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Performances of Introduced Bread Wheat Germplasm Under Ethiopian Conditions

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Abstract

The study was conducted at Kulumsa, Sinana, Adet, Debra Zeit, and Holeta, Ethiopia from 2018 to 2021. The purpose of the study was to evaluate the introduced genotypes of CIMMYT and ICARDA for their adaptation, yield performance, disease resistance, and stress tolerance under the conditions in Ethiopia. The International wheat breeding programs of CGIAR centers played a crucial role in providing germplasm for bread wheat varietal development in Ethiopia. This germplasm helped in the development of new high-yield and resistant wheat varieties to overcome the recurring rust epidemic in the country and to rehabilitate the agricultural sector. The national wheat research program continued to support the country in releasing new varieties developed and field-tested through intensive research programs. These new varieties are generating reliable yields in different environments and showing excellent performance. The development of the varieties focused on their maturing groups (early, medium, and late), adaptability to different agroecological conditions, quality, and cultivation systems such as irrigation. To develop the resistant cultivar, over 8175 bread wheat germplasm from CIMMYT (6405) and ICARDA (170) sources were evaluated in Ethiopia since 2018, requested by the national wheat research programs, of which 1695 (26.46%) lines were selected from CIMMYT and 235 (13.28%) were selected from ICARDA. From the 8175 introduced genotypes, 1932 (23.63%) were selected and advanced to the next stage of cultivar development based on their combined disease resistance and agronomic traits.

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Introduction

Bread wheat, scientifically known as *Triticum aestivum* L., is the most commonly cultivated wheat species, accounting for up to 95% of the wheat grown around the world. It is considered a staple food for consumers globally (Dinu *et al.*, 2018; Lukaszewski *et al.*, 2014). Wheat is a primary cereal and staple crop in Africa, with increasing demand in Sub-Saharan Africa due to income growth, urbanization, and capacity for dietary diversity, as stated by Jayne *et al.*, (2010a); Negassa *et al.*, (2013) and Dessalegn *et al.*, (2014). Ethiopia cultivates wheat on a total area of 2.1 million hectares annually, producing 6.7 million tonnes, making it one of the most important food security crops in the country (Tadesse *et al.*, 2022). Cultivated grains are used in various forms such as enjera, bread, porridge, soup, and roasted cereal (Atinafu *et al.*, 2022), and as industrial raw materials like pasta and macaroni (Brasesco *et al.*, 2019; Nigussie *et al.*, 2015). Besides grain, bread wheat straw is also used for animal feed, thatched roofs, and bed covers (Anteneh and Asrat, 2020; Bledzki *et al.*, 2010). Wheat is a strategic commodity that generates farm financial gain and improves food security status (Brasesco *et al.*, 2019; Amentae *et al.*, 2017; Minot and Sawye, 2015). According to studies conducted by Rosegrant and Agcaoili (2010); Nelson *et al.*, (2010) and Shiferaw *et al.*, (2013), wheat demand will increase dramatically by 2050 in developing countries.

It is essential to accurately identify the cultivars grown by farmers for crop management, food security, and cultivar development and dissemination, among other things (Jaleta *et al.*, 2020). Several factors such as genotypes, low agricultural input utilization, environments, wheat rust, management practices, and their interactions affect bread wheat productivity (Gemechu *et al.*, 2019; Misganaw, 2017). Wheat production is on the rise, despite facing significant challenges such as ongoing disease epidemics, particularly rust and septoria (Singh *et al.*, 2008; Teferi and Gebreslassie, 2015). Increasing yield is often considered a crucial factor in ensuring food security (Bekele *et al.*, 2009; Jayne *et al.*, 2010b). Wheat breeding plays a crucial role in developing high-yielding varieties that are resistant or tolerant to pests and diseases at both international and national levels (Tadesse *et al.*, 2018). Ethiopian wheat breeding programs use techniques such as introductions and selection, hybridizations, and selection to improve wheat plants. Developing and identifying high-yielding genotypes with broad adaptation and resistance to biotic and abiotic stress is a top priority for these programs.

The rate of replacement of wheat varieties in Ethiopia is high due to the rapid breakdown of resistance to rust, specifically yellow and stem rust (Tadesse *et al.*, 2022). To combat this, development activities were carried out using imported wheat germplasm from ICARDA and CIMMYT at various sites. More than 130 varieties of wheat have been officially published by the National Variety Releasing Committee for Rain Wheat-Cultivated Areas and Irrigated Lowland Areas of Ethiopia, based on data from multiple locations. Ethiopia introduces over 2,000 genetically distinct genotypes annually from CIMMYT and ICARDA for varietal development. This work aims to evaluate the introduced genotypes of CIMMYT and ICARDA for their adaptation, yield performance, disease resistance, and stress tolerance in various environments in Ethiopia.

