and factor analytic (FA) models and the heritability measure was employed to account for spatial field trends and the varying nature of variance-covariance structures. While fitting a linear mixed model in this study, spatial field trends fitted for each environment to assess neighbor plot interactions. Furthermore, global variability and extraneous variation have been checked and included in the standard linear mixed model. Finally, the study data combined from multiple trials, considering their specific spatial and environmental conditions, to provide a comprehensive understanding of genetic effects on biological yield.

3. RESULTS AND DISCUSSION

3.1. Grain yield and yield components

The tested genotypes were found to be late to medium maturing, with days to 50% heading ranging from 65 (EBW183001) to 75.4 days (Danda'a) with an average value of 69.8 days (Table 3). According to Goodwin et al. (2018), plant height has a significant impact on wheat's plant architecture and yield potential. Both high and short wheat plants can cause low yields. Tall plants can result in lodging, which reduces yields directly, while short plants can crowd canopy leaves, slow photosynthetic rate, and have insufficient biomass to serve as an adequate "source" (Hedden, 2003). The study examined semi-dwarf genotypes with a mean height of 87.4 cm, ranging from 82.5 to 98.9 cm. The 1000 kernel weight ranged from 32.7 g (Danda'a) to 39.9 g (EBW182767 and EBW192345) with an average value of 36 g, while the hectoliter weight ranged from 64.3–71.7 kg hl^{-1} with the mean value of 68.7 kg hl^{-1}. Hectoliter weight was a crucial indicator of wheat flour yield potential, serving as a rough estimate for millers and producers alike. The hectoliter weight has also been positively correlated with grain yield (Iqbal et al., 2016) but greatly influenced by the environment (Joshi et al., 2018).

The study revealed significant variations in grain yield among bread wheat genotypes across test environments, suggesting that effective genotype selection may be possible. The genotypes' mean yields ranged from 3 t ha^{-1} (Danda'a)

Table 3: Mean performance of some important agronomic traits of 10 genotypes and 2 checks tested in the 2020–2022 trial season

Environment	EBW192345	Over Boru	Over Danda'a	EBW 182767	Over Boru	Over Danda'a
KF20BWOL	2.3	0.0	-34.3	3.5	52.2	0.0
KU20BWOL	2.9	-12.1	-25.6	4.0	21.2	2.6
KU20BWPL	4.0	2.6	66.7	4.5	15.4	87.5
RA20BWPL	2.6	36.8	52.9	2.4	26.3	41.2
SN20BWPL	3.2	190.9	146.2	2.0	81.8	53.8
DM21BWNL	4.4	-10.2	10.0	5.0	2.0	25.0
HL21BWNL	3.3	26.9	83.3	3.8	46.2	111.1
RA21BWNL	4.2	31.3	31.3	4.0	25.0	25.0
SN21BWNL	5.4	80.0	68.8	4.3	43.3	34.4
BE21BWNL	4.7	95.8	261.5	4.3	79.2	230.8
BE21BWPL	4.4	83.3	144.4	4.2	75.0	133.3
KF21BWPL	5.2	173.7	225.0	4.2	121.1	162.5
BE22BWNL	4.4	18.9	41.9	5.2	40.5	67.7
KF22BWNL	6.9	430.8	430.8	6.6	407.7	407.7
RA22BWNL	6.7	26.4	67.5	6.7	26.4	67.5
CD22BWNL	5.2	-3.7	4.0	5.5	1.9	10.0
DM22BWNL	4.6	-20.7	-6.1	5.9	1.7	20.4
EW22BWNL	7.1	-4.1	7.6	7.6	2.7	15.2
GD22BWNL	5.2	0.0	48.6	5.3	1.9	51.4
HL22BWNL	3.1	-18.4	47.6	4.4	15.8	109.5
KU22BWNL	5.9	7.3	110.7	6.2	12.7	121.4
Mean	4.6	25.4	51.9	4.7	30.5	58.1

