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Enhancing the production and productivity of bread wheat (*Triticum aestivum* L.) varieties through participatory variety selection

Ahmed Getachew¹, Arebu Hussen Yimer^{1,2*}, Agegn Shibeshi¹, Melese Woldesilase¹ and Melese Abebaw Abate³

*Correspondence:

Arebu Hussen Yimer
arebu.hussen@gmail.com

¹Department of Plant Science,
College of Agriculture and Natural
Resource, Mekdela Amba
University, P.O. Box 32, Tulu Awuliya,
Ethiopia

²Institute of Agronomy, Doctoral
School of Plant Science, Hungarian
University of Agriculture and Life
Sciences, 2100 Gödöllo, Hungary

³Department of Rural Development
and Agricultural Extension,
College of Agriculture and
Natural Resource, Mekdela Amba
University, P.O. Box 32, Tulu Awuliya,
Ethiopia

Abstract

The effectiveness of varietal release and distribution can be limited when based only on average performance without accounting for genotype by environment interactions, farmer preferences, and actual adoption. Participatory varietal selection (PVS) addresses these limitations by integrating farmer knowledge with scientific evaluation, thereby promoting locally adapted, resilient, and widely acceptable varieties and contributing to sustainable agricultural development. To this end, eleven bread wheat varieties, including a local check, were tested during the 2023/24 main cropping season in the Borena and Wogdie districts using a mother-and-baby trial design. The mother trial followed a randomized complete block design with three replications. Combined analysis of variance across locations revealed highly significant differences ($P < 0.01$) among varieties for all traits studied. Grain yield ranged from 3.27 t/ha (Wane) to 4.43 t/ha (Boru). Farmers evaluated the varieties during maturity using their own selection criteria and applied pairwise and matrix ranking methods. Abay was ranked first in Borena and Boru in Wogdie, reflecting differences in local preferences. Genotypic correlation analysis showed grain yield had a very strong positive association with the harvest index (0.95), number of grains per spike (0.92), and biological yield (0.90). It also displayed significant positive correlations with thousand seed weight (0.89), spike weight (0.88), number of productive tillers per plant (0.86), plant height (0.74), and spike length (0.69). Path analysis further confirmed the positive direct effects of these traits on grain yield, with the strongest direct effects from productive tillers (0.61), harvest index (0.31), and grains per spike (0.27). Based on both field performance and farmers' preferences, Boru and Abay were recommended for production with their full management packages in the study areas and similar agro-ecologies. These findings underscore the importance of integrating Participatory Varietal Selection (PVS) with conventional breeding strategies, with particular emphasis on harvest index, productive tillers, grains per spike, thousand-seed weight, and spike-related traits as critical selection criteria for enhancing bread wheat improvement and ensuring sustainable crop productivity.

Keywords Farmers, Preference, Selection, Variety, Participatory, Wheat, Yield



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1 Introduction

Bread wheat (*Triticum aestivum* L.) is a self-pollinating, annual allohexaploid species with a complex genome consisting of three distinct sub-genomes (A, B, and D) and 42 chromosomes ($2n=6x=42$). Often referred to as the "queen of cereals," it is a cornerstone of global food security and a primary source of calories and protein [12, 30].

Wheat dominates global agriculture, occupying approximately 25% of cultivated land and feeding one-third of the world's population [35]. In the 2020/2021 season alone, global production reached 776 million metric tons harvested from 221 million hectares [8]. Uniquely adaptable, it thrives from temperate to semi-arid regions (latitudes 30–60°), ideally at elevations of 1500–3000 m above sea level with an optimal temperature of 25 °C [33]. However, a critical production gap remains; while annual yield growth is currently below 1%, a 2% increase is necessary to meet rising global demand [35].

In Ethiopia, wheat is a pivotal crop for achieving national food self-sufficiency [28]. The country offers favorable growing conditions, particularly at altitudes between 1800 and 2800 m.a.s.l., with temperatures of 15–25 °C and annual rainfall of 400–1200 mm [14, 23]. Between 1995 and 2013, Ethiopia successfully doubled both its wheat cultivation area (to 1.6 million hectares) and yield (to 2.1 t/ha) [11]. Despite this progress, the current national average yield of 2.76 t/ha [8] remains significantly lower than the experimental potential of 5 t/ha, the global average of 3.51 t/ha, and the high yields achieved by leading producers like Germany (7.4 t/ha) [15, 39].

The yield gap in Ethiopia is driven by severe biotic and abiotic stresses. Biotic factors are particularly devastating: wheat rust diseases can reduce yields by 30–50%, while weed infestations account for up to 29% of production losses [27]. Additionally, abiotic stresses such as drought can cause yield losses of up to 64% [29]. These challenges are compounded by systemic issues, including insufficient research and the limited adoption of improved varieties, which are used by less than 8% of farmers [9].

Thus, to alleviate such problems, Participatory Varietal Selection (PVS) has emerged as a transformative alternative to traditional top-down breeding, serving as a vital link between sustainable agriculture and farmer-driven improvement. By actively engaging farmers in the evaluation process under local agroecological conditions, PVS ensures that selected cultivars are resilient to environmental stresses and aligned with user preferences [1]. This approach integrates indigenous knowledge with scientific breeding, prioritizing critical traits such as drought tolerance and disease resistance while simultaneously maintaining on-farm genetic diversity and strengthening seed sovereignty. Consequently, PVS fosters trust, accelerates the adoption of superior genotypes, and facilitates their dissemination through informal exchange networks [25, 38]. In the context of sustainable development, improving wheat productivity requires not only higher yields but also resilience, inclusivity, and environmental sustainability. Participatory Varietal Selection contributes to this by aligning breeding outcomes with farmers' needs, promoting resource-efficient and locally adaptable technologies, and supporting climate resilience and sustainable intensification. Therefore, it plays a vital role in improving food security and sustaining rural livelihoods. Therefore, this study was conducted with the following objectives to:

- I. Evaluate the agronomic performance of bread wheat varieties in the specific study areas.

Table 1 Description of the experimental site. Source: (South Wollo Zone Agricultural office, 2019), m.a.s.l—meter above sea level

Sn	Description	Borena (Location)	Wogdie (Location)
1	Soil type	Vertisol	Vertisol
2	Mean annual rainfall (mm)	900–1200 mm	900–1100 mm
3	Mean temperature(°C)	7.5 to 25°C	8 to 25.5°C
4	Altitude (m. a.s.l)	2800 m.a.s.l	2725 m.a.s.l
5	Latitude	10 °N	10 °N
6	Longitude	14°E	13 °E
7	Maximum rainfall recorded	June to August end	June to August end

Table 2 Description of bread wheat varieties used in the study

SN	Variety	Pedigree	Source center	Year of release
1	Abay	ETBW-9396	KARC	2021
2	Balcha		KARC	2019
3	Biftu	ETBW9089	KARC	2021
4	Boru	SAUAL/MUTUS/6/CNO79//PF70354/MUS/3/PASTOR/4/BAV92* 2/5/FH6	KARC	2020
5	Daka	ETBW9578	KARC	2018
6	Dursa	UTQUE96/3/PYN/BAU//MILAN	KARC	2020
7	Lemu	WAXWING * 2/HEILO 2016	KARC	2016
8	Shaki	ETBW7638	KARC	2018
9	Shorima	UTQUE96/3/PYN/BAU//MILAN 2011	KARC	2011
10	Wane	SOKOLL/EXCALIBUR 2016	KARC	2016
11	Danda	KIRITATI//2 * PBW65/2 * SERI.1B	Local check	2010

KARC—Kulumsa Agricultural Research Center.