Materials and Methods

Germplasm Source

CIMMYT and ICARDA are the main sources of wheat germplasm for wheat development in Ethiopia. Every year, the national wheat research coordinator requests around 1500-2000 different bread wheat genotypes for evaluation in quarantine sites, obtained from both CIMMYT and ICARDA. The introduced materials are screened for rust diseases (stem, leaf, and yellow rusts), septoria, and fusarium head blight at Kulumsa, Debrezeit, Holeta, Adet, Sinana Agricultural Research Centers, and Melkasa in Ethiopia for shuttle breeding in Werer agricultural research center from 2018 to 2021. Additionally, they are assessed for any foreign pests introduced with the seeds.

After one year of evaluation and screening for diseases/ pests, the resistant materials/ good agronomic traits are advanced to the next breeding stage (observation nursery, preliminary variety trial, and national variety trials) based on the maturity groups (product concepts defined), while selecting the priority traits at each location.

Germplasm Composition

Every year, a wide range of wheat germplasms with varying genetic backgrounds are brought in from CIMMYT and ICARDA and are evaluated under Ethiopian conditions. For instance, between 2018 and 2021, 55 international wheat nurseries consisting of 6405 advanced lines were introduced from CIMMYT, while ICARDA introduced 16 nurseries with 1770 advanced lines. These nurseries were tested at various quarantine sites.

Plot size and testing sites

The seeds were thoroughly inspected for any new pests before planting them in 2-4 rows that were 20 cm apart and 2.5 meters long at the quarantine sites. Standard and local checks were included at certain intervals to ensure quality. The different genotypes were evaluated at various locations for their rust resistance, high yield potential, moisture stress, rain resistance, septoria conditions, stem rust, and yellow rust. All recommended management practices for each site were implemented to ensure the best possible results.

Data collection

All genotypes were evaluated for adaptation, including agronomic performance, disease resistance, stress tolerance, and end-use quality. Relevant data were recorded, and genotypes were selected based on the results.

Statistical analysis

The AMMI analysis was performed using the model suggested by Crossa *et al.,* (1990):

$$Y_{ij} = \mu + G_i + E_j + \sum_{n=1}^{n} \lambda_n \alpha_{in} y_{jn} + e_{ijk}$$

Where is the yield of the genotype in the environment, μ is the grand mean, is the mean of the genotype minus the grand mean, is the mean of the environment minus the grand mean, is the square root of the Eigenvalue of the principal component analysis (PCA) axis, c and are the principal component scores for PCA axis n of the genotype and environment and ϵ is the error term.

Results and Discussion

The international wheat breeding programs of CIMMYT and ICARDA are crucial in providing germplasm for the development of bread wheat varieties in Ethiopia. National wheat programs in Ethiopia have evaluated and tested this germplasm for many years. It is believed that this germplasm plays an important role in the successful release of cultivars and increases productivity.

Through intensive research programs under the National Wheat Research Program, new varieties have been developed and field-tested. These new varieties have shown excellent performance and have produced the highest yields in several environments.

To develop resistant cultivars, more than 8,175 bread wheat germplasm sources from CIMMYT and ICARDA in Ethiopia (Kulumsa, Sinana, Adet, Debra Zeit, and Holeta) have been tested since 2018. National research programs have requested these sources, from which 1695 (26.46%) lines were selected from CIMMYT and 235 (13.28%) from ICARDA. Out of the 8,175 genotypes tested, 1,932 (23.63%) were selected based on their combination of disease resistance and agronomic traits and advanced to the next stage of cultivar development. (Figure 2)

CIMMYT Germplasm Acquisitions and Evaluations in Ethiopia

In Ethiopia, most CIMMYT germplasm shows good agronomic performance, but rust and septoria are the main limiting factors. Since 2018, 55 international nurseries in Ethiopia have evaluated 6,405 introduced bread wheat genotypes from CIMMYT sources (Kulumsa, Sinana, Adet, Debra Zeit, and Holeta) requested by national wheat research programs.

Some nurseries were planted in Debra Zeit during the off-season to detect stem rust, as the incidence of stem rust was quite high during the off-season in Ethiopia, while yellow rust and septoria were more prevalent during the main season. An identical result was reported by Abeyo *et al.,* (2009).