DTH: Days to heading; DTM: Days to maturity; PHT: Plant height; TKW: Thousand kernel weight; HLW: Hectoliter weight

to 4.7 t ha^{-1} (EBW182767), with a mean of 3.6 across all environments. EBW182767 (4.7 t ha^{-1}) had the highest grain yield, followed by EBW192345 (4.6 t ha^{-1}). The average performance of all genotypes at EN22BWNL was higher than in the other trials. However, most genotypes performed worse in the SN20BWPL, BE21BWNL and KF22BWNL trials. Interestingly, the genotypes EBW182767 and EBW192345 consistently produced high yields, even in less favorable environments (as shown in Table 5). However, the order of the genotypes in terms of performance varies across different test environments. This suggests that the interaction between genotype and environment (GEI) was not simple and could lead to different genotypes performing better or worse in different conditions. The result was consistent with the previous reports by (Gadisa et al., 2020; Gadisa et al., 2021; Alemu et al., 2021; Alemu et al., 2023, Alemu et al., 2024) of varying genotype ranks across various environments. However, in most of the test environments, the genotypes viz. EBW182767 (melka) and EBW192345 (Gutu) were the highest-yielding and the most stable. The two genotypes had the short projection from the AEC x-axis indicating the highest mean yield and stability across test environments, because of which it was comparatively closer to the concentric circle. Therefore, the two genotypes selected as high yielding and the most stable genotypes across the testing environment compared to the other test genotypes (Figure 2 and Table 5). The genotypes EBW182767 (Melka) and EBW192345 (Gutu) consistently demonstrated a higher level of performance than the other test genotype across a majority of the experimental environments (Figure 1). The genotype EBW182767 shows a significant yield advantage over the standard check, with an overall mean of 30.5% over Boru and 58.1% over Danda'a. The genotype EBW182767 was stable and adaptable for Ethiopian highland agro ecologies. It exceeded standard checks in grain yield and

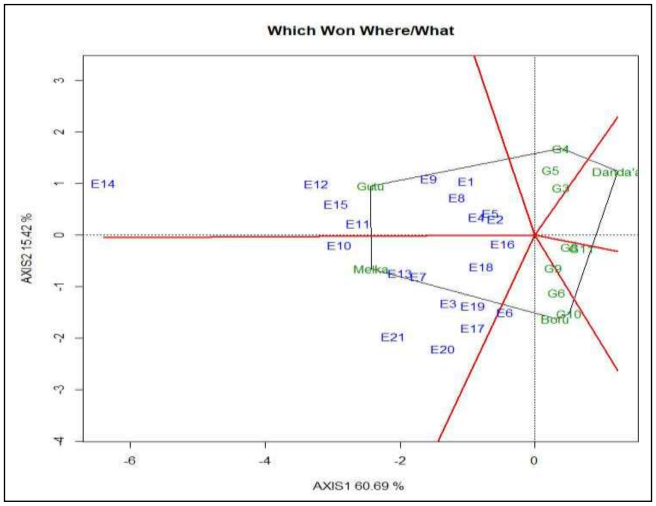

Figure 1: Which win where: GGE biplot analysis of the polygon view of the environments and genotypes for the PC1 and PC2; E1: KF20BWOL; E2: KU20BWOL; E3: KU20BWPL; E4: RA20BWPL; E5: SN20BWPL; E6: DM21BWNL; E7: HL21BWNL; E8: RA21BWNL; E9: SN21BWNL; E10: BE21BWNL; E11: BE21BWPL; E12: KF21BWPL; E13: BE22BWNL; E14: KF22BWNL; E15: RA22BWNL; E16:CD22BWNL; E17: DM22BWNL; E18: EW22BWNL; E19: GD22BWNL; E20: HL22BWNL; E21: KU22BWNL