- II. Identify farmer-preferred traits and varieties using PVS methods to promote the sustainable adoption of new varieties.
- III. Determine the association and direct/indirect effects of yield-related traits on grain yield.
- IV. Assess genotype × environment interactions for key yield traits to identify environmentally stable genotypes.

2 Materials and methods

2.1 Description of the study area

A field experiment was conducted in South Wollo Zone, at the Farmers' Training Centers of Borena and Wogdie districts, during the main cropping season (see Table 1).

2.2 Experimental planting materials

The plant materials used in the study comprised 11 bread wheat varieties, 10 obtained from Kulumsa Agricultural Research Center, and one local check (see Table 2).

2.3 Experimental design and treatment management

The experiments were conducted during the 2023/24 main cropping season to test the performance of ten improved bread wheat varieties and one check variety in the Borena and Wogdie districts. The experiments were conducted using a mother and baby trial approach. The mother trials were conducted at farmers' training centers, whereas the baby trials were conducted at three selected farmers' field sites/locations in each district.

Thus, each farmer's field was considered as a replication. The experiments were laid out on a randomized complete block design (RCBD) with three replications for the mother trial (plants at farmers training center were used to generate breeder's data). Farmers' fields were used as a single replication for baby trials. Each farmer evaluated ten improved varieties alongside one standard check variety, which was included to facilitate participatory varietal selection and assess farmers' preferences.

At both trial sites, the materials were planted by row planting on the net plot sizes were 3.6 m^2 ($3 \text{ m} \times 1.2 \text{ m}$) having 6 rows with 20 cm between rows. The spacing between the blocks and plots was 1 m and 0.5 m, respectively. Fertilizer both Urea (46%) and NPS (19% N, 38 P_2O_5 & 7% S) was applied at rates of 150 and 100 kg/ha, respectively, at the rate recommended by the Amhara Regional State Agriculture and Rural Development Bureau package of 2020/21. Full dose of NPS and half dose of Urea were applied at the time of planting, and the remaining half dose of Urea was applied at the tiller stage. Seeds were sown at a rate of 150 kg/ha. The seeds and fertilizer were uniformly drilled by hand. The necessary data were obtained from the net plot of the mother trials. Weeding and other appropriate management practices were performed according to the recommendations.

2.4 Data collection

Data were collected on a plant and plot basis. For data collection on plant bases, ten plants were randomly selected from the four central rows of each plot excluding the two rows from each plot which were considered as a border. The mean value of these ten (10) plants was used as plot data for analysis. Yield and biomass data was taken from the plot net area and then, converted to t/ha. The data were recorded and the mean values for the treatment were computed on the following phenological, growth, yield, and yield component traits.

I. Phenological and growth traits.

Days to heading (DH): The number of days from the date of sowing to the stage at which 50% of the spikes had fully emerged.

Days to maturity (DM): number of days to maturity at the optimum plant harvesting stage when 90% of the plants in a plot have reached physiological maturity.

Grain filling period (GFP): The number of days from heading to maturity, that is, the number of days to maturity minus the number of days to heading.

Plant height (PH): The length in cm between the ground level and the tip of the terminal spikelet of ten plants (excluding the awns) at maturity.

Number of productive tillers per plot (NPP): The actual count of the fertile number of tillers of ten plants (spike bearing).

Spike length (SL): Length measured in cm from base of spike to the tip of the highest spikelet of ten plants (excluding the awns) in cm at maturity.

Number of spikelets per spike (NSPS): The total number of spikelets on the main spike of all ten plants from four rows was counted at the time of maturity, and the average was recorded.

Number of grains per spike (NGS): The actual count of the number of kernels per spike of all ten plants after manual threshing at the time of harvest.

II. Yield and Yield component traits.

Spike Weight (SW): The actual measure of the weight of spikes taken from ten plants at maturity.

Thousand Seed weight (TSW): Weight of 1000 seeds randomly taken from each plot in grams.

Biological yield (BY) (t/ha): The four central rows will be harvested and weighed in kilograms after exposing them to the sun drying for more than a week after harvest.

Grain yield (GY) (t/ha): Obtained from the central four rows of each plot, and the moisture of the seed was adjusted to 12.5% moisture content.

Harvest index (%): The ratio of the yield of dried grain weight to the dried above-ground biomass weight of the harvestable plot multiplied by 100.

2.5 Statistical analysis

Quantitative data from the mother trials were subjected to Analysis of Variance (ANOVA) using the General Linear Model (PROC GLM) in SAS software (version 9.4). Means were separated using the Duncan's Multiple Range Test (DMRT) at a 5% level of significance ($p \leq 0.05$), following the statistical procedures described by [16]. Additionally, SPSS software (version 29.0) for ranking scores and R programming (version 4.5.0) for GGE Biplot were used.

ANOVA was performed using the following mathematical model:

$$Y_{ij} = \mu + r_j + g_i + E_{ij} \text{ } pl_{(j)} + \varepsilon_{ij1}$$

Where, Y_{ij} = the observed value of the trait Y for the i^{th} variety in j^{th} replication. μ = the general mean of trait Y. r_j = the effect of j^{th} replication. g_i = the effect of i^{th} varieties.

E_{ij} = the experimental error associated with the trait y for the i^{th} variety in j^{th} replication (Table 3).

The GGE biplot model is

$$Y_{ij} - \mu - \beta_j = \rho_1 \sigma_{i1} \delta_{1j} + \rho_2 \sigma_{i2} \delta_{2j} + \varepsilon_{ij}$$

Table 3 Analysis of variance in the case of a series of genotypes evaluated across environments

Source of variation	Degrees of freedom	Mean squares	Expected mean squares
Environment	e-1	MS_E	$\sigma^2_{e+g} \sigma^2_{r(E)+r} \sigma^2_{GE+rg} \sigma^2_E$
Rep(block)	(r-1)e	MS_R	$\sigma^2_{e+g} \sigma^2_{r(E)}$
Genotype	g-1	MS_G	$\sigma^2_{e+r} \sigma^2_{GE+re} \sigma^2_G$
Genotype × environment	(g-1)(e-1)	MS_{GE}	$\sigma^2_{e+r} \sigma^2_{GE}$
Error	(g-1)(e-1)e	MS_E	σ^2_e

Total phenotypic variance: $\text{Var}(Y_{ijk}) = \sigma^2_p + \sigma^2_e + \sigma^2_{GE} + \sigma^2_G$.