Most of the germplasm had the best agronomic performance and thus advanced to different stages of variety testing for further testing at multiple sites. Nearly 26.46% (1,695) of the tested genotypes were promoted to the successive breeding stages (observation nursery, preliminary variety trials, and national variety trials) of respective product concepts (early, medium, and late maturity groups) through selections based on combined disease resistance (stem, leaf, yellow rust, and septoria diseases), agronomic traits (medium plant height, large spike, large seed size, etc.), and high yield potential.

From 2018-2021, the highest proportion of genotypes was maintained in 2020 (35.3%) and 2019 (31.58%), while the lowest (14.1%) was in 2018. This could be due to the recurrence of the epidemic in the first year. A total of 26.30% of bread wheat genotypes were selected from material introduced from CIMMYT in four consecutive years (Figure 3).

The number of genotypes selected does not relate to the number of entries tested under each nursery. Thus, a sizable amount of genotypes were selected from the bread wheat elite-Njoro trial and were directly included in national variety trials. These genotypes were immune to *Puccinia graminis* and showed sensible agronomical performance under Ethiopian conditions as they were specifically targeted for Ethiopia's conditions. For example, the genotypes that will be tested under a variety of verification trials in 2022 are from these trials. Therefore, despite the opportunities to introduce and evaluate nurseries with a large number of entries, the details, and genetic background must be considered to maximize the genetic gain from the selection. Well-adapted elite lines with outstanding performance have been identified and released.

AMMI Analysis

The Genotype by environment interaction (GEI) component of variation was divided into ten possible interaction principal component axes (IPCA). The first six IPCAs were found to be highly significant ($P \leq 0.001$) through an F-test and they explained 93.43% of the total GEI sum of a square.

The remaining IPCAs only explained 6.57% and were non-significant. The first two IPCAs explained 65.97% of the total GEI sum of the square. Based on prediction assessment, the AMMI model with only two IPCAs was found to be the best predictive model (Yan *et al.*, 2000).

To visualize and interpret the GEI patterns and identify genotypes or locations that exhibit low, medium, or high levels of interaction effects, an AMMI-2 biplot was generated using the first two interaction principal component axes (IPCA1 and IPCA2) (Yan, 2002). Figure 4 shows the AMMI-2 interaction bi-plot for grain yield of 25 bread wheat genotypes tested in 2018 and 2019. The AMMI-2 analysis positioned the genotypes in different locations, indicating the interaction pattern of the genotypes.

The AMMI-2 analysis for the IPCA1 captured 44.53% and the IPCA2 explained 21.44%, cumulatively capturing 65.97% of the mean sum of the square of the GEI of bread wheat genotypes. According to Purchase (1997), when the IPCA1 was plotted against IPCA2, the closer the genotypes' score to the center of the biplot, the more stable they are, and the further the genotypes' score from the center, the less stable they are. Genotypes near the origin are non-sensitive to environmental interactive forces, and those distant from the origin are sensitive and have large interactions (Samonte *et al.*, 2005).

Based on the AMMI-2 biplot, genotypes G3, G4, G13, G14, G17, and G20 are considered stable genotypes as they are not sensitive to environmental interactive forces. On the other hand, G2, G8, G9, G11 G21, G22, and G24 were highly influenced by the interactive force of the environment and sensitive to environmental changes, so these varieties are considered unstable genotypes due to the long projections from the origin (Figure 4).

ICARDA Germplasm Acquisitions and Evaluations in Ethiopia

Annually, the National Wheat Research Program requests the Dry-land Spring Bread Wheat Observation Nursery and Heat Tolerance Spring Bread Wheat Observation Nursery and Dry-land Spring Bread Wheat Yield Trial, Elite Spring Bread Wheat Yield and Heat Tolerance Spring bread wheat yield trials) with a different number of entries. Every of the observation nurseries consists of 120-200 genotypes targeted for several environments, whereas the respective yield trials consist of 48 genotypes with the two reserved for the local check commercial varieties. In Ethiopia, bread wheat has become increasingly popular in response to the introduction of improved varieties and farming practices. Each year, ICARDA provides genetically diverse bread wheat germplasm with favorable traits to improve crop growth and yield in the face of climate change in a manner that meets and is international scientific standards profitable, safe, and reliable for Ethiopian wheat improvements. Since 2018, about 1770 genotypes have been introduced and tested in the country's quarantine station, and 235 of the most effective genotypes with rust resistance, good agronomic performance, and high yield have been selected and included in the observation nursery and preliminary variety trials (Figure 5). The germplasm performed well agronomically and thus were advanced to different stages of a variety of trials for further testing at multiple locations. From 2018–2021, the highest proportion of genotypes was preserved in 2021 (21.2%) and 2020 (14%), whereas the lowest (10%) was in 2018 (Figure 5). In four years about 13.28% were selected and advanced to the next breeding stages (Figure 5). Well-adapted elite lines with outstanding performance were identified and released. Recently, the national wheat research program released one variety of wheat from ICARDA germplasm with the given name Abay, which is resistant to rust, high yielder, and has the early maturing variety to improve.