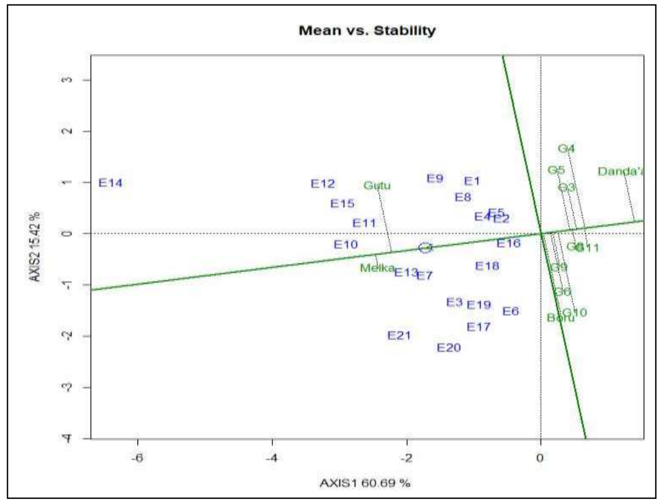

Figure 2: Mean Vs Stability: GGE biplot analysis of the polygon view of the environments and genotypes for the PC1 and PC2; E1: KF20BWOL; E2: KU20BWOL; E3: KU20BWPL; E4: RA20BWPL; E5: SN20BWPL; E6: DM21BWNL; E7: HL21BWNL; E8: RA21BWNL; E9: SN21BWNL; E10: BE21BWNL; E11: BE21BWPL; E12: KF21BWPL; E13: BE22BWNL; E14: KF22BWNL; E15: RA22BWNL; E16:CD22BWNL; E17: DM22BWNL; E18: EW22BWNL; E19: GD22BWNL; E20: HL22BWNL; E21: KU22BWNL

Table 4: Relative yield advantages of the candidates over the standard checks

Environment	EBW192345	Over Boru	Over Danda'a	EBW182767	Over Boru	Over Danda'a
KF20BWOL	2.3	0.0	-34.3	3.5	52.2	0.0
KU20BWOL	2.9	-12.1	-25.6	4.0	21.2	2.6
KU20BWPL	4.0	2.6	66.7	4.5	15.4	87.5
RA20BWPL	2.6	36.8	52.9	2.4	26.3	41.2
SN20BWPL	3.2	190.9	146.2	2.0	81.8	53.8
DM21BWNL	4.4	-10.2	10.0	5.0	2.0	25.0
HL21BWNL	3.3	26.9	83.3	3.8	46.2	111.1
RA21BWNL	4.2	31.3	31.3	4.0	25.0	25.0
SN21BWNL	5.4	80.0	68.8	4.3	43.3	34.4
BE21BWNL	4.7	95.8	261.5	4.3	79.2	230.8
BE21BWPL	4.4	83.3	144.4	4.2	75.0	133.3
KF21BWPL	5.2	173.7	225.0	4.2	121.1	162.5
BE22BWNL	4.4	18.9	41.9	5.2	40.5	67.7
KF22BWNL	6.9	430.8	430.8	6.6	407.7	407.7
RA22BWNL	6.7	26.4	67.5	6.7	26.4	67.5
CD22BWNL	5.2	-3.7	4.0	5.5	1.9	10.0
DM22BWNL	4.6	-20.7	-6.1	5.9	1.7	20.4
EW22BWNL	7.1	-4.1	7.6	7.6	2.7	15.2

Table 4: Continue...

Environment	EBW192345	Over Boru	Over Danda'a	EBW182767	Over Boru	Over Danda'a
GD22BWNL	5.2	0.0	48.6	5.3	1.9	51.4
HL22BWNL	3.1	-18.4	47.6	4.4	15.8	109.5
KU22BWNL	5.9	7.3	110.7	6.2	12.7	121.4
Mean	4.6	25.4	51.9	4.7	30.5	58.1

20BWPLRA, 21BWNLRA and 22BWNLRA = Arsi Robe, 20BWOLKU, 20BWPLKU and 22BWNLKU= Kulumsa, 21BWNLHL, 22BWNLHL= Holeta, 22BWNLGD= Gonder, 2BWNLEW=Enwari, 22BWNLCD= Chefedosa, 21BWNLBE, 22BWNLBE= Bekoji, 20BWOLKF, 21BWPLKF = Kofele, 20BWPLSN = Sinana

was more resistant to yellow and stem rust than other varieties. This offers new hope for resource-poor farmers in stem rust-prone and yellow rust-prone areas, proving the genotypes' broad adaptability. Similarly, the second genotype EBW192345 (4.6 t ha^{-1}) also produced a 25.40% and 51.9% yield advantage over the standard check (Boru) and (Danda'a), respectively (Table 4). It was also a stable and adaptable wheat genotype for different bread wheat-growing highland agro ecologies of Ethiopia (Table 5). The 'EBW192345'surpassed standard checks in terms of grain yield, proving the broad adaptability of the genotypes. Finally, because of their overall performance and disease resistance, EBW182767 (named "Melka") and EBW192345 (named "Gutu") were released as new commercial varieties in 2024. These varieties can be used to create even better wheat varieties in the future and were also suitable for large-scale wheat farming in highland areas of Ethiopia.