Phenotypic variance of genotypic means:

$$\text{Var}(Y_{ijk}) = \sigma^2_p = \frac{\sigma^2_e}{re} + \frac{\sigma^2_{GE}}{e} + \sigma^2_G = \frac{MS_G}{re}$$

Genotypic variance = $\sigma^2_G = (MS_G - MS_{GE})/re$.

Heritability on individual experimental unit basis:

$$H^2 = \frac{\sigma^2_G}{\sigma^2_G + \sigma^2_{GE} + \sigma^2_e}$$

Heritability on a genotypic-mean basis:

$$H^2 = \frac{\sigma^2_G}{\sigma^2_G + \frac{\sigma^2_{GE}}{e} + \frac{\sigma^2_e}{re}}$$

where: σ^2_g = variance due to genotypes, σ^2_{Ge} = variance due to genotypes with environment interaction, σ^2_e = variance due to environments.

where: Y_{ij} is the expected yield of genotype i in environment j ; μ is the grand mean of all observations; β_j is the main effect of environment j ; p_1 and p_2 are the singular values of first and second-largest principal components, PC1 and PC2, respectively; the square of the singular value of a PC is the sum of squares explained by the PC; σ_{i1} and σ_{i2} are the eigenvectors for the i -th genotype for PC1 and PC2, respectively; and δ_{j1} and δ_{j2} are the eigenvectors for the j -th environment for PC1 and PC2, respectively; and e_{ij} is the residue not explained by the primary and secondary effects.

2.6 Participatory approaches to varietal selection

In consultation with kebele development agents, male and female farmers were purposively selected to participate in variety evaluation and selection process based on their experience in bread wheat production, knowledge and skills in crop variety selection and conservation, gender representation, age, and willingness to participate. The study involved a total of twenty farmers (12 men and 8 women), with ten participants from each study site, who jointly established the selection criteria. Qualitative data on bread wheat varieties, including a local check, were collected across locations with similar agro-ecologies using focus group discussions and participatory evaluation tools such as direct ranking, pairwise ranking, and matrix ranking. Matrix ranking was particularly effective in identifying the most important traits, while pairwise ranking facilitated structured discussion and comparison of decision-making criteria among alternative traits [21].

2.7 Evaluation methods of the farmers' PVS program

Mother trials were conducted at Farmers Training Centers (FTCs) using three replications, while baby trials were established on the fields of three individual farmers, with each farmer serving as a replication. The released bread wheat varieties were evaluated based on farmers' own selection criteria. In each study kebele, ten farmers (6 men and 4 women) participated in the evaluation process. Variety assessment was carried out at two growth stages, flowering and maturity. At each stage, farmers first identified their preferred selection criteria, after which male and female participants prioritized these traits separately and then reached a joint agreement on the most important traits for baby trials. The collected information was organized into matrix scoring tables, and selection criteria were compared using pairwise ranking. Rankings were determined by counting how often each criterion was preferred by the group. In addition, a direct matrix scoring table was prepared, with bread wheat varieties listed in rows and farmer preferred traits in columns. Each variety was scored according to the selection criteria using a five-point scale (5=excellent, 4=very good, 3=good, 2=poor, and 1=very poor). To facilitate scoring during direct matrix evaluation, color codes deep green, pale green, blue, yellow, and red were used to represent scores of 5, 4, 3, 2, and 1, respectively. According to Boef & Thijssen [36] the scoring and ranking were done on consensus, and differences were resolved by discussion.

3 Results and discussion

3.1 Combined analysis of variance over two locations

Prior to conducting the combined analysis across locations, the homogeneity of error mean squares (MS) for each trait was assessed using the error MS obtained from the

individual analyses of variance (Table 4). Homogeneity of variances was evaluated using either the F-test or the chi-square test, following the procedure described by [16]. For practical interpretation, error variances were considered homogeneous when the largest error MS did not exceed three times the smallest error MS.

Therefore, the F test is applied as:

$$F \text{ test} = \frac{\text{Larger Error MS}}{\text{Smaller Error MS}}$$

The results showed that the computed F values were lower than the corresponding tabulated F value (3.44) at the 5% level of significance. This indicates that the null hypothesis of homogeneous error variances across locations could not be rejected, confirming the suitability of the data for combined analysis.

The combined analysis of variance for the studied traits is presented in Table 5. Location effects were highly significant for number of reproductive tillers per plant, number of spikelets per spike, number of grains per spike, spike weight, and thousand seed weight, and significant for days to maturity and spike length. These findings demonstrate that environmental variation among locations markedly influenced trait expression, indicating differential genotypic responses to contrasting climatic and soil conditions. The location $\times$ genotype interaction was non-significant for all traits except number of reproductive tillers per plant and thousand seed weight, suggesting that most bread wheat genotypes exhibited stable and consistent performance across the two locations.

Moreover, the mean squares due to varieties were highly significant ($P < 0.01$) for all the traits studied, indicating the presence of substantial genetic variability among the bread wheat varieties. This variability, also evidenced by the wide ranges observed for each trait (Table 5), suggests considerable potential for effective selection and genetic improvement in breeding programs. These findings are consistent with the results of Belete [7], who similarly reported highly significant varietal differences for all evaluated traits, reflecting differential performance among bread wheat varieties. The improved varieties Boru and Abay showed high consistency and best performance across locations in mean grain yield and other yield-related traits that had 15.3% and 13.46% grain yield advantage, respectively, as compared to the reference variety Danda. This was supported by Alemu et al. [2], who stated that the Boru variety is high-yielding and resistant to diseases, which allows it to thrive in a range of environments.

3.2 Mean performance of varieties across locations

Farmers were invited to select the varieties based on their selection criteria at maturity time in both districts. Based on the combined over location, the mean performance of genotypes for studied traits showed significant and a wide range of variation among all parameters of wheat varieties (Tables 6 and 7).