Highly significant differences among environments, genotypes, and GxE interaction explained 88.6%, 3.1%, and 8.3% total sum of squares, respectively (Table 5). The significant GE interaction sum of squares is further partitioned into four significant Interaction Principal Component Axes (IPCAs) and a residual term.

Table.1 List of test locations and their description

Locations	**Geographic positions**		**Altitude**	**Temperature (^{o}C)**		**Rainfall (mm)**
	Latitude	Longitude		Min	Max	
Adet	11°16’ N	37° 29’ E	2216	9.2	25.5	1250
Debre Zeit	08°38'08"N	38°30'15"E	2050	NA	NA	900
Holeta	09°03'414"N	38°30'436"E	2400	6.1	22.4	976
Kulumsa	08°01'10"N	39°09'11"E	2200	10.5	22.8	820
Sinana	7°N	40°E	2400	NA	NA	NA
NA: Data is not avialable						

Table.2 List of introducing entries from ICARDA and CIMMYT in the last four years

SN	*Year*	**Number of entries introduced from CIMMYT**	**Number of entries introduced from** *ICARDA*	*Total entry*	*Nursery from CIMMYT*	*Nursery from ICARDA*
1	2018	1340	470	1810	10	5
2	2019	1501	500	2001	13	4
3	2020	1793	550	2343	16	5
4	2021	1771	250	2021	16	2
	Total	6405	1770	8175	55	16

Table.3 AMMI analysis of variance for grain yield (t ha-1) of 25 genotypes tested across eight locations in 2018 and 2019

Source of variation	Df	Sum square	% explained	Mean Square	F value	Pr>F
Loc	10	2477.07	83.02	247.71***	450.89	<.001
Gen	24	93.26	3.13	3.89***		<.001
Loc x Gen	240	413.38	13.85	1.72***	7.07	<.001
PC1	33	185.53	44.53	5.62***	3.14	<.001
PC2	31	89.53	21.44	2.88***	13.88	<.001
PC3	29	39.97	9.59	1.38***	7.11	<.001
PC4	27	30.36	7.29	1.12***	2.78	<.001
PC5	25	22.84	5.48	0.91***	2.26	<.001
PC6	23	21.19	5.02	0.92***	2.28	<.001
Error	528	290.07				
Total	824	3309.12				

Table.4 AMMI analysis of variance for grain yield of 25 bread wheat genotypes evaluated across nine environments in Ethiopia in 2019 and 2020

Source of variations	**Df**	**Sum Square**	**Mean square**	**Prob**	**% Explained**
Env	8	2894.95	361.87	P<.0.001	88.55
Gen	24	102.30	4.26	P<.0.001	3.13
Gen X Gen	192	271.84	1.41	P<.0.001	8.32
PC1	31	111.97	3.61	P<.0.001	41.30
PC2	29	44.68	1.54	P<.0.001	16.48
PC3	27	41.89	1.55	P<.0.001	15.45
PC4	25	26.85	1.07	P<.0.001	9.90
Residuals	446	293.45	0.66		