3.2. Genetic correlation between trials conducted across 21 environments

The effectiveness of multi-environmental breeding programs depends on the ability to evaluate the performance of genotypes across different environments. This information helps breeders identify genotypes that consistently perform well or show significant changes in ranking. The performance of genotypes in each environment was crucial for selecting genotypes for future trials or release. When trials were correlated, the ranking of genotypes tends to be similar, meaning that the top-performing genotypes in one environment often perform well in highly correlated environments (Diriba, and Mekuria, 2021). In this study, the 21 testing environments were divided into four groups based on their similarities, which were cut off at a similarity level of about 0.5. The performance of different genotypes was found to be consistent within each of these groups,

Table 5: Mean grain yield (t/ha) performance of 10 genotypes and 2 checks tested in 2020 and 2022 cropping season

Sl. No.	Genotype	KF20BWOL	KU20BWOL	KU20BWPL	RA20BWPL	SN20BWPL	DM21BWNL
1.	EBW192345	2.3	2.9	4.0	2.6	3.2	4.4
2.	EBW182767	3.5	4.0	4.5	2.4	2.0	5.0
3.	EBW192022	1.5	2.5	2.7	2.1	1.6	4.0
4.	EBW192387	2.2	2.9	2.8	2.0	2.3	3.6
5.	EBW182981	2.7	3.2	3.6	2.1	3.0	3.9
6.	EBW192874	1.5	2.6	3.9	2.1	1.5	4.9
7.	Boru	2.3	3.3	3.9	1.9	1.1	4.9
8.	EBW192873	0.5	1.8	3.8	2.4	1.7	4.4
9.	EBW192140	2.3	3.2	4.0	2.0	2.4	4.8
10.	EBW183001	0.8	2.3	3.7	1.3	3.0	5.0
11.	EBW182999	1.9	2.9	3.4	1.3	3.4	4.5
12.	Danda'a	3.5	3.9	2.4	1.7	1.3	4.0
Genotype		270.0	270.0	186	186	186	29
G. Mean		2.2	3.1	3.0	1.5	1.7	4.4
Genetic Variance		0.8	0.4	0.9	0.3	1.0	0.5
Error Variance		0.9	0.5	0.2	0.2	0.1	0.4

Table 5: Continue...

Sl. No.	Genotype	HL21BWNL	RA21BWNL	SN21BWNL	BE21BWNL	BE21BWPL	KF21BWPL
1.	EBW192345	3.3	4.2	5.4	4.7	4.4	5.2
2.	EBW182767	3.8	4.0	4.3	4.3	4.2	4.2
3.	EBW192022	2.4	3.5	4.0	2.9	3.3	3.3
4.	EBW192387	1.7	3.5	4.2	2.4	2.5	2.9
5.	EBW182981	2.0	3.7	4.3	2.3	2.0	2.2
6.	EBW192874	2.6	3.3	3.4	2.5	2.4	2.0
7.	Boru	2.6	3.2	3.0	2.4	2.4	1.9
8.	EBW192873	2.3	3.4	3.7	2.4	2.2	2.0
9.	EBW192140	2.4	3.3	3.7	2.3	2.0	1.8
10.	EBW183001	2.5	2.5	3.5	2.8	2.4	2.3
11.	EBW182999	2.2	2.8	3.8	2.4	2.1	2.2
12.	Danda'a	1.8	3.2	3.2	1.3	1.8	1.6
Genotype		29	29.0	29.0	29.0	125.0	125.0
G. Mean		2.3	3.3	3.8	2.5	2.2	2.3
Genetic variance		1.3	0.4	0.8	1.2	1.1	1.7
Error variance		0.2	0.5	0.3	0.1	0.1	0.8

Table 5: Continue...