3.2.1 Phenology trait

The mean performance of the wheat genotypes for days to heading, days to maturity, and grain filling periods ranged from 63 to 73 days (mean 68.5), 116 to 131 days (mean 123), and 51 to 60 days (mean 54.5), respectively (Table 6). As days to heading is a critical predictor of crop earliness [17], the study highlighted significant variations among the varieties. The variety Wane demonstrated the earliest development, recording the

Table 4 A combined analysis of variance over two crop locations was computed

Location	Traits												
	DH	DM	GFP	NPT	PH	SL	NSPS	NGS	SW	TSW	GY	BY	HI
Wogdie MSE	2.95	4.15	1.60	0.03	9.20	0.265	0.50	5.23	0	6.58	6.7	15.64	0
Borena MSE	1.94	3.40	1.00	0.032	5.94	0.032	0.56	11	0	6.8	6	12.96	0
F-test = $\frac{\text{Larger Error MS}}{\text{Smaller Error MS}}$	1.52	1.22	1.60	1.07	1.55	1.10	1.12	2.1	0	1.03	1.12	1.21	0

Table 5 Mean performance and statistical values for 13 traits of 11 bread wheat varieties tested in study areas at Borena and Wogdile districts during the 2023/2024 main cropping season

Traits	Sources of variance													
	Loc DF= 1	Rep DF= 4	Variety DF= 10	Loc x V DF= 10	Root MSE	DF= 40	MSE	R ² (%)	C.V (%)	Mean	LSD at 5%	Sdt	Min	Max
DH	1.52 ^{ns}	0.88 ^{ns}	19.78**	2.95 ^{ns}	1.56		2.45	0.70	2.27	68.42	1.8	2.25	63	73
DM	15.5*	1.47 ^{ns}	84.4**	1.45 ^{ns}	1.95		3.8	0.85	1.51	122.76	2.14	3.98	116	131
GFP	2.2 ^{ns}	1.67 ^{ns}	30**	0.55 ^{ns}	1.14		1.3	0.86	2.01	54.52	1.27	2.37	51	60
NPT	2.31**	0.11*	0.31**	0.068*	0.177		0.031	0.84	9.54	3.06	0.34	0.35	2.3	3.7
PH	5.52 ^{ns}	36.88*	68.54**	2.63 ^{ns}	2.75		7.57	0.74	3.3	89.66	3.43	4.24	76	99.4
SL	1.05*	1.28*	2.93**	0.43 ^{ns}	0.50		0.25	0.80	8.22	7.44	0.71	0.88	5.6	9.2
NSPS	9.55**	0.48 ^{ns}	9.9**	0.68 ^{ns}	0.73		0.53	0.85	5.33	15.91	0.98	1.46	13.3	19.3
NGS	459**	5.92 ^{ns}	73.23**	7.33 ^{ns}	2.85		8.11	0.80	8.45	47.34	4.63	4.98	37.2	62.3
SW	0.03**	0.001 ^{ns}	0.008**	0.000 ^{ns}	0.03		0.00	0.79	13.93	0.26	0.04	0.05	0.15	0.35
TSW	893**	3.25 ^{ns}	148**	42**	2.6		6.7	0.91	12.81	42.03	6.23	6.88	29	57
GY	12.6 ^{ns}	9.2 ^{ns}	103.6**	3.56 ^{ns}	2.52		6.35	0.82	6.76	3.67	2.87	4.6	29	46
BY	15.72 ^{ns}	25*	124**	9.33 ^{ns}	3.78		14.3	0.72	4.04	9.32	4.36	5.57	85	105
HI	0.00 ^{ns}	0.000 ^{ns}	0.005**	0.000 ^{ns}	0.013		0.00	0.89	3.7	0.39	0.02	0.03	0.34	0.452

NB: Loc=location, Rep = replication, Loc x V= location with Variety interaction mean square, R²= Coefficient of determination, LSD=Least significant difference, Sdt= Standard deviation, min=minimum, max=maximum, CV=coefficient of Variation, DF=degrees of freedom, R²= Coefficient of determination. DH=Days to heading, DM=Days to maturity, GFP= grain filling period, NPT=number of productive tillers, PH=plant height, SL =Spike length, NSPS=Number of spikelets per spike, NGS=Number of grains per spike, BY=Biological yield, HI=Harvest index, SW= Seed weight, TSW = Thousand seed weight and GY=Grain yield.

Table 6 Mean separation for phenological and growth traits of 11 bread wheat varieties for 13 traits tested in study areas at Borena and Wogdie districts during the 2023/2024 main cropping season

Genotype	DH	DM	GFP	NPT	PH	SL	NSPS	NGS
Abay	67.17 ^b	119.67 ^{cd}	52.83 ^{cd}	3.33 ^a	94.28 ^a	7.80 ^{abc}	16.07 ^b	51.77 ^{ab}
Balcha	68.50 ^{ab}	123.50 ^b	55.50 ^b	2.82 ^{abc}	88.18 ^b	6.83 ^c	13.60 ^c	42.93 ^c
Biftu	69.67 ^{ab}	122.17 ^{bc}	53.17 ^{cd}	3.21 ^{abc}	88.40 ^b	8.11 ^{ab}	17.03 ^b	46.78 ^{bc}
Boru	67.67 ^{ab}	119.50 ^{cd}	51.83 ^d	3.28 ^{ab}	94.10 ^a	8.62 ^a	18.02 ^a	54.33 ^a
Daka	70.33 ^a	128.17 ^a	57.67 ^a	3.00 ^{abc}	91.25 ^{ab}	7.52 ^{bc}	16.63 ^b	46.90 ^{bc}
Dursa	67.83 ^{ab}	122.17 ^{bc}	54.33 ^{bc}	3.20 ^{abc}	89.48 ^{ab}	7.28 ^{bc}	15.68 ^b	48.33 ^{abc}
Lemu	70.33 ^a	128.50 ^a	58.17 ^a	2.78 ^{abc}	86.95 ^b	7.43 ^{bc}	16.45 ^b	45.12 ^{bc}
Shaki	67.00 ^b	120.00 ^{cd}	53.00 ^{cd}	3.30 ^{ab}	90.75 ^{ab}	7.48 ^{bc}	14.47 ^c	47.67 ^{bc}
Shorima	69.50 ^{ab}	121.83 ^{bc}	53.00 ^{cd}	2.87 ^{abc}	89.57 ^{ab}	7.32 ^{bc}	15.78 ^b	42.25 ^c
Wane	64.50 ^c	117.50 ^d	53.00 ^{cd}	2.73 ^c	82.17 ^c	5.87 ^d	14.55 ^c	46.43 ^{bc}
Danda	70.17 ^a	127.33 ^a	57.17 ^a	3.12 ^{abc}	91.12 ^{ab}	7.58 ^{bc}	16.70 ^b	48.27 ^{abc}
Mean	68.42	122.76	54.52	3.06	89.66	7.44	15.91	47.34
SE ±	0.63	0.75	0.45	0.12	1.21	0.25	0.35	1.63
CV (%)	2.27	1.51	2.01	9.54	3.3	8.22	5.33	8.45
LSD (0.05)	1.8	2.14	1.27	0.34	3.43	0.71	0.98	4.63

*Means within a column followed by the same letter are not significantly different (DMRT). LSD=Least significant difference, SE=Standard error, CV=coefficient of Variation, DH=Days to heading, DM=Days to maturity, GFP=grain filling period, NPT=number of productive tillers plant, PH=plant height, SL=Spike length, NSPS=Number of spikelets per spike, NGS=Number of grains per spike

Table 7 Mean separation for yield and yield related traits of 11 bread wheat varieties for 13 traits tested in study areas at Borena and Wogdie districts during the 2023/2024 main cropping season