Figure.1 Total selected genotypes from both CIMMYT and ICARDA since 2018

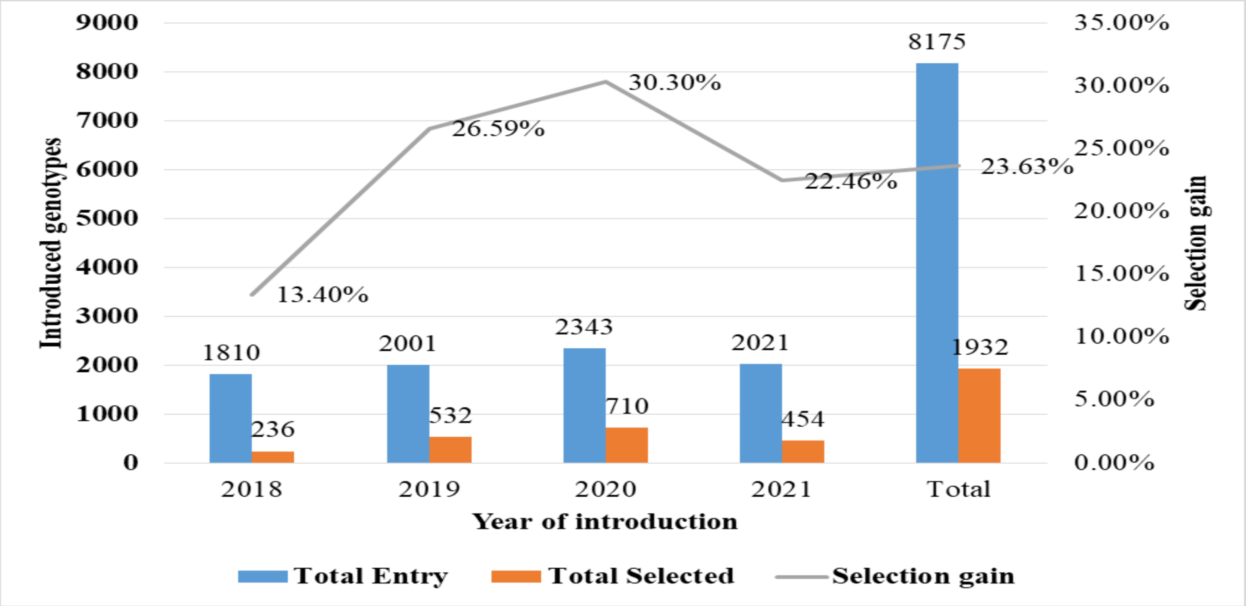


Figure.2 Selected genotypes from CIMMYT introduced materials from 2018–2021.

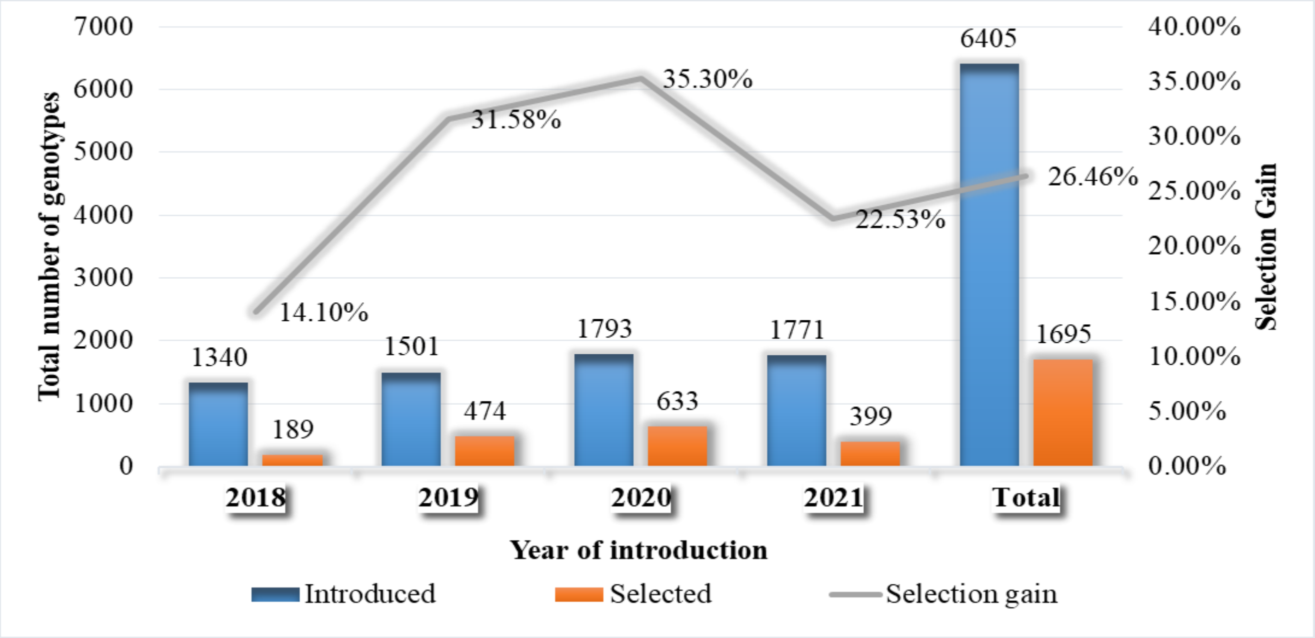


Figure.3 AMMI Biplot showing the interaction of 25 genotypes with eleven environments (note that the blue color in the biplot indicates the genotypes while the red color indicates the environments)