Sl. No.	Genotype	BE22B-WNL	KF22B-WNL	RA22B-WNL	CD22B-WNL	DM22B-WNL	EW22B-WNL	GD22B-WNL	HL22B-WNL	KU22B-WNL
1.	EBW192345	4.4	6.9	6.7	5.2	4.6	7.1	5.2	3.1	5.9
2.	EBW182767	5.2	6.6	6.7	5.5	5.9	7.6	5.3	4.4	6.2
3.	EBW192022	3.3	1.6	4.6	5.2	4.2	6.6	4.3	2.2	3.9
4.	EBW192387	3.0	2.3	5.1	5.0	3.5	6.5	4.3	1.8	4.1
5.	EBW182981	2.8	2.6	5.5	4.8	3.4	6.8	4.5	2.1	4.7
6.	EBW192874	3.6	1.6	5.1	5.3	5.0	7.2	5.2	3.3	5.2
7.	Boru	3.7	1.3	5.3	5.4	5.8	7.4	5.2	3.8	5.5
8.	EBW192873	3.0	1.7	5.3	5.2	3.6	6.9	5.2	2.5	5.1
9.	EBW192140	3.2	2.0	5.1	5.0	4.6	7.3	5.0	3.2	5.4
10.	EBW183001	3.6	1.7	3.1	4.7	5.0	6.5	5.3	3.7	5.5
11.	EBW182999	3.1	1.7	3.2	4.5	4.5	6.4	4.7	3.0	4.9
12.	Danda'a	3.1	1.3	4.0	5.0	4.9	6.6	3.5	2.1	2.8
Genotype		50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
G. Mean		3.7	3.2	5.2	5.2	4.7	7.0	4.9	3.0	5.0
Genetic variance		0.8	4.0	1.0	0.1	1.0	0.2	0.3	0.8	0.9
Error variance		0.4	0.3	0.2	0.5	0.5	0.3	0.5	0.2	0.4

20BWPLRA, 21BWNLRA and 22BWNLRA: Arsi Robe, 20BWOLKU, 20BWPLKU and 22BWNLKU: Kulumsa, 21BWNLHL, 22BWNLHL: Holeta, 22BWNLGD: Gonder, 2BWNLEW: Enwari, 22BWNLCD: Chefedosa, 21BWNLBE, 22BWNLBE: Bekoji, 20BWOLKF, 21BWPLKF: Kofele, 20BWPLSN: Sinana

indicating that the environments in each group have similar characteristics that affect how genotypes perform. Figure 1B, a heatmap, supports these groupings by showing how the yield data varies across these groups, confirming the existence of interaction effects between environments.