Genotype	SW	TSW	GY	BY	HI
Abay	0.32 ^a	49.44 ^a	4.33 ^a	9.96 ^a	0.43 ^a
Balcha	0.23 ^{cde}	36.60 ^{bc}	3.27 ^d	9.03 ^{bc}	0.36 ^e
Biftu	0.28 ^{abc}	45.77 ^{ab}	3.67 ^{bcd}	9.51 ^b	0.39 ^{cd}
Boru	0.30 ^{ab}	49.87 ^a	4.43 ^a	10.32 ^a	0.43 ^a
Daka	0.26 ^{abcde}	43.11 ^{abc}	3.33 ^d	8.80 ^c	0.38 ^{de}
Dursa	0.28 ^{abc}	43.80 ^{abc}	3.84 ^b	9.21 ^{bc}	0.42 ^{ab}
Lemu	0.24 ^{bcde}	38.75 ^{bc}	3.42 ^{cd}	8.99 ^{bc}	0.38 ^{cde}
Shaki	0.26 ^{abcde}	41.94 ^{abc}	3.84 ^b	9.21 ^{bc}	0.42 ^{ab}
Shorima	0.20 ^e	35.59 ^c	3.28 ^d	9.17 ^{bc}	0.36 ^e
Wane	0.22 ^{de}	36.55 ^{bc}	3.27 ^d	8.98 ^{bc}	0.36 ^e
Danda	0.28 ^{abc}	41.10 ^{abc}	3.75 ^{bc}	9.36 ^{bc}	0.40 ^{bc}
Mean	0.26	42.05	3.67	9.32	0.39
SE ±	0.01	2.2	1.01	1.54	0.01
CV (%)	13.93	12.81	6.76	4.04	3.7
LSD (0.05)	0.04	6.23	2.87	4.36	0.02

*Means within a column followed by the same letter are not significantly different (DMRT). LSD=Least significant difference, SE=Standard error, CV=coefficient of Variation, SW=Seed weight, TSW=Thousand seed weight GY=Grain yield, BY=Biological yield, and HI=Harvest index

lowest number of days for both heading (64.5 days) and maturity (117.5 days). Other genotypes, including Shaki, Abay, Boru, and Dursa, also showed comparatively early spike emergence (67–67.8 days) and subsequent early maturity (119.5–120 days). In contrast, Lemmu and Daka were the latest to develop, recording the highest days to heading (70.33 days) and maturity (128.5 and 128.2 days, respectively), which was comparable to the standard check variety, Danda (127.33 days). These results align with the findings of Amanu & Jembre [5] who also identified Lemmu and Daka as late heading and maturing varieties. Regarding grain filling, which is essential for yield, Lemmu had the longest duration (58.17 days), while Boru had the shortest (51.83 days); notably, eight varieties

performed lower than the standard check Danda across all three traits. Ultimately, the study confirmed a positive correlation where early heading resulted in early maturity and delayed heading caused late maturity, similar with previous findings by [13, 31].

3.2.2 Growth trait

The mean performance for plant height and fertile tillers per plot ranged from 76 to 99.4 cm (mean 89.66 cm) and 2.3 to 3.4 (mean 3.06), respectively. Regarding plant height, Abay (94.28 cm) and Boru (94.1 cm) were the tallest varieties, followed by Daka (91.25 cm) and the standard check Danda (91.12 cm), while Wane (82.17 cm) and Lemu (86.95 cm) recorded the shortest heights (Table 6); overall, three varieties proved taller than the standard check (Danda), while seven were shorter. For fertile tillers a trait [17] identify as directly contributing to increased grain yield Abay (3.33) and Shaki (3.3) produced the highest numbers per plot, followed by Boru (3.28) and Dursa (3.2). Thapa et al. [34] also found plant height and productive tillers are key traits that significantly impact yield in cereals like wheat and teff. Conversely, Wane recorded the lowest fertile tillers (2.73), followed by Lemu, Balcha, and Shorima. In comparison to the control, four varieties outperformed the standard check (Danda) in tiller production, while six produced fewer tillers. These observed ranges and means are consistent with similar findings reported by [2, 26, 31].

3.2.3 Spike traits

The results indicated that spike traits were significantly influenced by both genetic potentials and environmental conditions, as evidenced by significant performance differences across locations. The mean performance for spike length, number of spikelets per spike, grains per spike, seed weight, and thousand kernel weight (TKW) ranged from 5.6 to 9.2 cm, 13.3–19.3, 37.2–62.3, 0.15–0.35 g, and 29–57 g, respectively. It is notable that the variety Boru consistently displayed superior performance. Boru recorded the longest spike length (8.62 cm), the highest number of spikelets per spike (18.02), the highest number of kernels per spike (54.33), and the highest TKW (49.87 g), often followed closely by varieties such as Abay and Biftu (Table 6). Similar to findings by Alemu et al. [2], this study observed that the Boru variety is characterized by bold seed size and superior Thousand Kernel Weight (TKW) compared to standard checks. In terms of spike weight, Abay (0.32 g) and Boru (0.30 g) were the top performers. Conversely, the variety Wane frequently recorded the lowest values across traits, including spike length (5.87 cm), spikelets per spike (14.55), and seed weight (0.22 g), often performing similarly to Balcha. When compared to the standard check variety, Danda, several genotypes showed superior mean performance: six varieties exceeded the check for TKW, three for spike length and kernel number, and two for spikelet number and spike weight. The study indicates that increased spike length directly contributes to enhanced grain yield by supporting a larger number of spikelets. This finding is supported by [24, 31], who link length to spikelet count, as well as [17], who identify spike length as a primary yield component.

3.2.4 Yield (biomass yield and grain yield) and harvest index trait

The mean biomass yield of the bread wheat varieties ranged from 8.5 to 10.5 t ha⁻¹, with an overall mean of 9.32 t ha⁻¹, while harvest index varied from 34 to 45%, averaging

39.29%. The highest biomass yield was recorded for Boru (10.32 t ha⁻¹), followed by Abay (9.96 t ha⁻¹) and Biftu (9.51 t ha⁻¹). In contrast, Daka (8.80 t ha⁻¹), Lemu (8.99 t ha⁻¹), and Wane (8.98 t ha⁻¹) exhibited the lowest biomass yields (Table 7). With respect to harvest index, Abay and Boru recorded the highest values (43%), followed by Dursa and Shaki (42%), whereas the lowest values were observed in Balcha, Shorima, and Wane (36%). Compared with the standard check variety, three varieties showed superior biomass yield and four varieties exhibited a higher harvest index. Overall, the results indicate that improved varieties generally possess a higher harvest index, reflecting greater efficiency in partitioning assimilates to grain rather than vegetative biomass. This finding aligns with [31, 38], who also observed that modern improved varieties possess a higher harvest index compared to traditional cultivars.