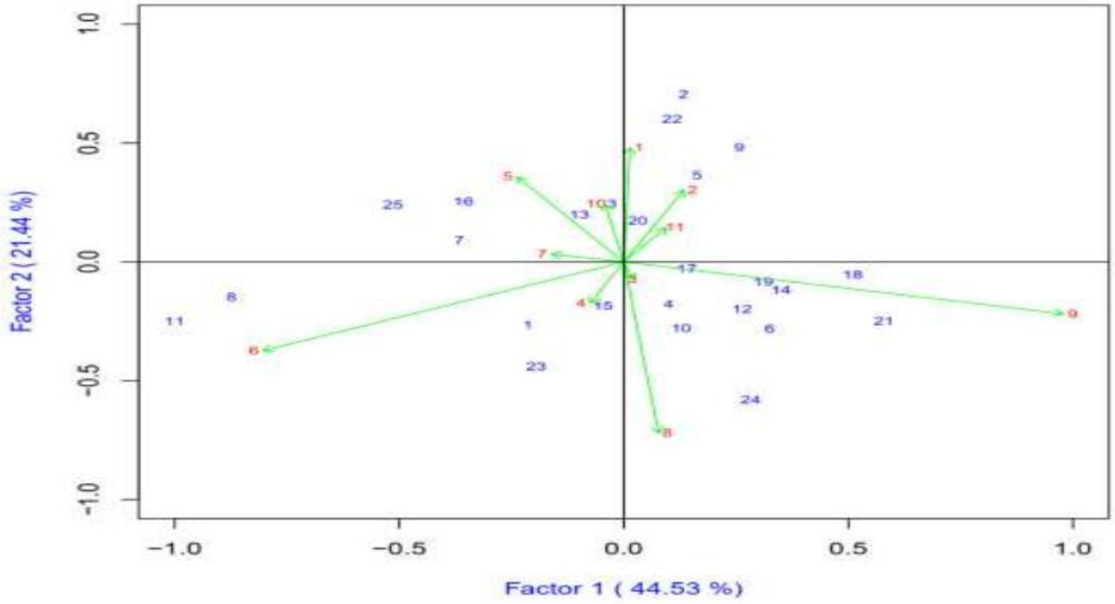


Figure.4 Selected genotypes from ICARDA-introduced materials since 2018

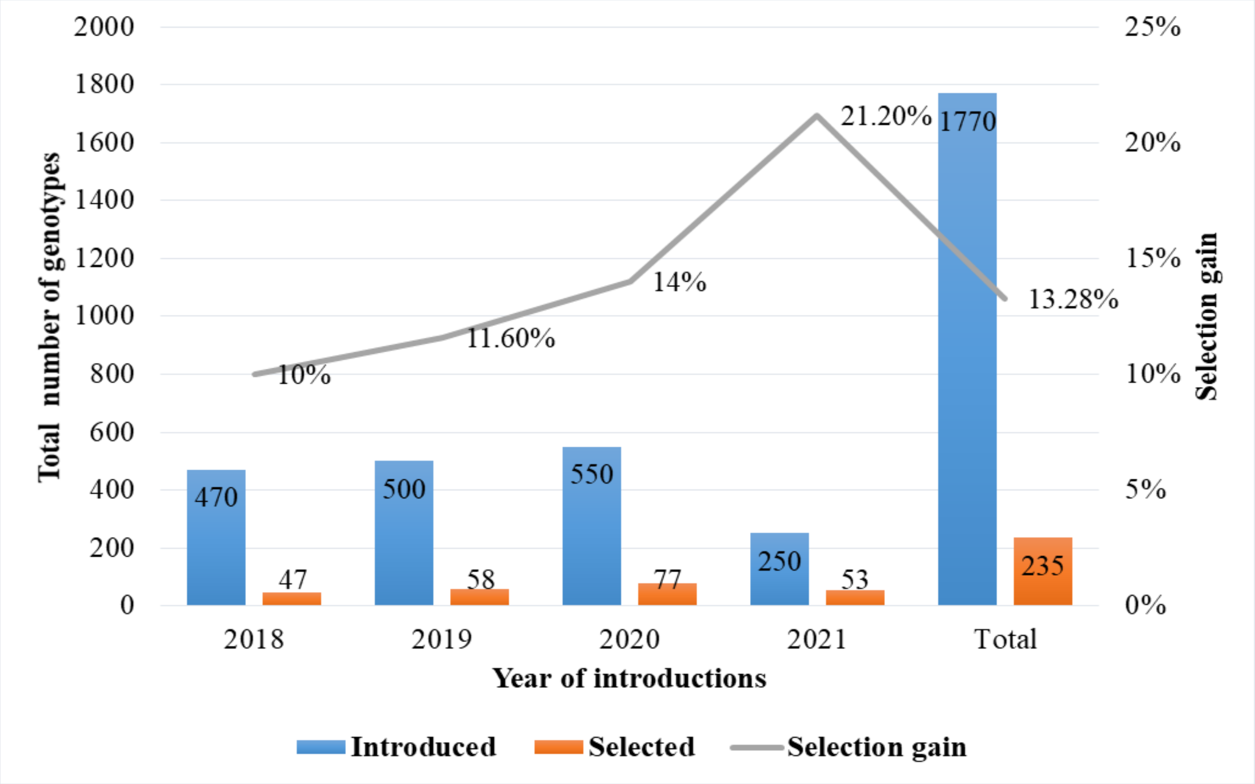
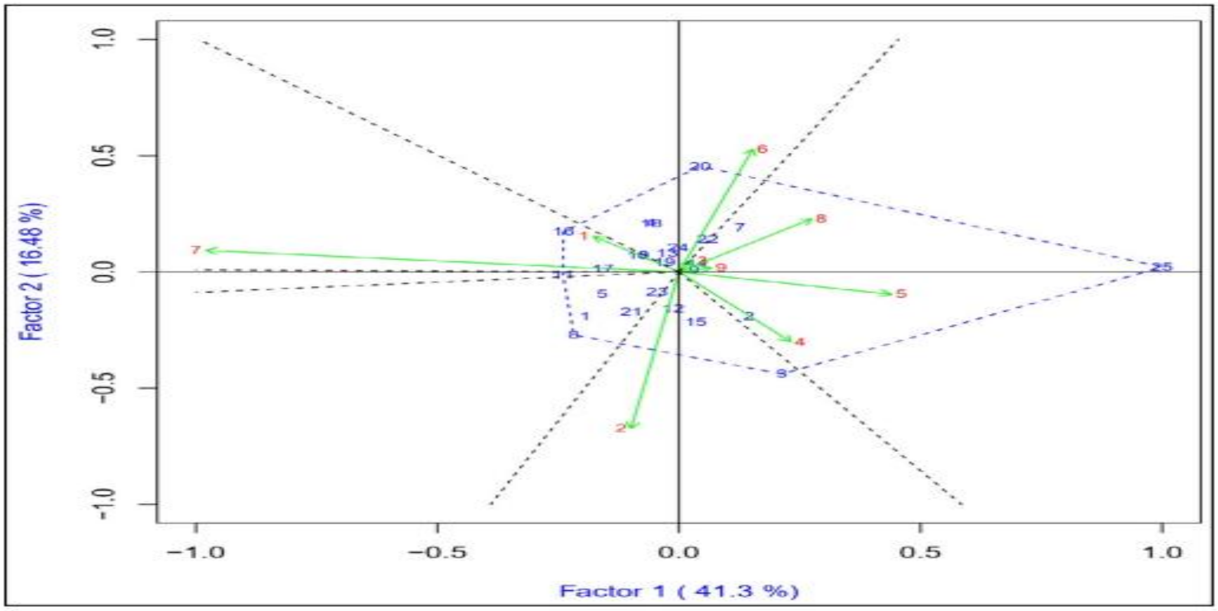


Figure.5 AMMI biplot analysis showing the mega environments and their respective high-yielding genotypes. Where, E1=Kulumsa-2018, E2=Asasa-2018, E3=Melkasa-2018, E4=Dhera-2018, E5=Atsela-2018, E6=Kulumsa-2019, E7=Asasa-2019, E8=Melkasa-2019, E9=Dhera-2019.



The first four interaction principal component analyses explained 41.3%, 16.5%, 15.5%, and 9.9% of the GE interaction variation, respectively. Similar results were reported by Golkari *et al.,* (2016) and Jeberson *et al.*, (2017) in wheat. These four IPCAs revealed an 83.1% of variation of the total sum of squares due to the interaction. The remaining 16.9% of the interaction effect is the residual, therefore, not interpreted and hence removed (Purchase *et al.*, 2000). The variation contributed by these four IPCAs showed differential performance of genotypes for grain yield across locations. However, for the confirmation of the variation revealed by GE, the first two multiplicative component axes were sufficient (Gauch, 2006), which explained 57.8% of the total GE variation among the wheat genotypes in the present study. This is due to the prominent reduction of dimensionality and graphical visualization for the adaptation of the genotypes.