Based on the dendrogram the first group consisted of 2

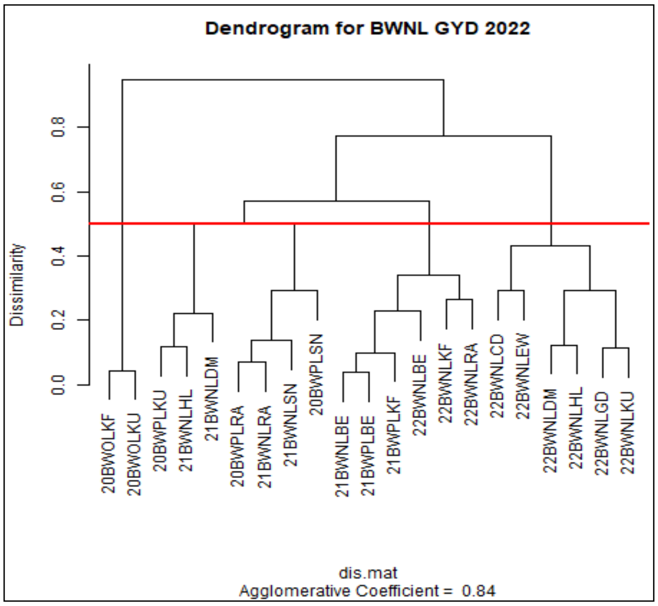

Figure 3A: Biplot Visualizations of Environment

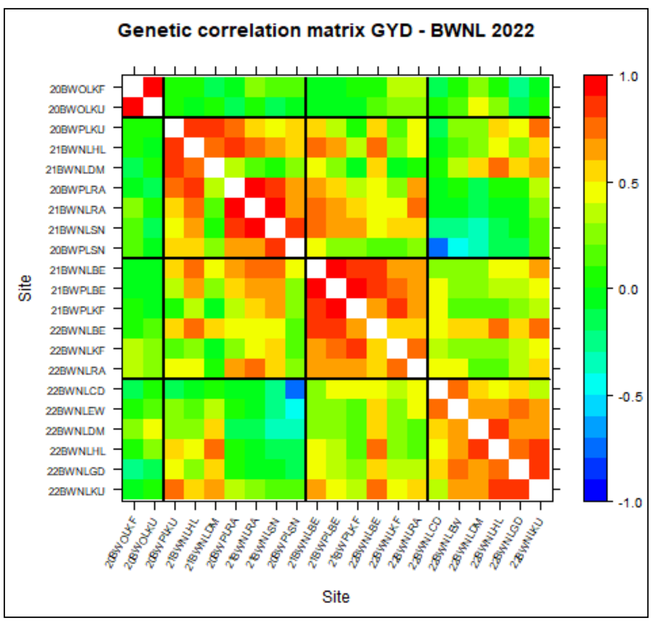

Figure 3B: Genetic correlation between trials conducted across 21 Environments

environments (20BWOLKF and 20BWOLKU). These environments showed yield performance of low to medium magnitude. The second group of environments consisted of 7 environments such as 22BWPLKU, 21BWNLHL, 21BWNLDM, 20BWPLRA, 21BWNLRA, 21BWNLSN, and 20BWPLSN. Yield performance of genotypes in the second group was relatively higher indicating the suitability of these testing sites. The third group consisted of 7 environments such as 21BWNLBE, 21BWPLBE, 21BWPLKF, 22BWNLBE, 22BWNLKF, and 22BWNLRA. These third groups of environments were more conducive to yellow rust disease occurrence than others. This negatively impacted the genotype yields, preventing them from demonstrating their full genetic potential. Consequently, these environments were not suitable for selecting yield potential but were effective for screening yellow rust resistance. However, due to their yellow rust disease resistance both genotypes BW182767 and EBW192345 scored the highest yield (table 3). The fourth group also consisted of six environments: 22BWNLCD, 22BWNLEW, 22BWNLDM, 22BWNLHL, 22BWNLGD, and 22BWNLKU. These environments, belonging to the fourth group, exhibited a lower incidence of yellow rust disease. Consequently, most genotypes demonstrated their full genetic potential. However, what's intriguing was that all environments within this group were from the same growing season, suggesting that the year itself played a significant role.

3.3. *Disease resistance*

Resistance and susceptibility were relative terms they represent a continuum on a scale. Breeders want resistance that was easy to select, minimizes yield loss, and was durable. Rust diseases of wheat were among the most important production constraints in all wheat-growing regions globally. Stem rust caused by *Puccinia graminis* f. sp. *tritici* (Pgt) and stripe rust caused by *P. striiformis* f. sp. *tritici* (Pst) can cause up to 100% yield loss on susceptible cultivars (Prank et al., 2019; Bansal et al., 2014). The recently developed bread wheat varieties were comparable to the Danda'a and Boru in terms of leaf rust disease and were only moderately better resistant to stem rust and yellow rust. The highland's current commercial bread wheat cultivars were susceptible to yellow rust. The newly released bread wheat variety with the local name EBW182767 showed a high level of yellow rust resistance with resistance and a moderately resistant response to stem rust in the face of severe stripe rust disease pressure (Table 6). Therefore, the development of new rust-resistant varieties may provide an excellent chance for producers of wheat in areas with limited resources.

The second recently developed bread wheat varieties were comparable to the Danda'a and Boru in terms of leaf rust disease and were only moderately better resistant to stem rust and yellow rust (Table 6). The highland's current commercial bread wheat cultivars were susceptible to yellow rust. The newly released bread wheat variety with the local name EBW192345 showed a high level of yellow rust resistance with resistance and a moderately resistant response to stem rust in the face of severe stripe rust disease pressure (Table 6). Therefore, the development of new rust-resistant varieties will provide an excellent chance for producers of wheat in areas with limited resources.

Table 6: Disease summary for newly released variety and checks

Diseases/ insects and other hazard	EBW 182767	EBW 192345	Boru	Danda'a
Stem rust (%+reaction)	10MRMS	10MRMS	40MS	50MS
Yellow rust (%+reaction)	5RMR-5MR	5RMR-5MR	30MSS	40MRMS
Leaf rust (%+reaction)	0	0	0	0

4. CONCLUSION

Two wheat genotypes, EBW182767 ("Melka") and EBW192345 ("Gutu"), were found to be the top-yielding and consistent across multiple locations. They significantly out yielded existing varieties (Boru and Danda'a) by 30–58%. Notably, both genotypes exhibited strong resistance to yellow and stem rust diseases. Due to their high yield and disease resistance, "Melka" and "Gutu" were officially released as new commercial bread wheat varieties in 2024 for mid to high land area of Ethiopia.

5. ACKNOWLEDGMENT

We acknowledge EIAR for their grateful role in facilitating the study, CIMMYT for providing the planting materials, and the AGGW project for providing financial support.

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