Grain yield is the primary goal of any plant breeding program, and in this study, performance ranged from 2.9 to 4.6 t ha⁻¹ with a mean of 3.67 t ha⁻¹. The variety Boru recorded the highest grain yield (4.43 t ha⁻¹), followed by Abay (4.33 t ha⁻¹), Dursa (3.84 t ha⁻¹), and Shaki (3.83 t ha⁻¹) (Table 7). As illustrated in Fig. 1, the genotypes Boru and Abay consistently demonstrate superior adaptability, recording the highest mean performance across all tested environments. Similarly [2, 5] reported that Boru is a recently released bread wheat variety superior grain yield. In contrast, the lowest mean yields were recorded for Wane, Balcha, and Shorima (approximately 3.27 t ha⁻¹) and Daka (3.33 t ha⁻¹). Based on mean performance, four varieties exceeded the yield of the standard check, while six varieties performed below it (Fig. 2). The result implies that the final grain yield is determined by several closely related morphological attributes, including

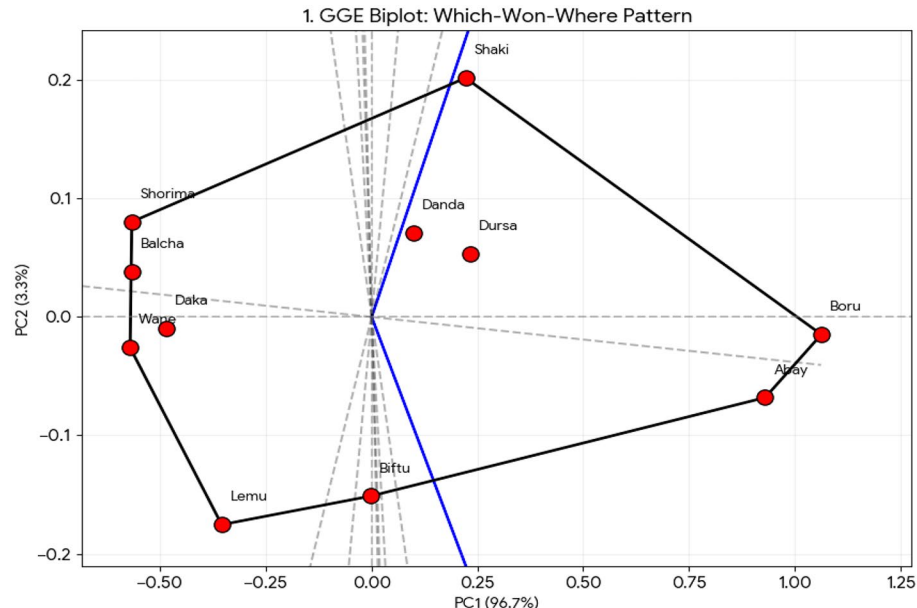


Fig. 1 The which-won-where GGE biplot identified genotype performance patterns and mega-environments using a polygon formed by the outermost genotypes (Shaki, Boru, Abay, Biftu, Lemu, and Shorima). Sector delineation by perpendicular lines indicated that vertex genotypes were the highest performers in environments falling within their respective sectors. The first principal component (PC1) explained 96.7% of the total genotype plus genotype-by-environment (G + GE) variation, while the second principal component (PC2) accounted for 3.3%, together explaining 100% of the GGE variation. Genotypes Boru and Abay, positioned farthest along the positive PC1 axis, exhibited superior performance across most environments, whereas Lemu and Shorima, located in opposite sectors, showed inferior performance in high-yielding environments. Genotypes near the origin, such as Danda, displayed greater yield stability and reduced environmental sensitivity, confirming the utility of the which-won-where GGE biplot for identifying winning genotypes and delineating mega-environments [7, 10, 26]

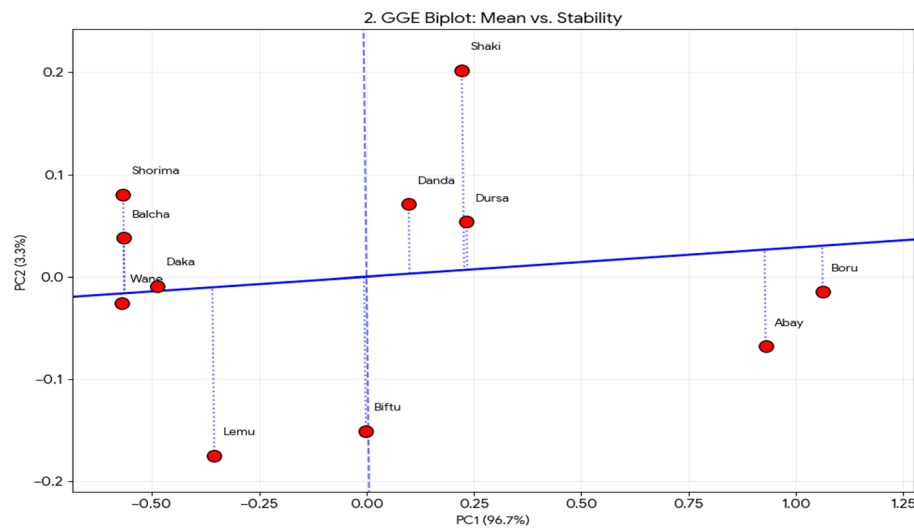


Fig. 2 The GGE biplot, based on the Principal Component Analysis (PCA) model with genotype-focused scaling, offers a superior method for visualizing both the mean performance and stability of the tested genotypes [20, 37]. The Average Environment Coordination (AEC) view was used to assess the 11 varieties, where the solid blue arrow indicates the direction of higher mean yield. Boru is positioned farthest to the right on this axis, showing the highest mean yield, followed by Abay, while Lemu, Wane, and Shorima lie to the left, indicating below-average performance. Stability is reflected by the length of the vertical dashed projections, with shorter projections indicating greater stability; Danda (the standard check) and Boru showed relatively stable performance, whereas Shaki had the longest projection, making it the most unstable despite its high yield potential. This combined evaluation of mean yield and stability, based on genotype-focused Singular Value Partitioning (SVP), is widely used in wheat breeding studies [37]

the number of productive tillers, spike length, number of grains per spike, and 1000-grain weight. The significant variation in yield recorded in this study aligns with earlier reports by [17].