AMMI 2 bi plot was generated using genotypic and environmental scores of the first two AMMI multiplicative components to cross-validate the interaction pattern of 25 bread wheat genotypes within nine environments. Figure 6 cross-validated the interaction patterns of the 25 bread wheat genotypes evaluated in nine diverse environments. The distance from the origin (0, 0) is indicative of the amount of interaction that was exhibited by genotypes either over environments or environments over genotypes (Yan and Tinker, 2006). With the current data set, genotypes ETBW9647 (20), Ogolcho (25), ETBW9119 (3), ETBW9065 (8), ETBW9080 (11), and ETBW9545 (16) exhibited a highly interactive behavior whereas Melkasa-2018 (E3) and Dhera-2019 (E9) were the least interactive of all environments against Asasa-2019 (E7) which was the most interactive of all environments.

The orthogonal projections of the genotypes over the environmental vector showed clear genotype's environment affinity. Environments within the same sector are assumed to share the same winner genotypes. The best genotypes with respect to Kulumsa-2019 (E6) AMMI 2 bi plot were generated using genotypic and environmental scores of the first two AMMI multiplicative components to cross-validate the interaction pattern of 25 bread wheat genotypes within nine environments. Connecting vertex cultivar markers in all directions form a polygon, so that all genotypes are contained within the polygon and a set of straight lines that radiate from the pi plot origin to intersect each of the polygon sides at right angles form sectors of genotypes and environments (Yan, 2011). Figure 6 cross-validated the interaction patterns of the 25 bread wheat genotypes evaluated in nine diverse environments. The distance from the origin (0, 0) is indicative of the amount of interaction that was exhibited by genotypes either over environments or environments over genotypes (Yan and Tinker, 2006). With the current data set, genotypes ETBW9647 (20), Ogolcho (25), ETBW9119 (3), ETBW9065 (8), ETBW9080 (11), and ETBW9545 (16) exhibited a highly interactive behavior whereas Melkasa-2018 (E3) and Dhera-2019 (E9) were the least interactive of all environments against Asasa-2019 (E7) which was the most interactive of all environments. The orthogonal projections of the genotypes over the environmental vector showed clear genotype's environment affinity.

Environments within the same sector are assumed to share the same winner genotypes. The best genotypes with respect to Kulumsa-2019 (E6) were ETBW9647 (G20). Ogolcho (G25) best performed at Dhera-2018 (E4), Atsela-2018 (E5) and Melkasa-2019 (E8). Similarly, ETBW9119 (G3) best performed at Asasa-2018 (E2), while ETBW9545 (G16) was the best for Asasa-2019 (E7) (Figure 2). On the other hand, genotypes like ETBW9065 (G8), ETBW9080 (G11), and Deka (G1) fall in sectors where there was no environment at all, indicating their poor adaptation to any of the testing environments. Genotypes, ETBW9077 (G9), ETBW9078 (G10), ETBW9172 (G12), ETBW9396 (G13), ETBW9452 (G14), ETBW9646 (G19), ETBW9650 (G22), ETBW9651 (G23) and ETBW9652 (G24) showed lower fluctuations to both spatial and temporal changes in the growing environments. ETBW9172 (G12), ETBW 9396 (G13), ETBW 9452 (G14) and ETBW 9646 (G19) were promising genotypes as they produced a grain yield that ranged from 5.4 t ha-1 to 5.8 tha^{-1}.

Environments viz. Dhera-2018 (E4), Atsela-2018 (E5), Kulumsa-2019 (E6), and Melkasa-2019 (E8) were associated with their higher positive IPC1 values, indicating their higher discriminative ability. Environment Asasa-2019 (E7) characterized by the largest IPC1 value, was completely the opposite in its ability to discriminate the genotypes. Based on their proximity to the origins Melkasa-2018 (E3) and Dhera-2019 (E9) showed the lowest genotypic discriminative ability, and proved to be more representative of the average environment.

On the other hand, environments Asasa-2018 (E2), Dhera-2018 (E4), Atsela-2018 (E5), Kulumsa-2019 (E6), Asasa-2019 (E7) and Melkasa-2019 (E8) demonstrated higher genotypic discriminating ability and found to be less representative of the average environment (Figure 6). And environments including Melkasa, Atsela, and Dhera were clustered into a single sector, indicating the consistency in the performance of genotypes in these locations. These locations could be considered as a separate mega environment for bread wheat variety evaluation.

Conclusion

To develop the resistant varieties since 2018, more than 8175 bread wheat germplasm from CIMMYT (6405) and ICARDA (170) sources were evaluated in Ethiopia of which 1695(26.46%) and 235(13.28%) lines were selected from CIMMYT and ICARDA materials respectively. From 8175 introduced genotypes, 1932(23.63%) were selected and advanced to the next stage of variety development, based on their combined disease resistance and agronomic traits. Finally, five and one improved variety were released from CIMMYT and ICARDA materials since 2018 respectively.

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