3.3 Association among traits

3.3.1 Interrelationship between grain yield and related components

The analysis of the interrelationship between grain yield and its contributing components revealed that genotypic correlations (r_g) were consistently higher than phenotypic correlations (r_p), indicating that these associations are primarily under genetic control rather than being driven solely by environmental influence [19, 24]. As illustrated in the correlation heatmap (Fig. 3), grain yield exhibited significant and strong positive correlations with biological yield, harvest index, thousand seed weight, and the number of grains per spike. These associations suggest that improvements in these traits directly contribute to higher yield. These findings consistent with those of Workineh et al. [38], who reported similar positive relationships among these traits. As illustrated in the correlation heatmap (Fig. 3), grain yield demonstrated a significant, strong positive correlation with biological yield, harvest index, thousand seed weight, and the number of grains per spike. These findings suggest that improvements in these traits directly enhance yield, a conclusion consistent with results reported by [38]. Furthermore, plant height and spike length also showed positive associations with yield, confirming their value in selection criteria [17, 24]. Conversely, phenological traits specifically days to heading, days to maturity, and grain filling period demonstrated negative associations with grain yield, implying that late-maturing varieties may face yield penalties in these

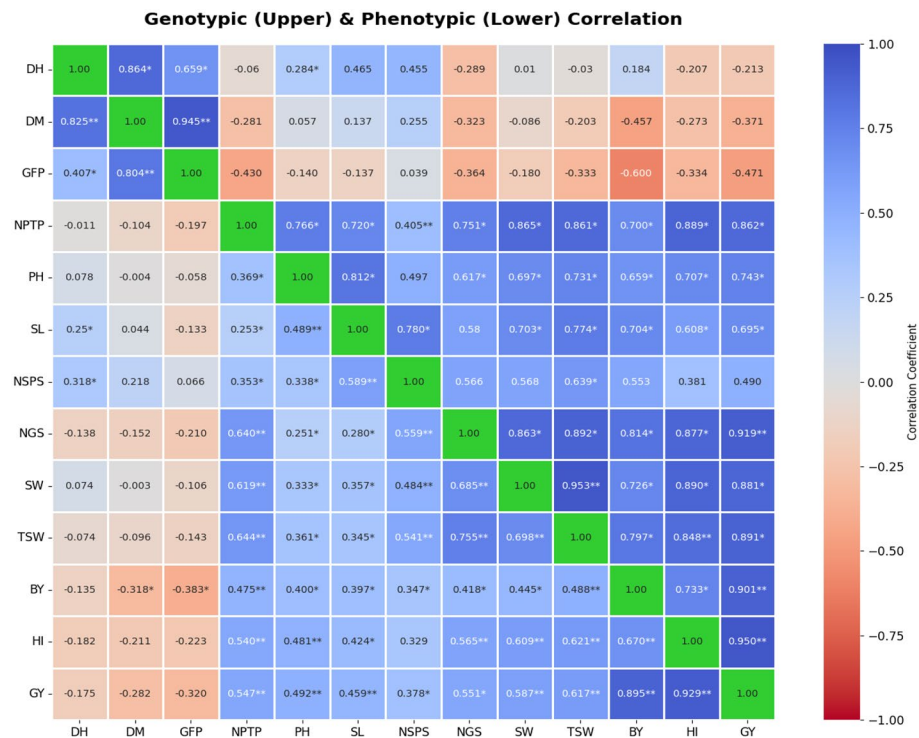


Fig. 3 The correlation heatmap exhibits genotypic correlations in the upper triangle and phenotypic correlations in the lower triangle, separated by a green diagonal representing perfect self-correlation (1.00). The color gradient distinguishes relationships: blue indicates a positive correlation where traits increase together, whereas red implies a negative, inverse relationship. Statistical reliability is denoted by asterisks, with double asterisks (**) indicating high significance and single asterisks (*) marking standard significance

Table 8 Estimate of direct (bold face and diagonal) and indirect (off-diagonal) effects at the genotypic level in eight traits of 11 bread wheat genotypes

Traits	NPTP	PH	SL	NGS	SW	TSW	BY	HI	rg
NPTP	0.610	0.141	-0.025	-0.222	-0.105	-0.150	-0.115	-0.272	0.862*
PH	0.249	0.184	0.028	-0.183	-0.085	-0.128	-0.108	-0.216	0.743*
SL	0.159	-0.149	0.035	0.172	-0.085	-0.135	-0.115	-0.186	0.695*
NGS	0.209	-0.114	-0.020	0.296	0.105	-0.156	-0.133	-0.268	0.919**
SW	0.393	-0.128	-0.025	-0.255	0.121	0.166	-0.119	-0.272	0.881*
TSW	0.386	-0.135	-0.027	-0.264	-0.116	0.174	0.131	-0.259	0.891*
BY	0.127	-0.121	-0.025	-0.241	-0.088	-0.139	0.164	0.224	0.901**
HI	0.431	-0.130	-0.021	-0.260	-0.108	-0.148	-0.120	0.306	0.950**

Residual effect=0.28, Coefficient of determination=0.488 *, ** indicate significance at 0.05 and 0.01 probability levels, NPTP=number of productive tillers, PH=plant height, SL=spike length, NGS=number of grains per spike, Spike weight, TSW=thousand seed weight, BY=biological yield, HI=harvest index, rg=genotypic correlation.

environments [6, 19]. Therefore, breeding programs should prioritize selecting for biological yield, harvest index, and seed-related traits to maximize productivity [13, 17].

3.4 Path coefficient analysis

Path coefficient analysis is a vital statistical tool used to partition correlation coefficients into direct and indirect effects, offering a clearer picture of cause and effect relationships than correlation alone [18]. In this study, the analysis revealed that the Number of Productive Tillers per Plot exerted the highest positive direct effect (0.610) on grain yield, followed by Harvest Index (0.306) and Number of Grains per Spike (0.296) (Table 8).

Other traits, including plant height, thousand-seed weight, biological yield, and spike weight, also showed positive direct effects, confirming their importance in yield improvement. The strong direct influence of these traits suggests that a slight increase in any of them would directly contribute to higher grain yield, aligning with findings by [3, 4]. Furthermore, many traits contributed indirectly; for instance, spike length and biological yield positively influenced yield through productive tillers and harvest index [24].

The analysis also highlighted the efficiency of biomass partitioning, noting that increases in Harvest Index and Biological Yield are primary drivers of cereal yield gains [32]. Consequently, traits such as productive tillers, harvest index, and grains per spike should be prioritized as selection indices for future breeding programs. The residual effect of the model was calculated at 0.28, indicating that the studied traits accounted for 72% of the variability in grain yield. This relatively low residual effect suggests that the selected traits are highly relevant for predicting yield, although environmental factors and other unmeasured traits still play a role. This finding is consistent with similar studies by [18, 22], reinforcing the reliability of these Traits for selection in wheat improvement programs.

3.5 Evaluation methods of the farmers' PVS program

During the selection process, farmers utilized self-defined criteria to evaluate the varieties, prioritizing traits according to personal preference. This approach revealed distinct differences in varietal preference among the ten participants. However, through a facilitated group discussion following the field assessment, the farmers were able to consolidate their views and identify the best-performing varieties. As summarized in Fig. 4, the study evaluated farmers' selection criteria, detailing the average scores and subsequent rankings of the varieties in the baby trials.

3.5.1 Pair-wise ranking

Farmers evaluated data from Participatory Varietal Selection (PVS) baby trials using pairwise and matrix ranking methods, as recommended by (Boef & Thijssen, 2007). As illustrated in Fig. 5, the pairwise ranking revealed distinct preference patterns across different contexts: in Borena, variety Abay was the most preferred overall and variety Boru

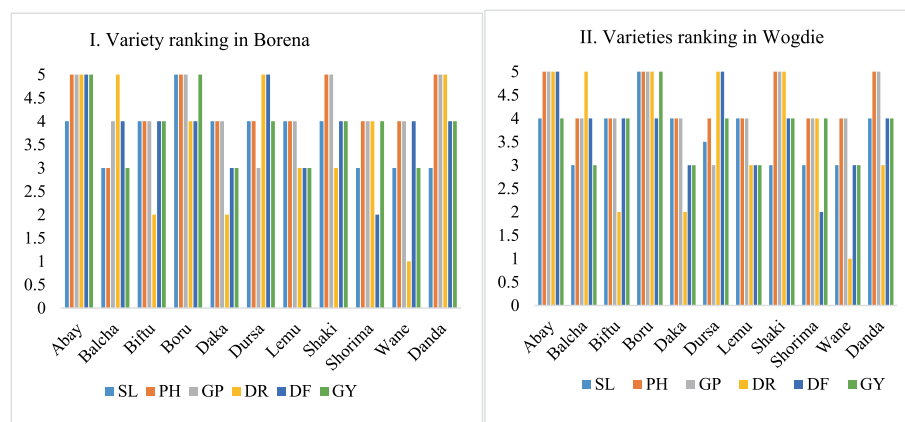


Fig. 4 Farmers' varietal selection criteria and the average scores and their ranks of varieties given by the farmers in baby trials in Borena and Wogdie districts. Where: DM=maturity date, SL=spike length, PH=plant height, GP=growth performance, GY=grain yield, DR=Reaction to Disease, and DF=Reaction to frost

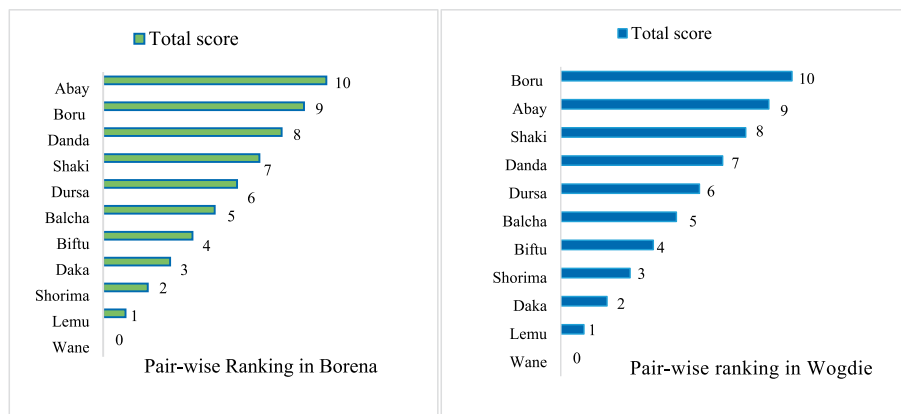


Fig. 5 A pair-wise ranking method was employed to evaluate 11 varieties in Borena and Wogdie, in which varieties were ranked based on multiple attributes through systematic comparison of each variety

was ranked higher than Danda, whereas in Wogdie, variety Boru was preferred to all others and Abay was ranked above Shaki, with variety Wane consistently identified as the least preferred option in both scenarios.

3.5.2 Matrix ranking

Matrix ranking methods can be very useful, especially in situations where many farmers cannot be brought together simultaneously to do the evaluation. For each study area there were 10 farmers carried out on-farm evaluation of the varieties in a particular location. The pair-wise ranking methods done by individual farmers can be compiled into a matrix to give the overall ranking by the participants. According to the matrix ranking results shown in Table 9, farmer preferences varied by district. In Borena, farmers ranked Abay as the most suitable variety, while in Wogdie, the Boru variety was prioritized as the best variety.

4 Summary and conclusion

To address the persistent yield gap and limited adoption of improved bread wheat (*Triticum aestivum* L.) varieties in Ethiopia, this study implemented Participatory Varietal Selection (PVS) during the 2023/24 cropping season in the Borena and Wogdie districts of South Wollo. Eleven bread wheat varieties ten improved genotypes and one local check were evaluated using a combined mother and baby trial approach to bridge the gap between scientific breeding and on real farm field. The mother trials were conducted using a randomized complete block design to ensure statistical rigor, while the baby trials enabled farmers to evaluate varieties on their own fields based on locally relevant selection criteria, using pairwise and matrix ranking methods to identify preferred genotypes for their respective agro-ecologies.

The quantitative analysis revealed highly significant differences among varieties, with grain yield ranging from 3.27 to 4.43 t ha⁻¹. The variety Boru recorded the highest mean grain yield (4.43 t ha⁻¹) and biomass yield (10.32 t ha⁻¹), followed closely by Abay (4.33 t ha⁻¹). Both varieties significantly outperformed the standard check and demonstrated superior adaptability across environments. Genotypic correlation and path coefficient analyses indicated that grain yield was strongly and positively associated with harvest index, number of grains per spike, and number of productive tillers, identifying these

Table 9 Overall ranking of varieties by a group of farmers

Varieties	Borena				Wogdie			
	Individual Rank		Rank index		Individual rank		Rank index	
	1	2	3	4	1	2	3	4
Abay	8	1	1	–	7	1	2	–
Balcha	2	4	3	1	3	4	2	1
Biftu	2	3	4	1	3	3	2	2
Boru	7	2	1	–	7	2	1	–
Daka	2	3	3	2	1	3	4	2
Dursa	3	3	3	–	4	4	1	1
Lemu	2	2	4	4	1	3	3	3
Shaki	3	4	2	1	6	2	2	–
Shorima	1	2	3	4	1	4	4	1
Wane	1	1	1	7	1	2	2	5
Danda	5	3	2	–	5	3	2	–

NB: Rank index = Summations of rank × number, i.e., for variety a Rank index = $(8 \times 1) + (1 \times 2) + (1 \times 3) = 8 + 2 + 3 = 13$. The lower the rank index, the more desirable the variety.

traits as key selection criteria for future breeding efforts. In contrast, varieties such as Wane and the local check exhibited relatively poor performance in terms of yield and stability.

Results from the PVS further demonstrated that farmer preferences were largely consistent with measured agronomic performance, although rankings varied by location due to site-specific environmental conditions. Farmers in Borena district ranked Abay as the most preferred variety, while Boru was the top choice in Wogdie district. In both locations, these varieties were consistently favored over the local check (Danda), thereby validating the quantitative findings with farmer-based evidence. Accordingly, Boru and Abay were identified as the most suitable bread wheat varieties for production in the study areas.

Overall, the findings highlight the critical role of integrating participatory varietal selection (PVS) with conventional breeding approaches in advancing sustainable agricultural development. The identification of Boru and Abay as high performing and farmer preferred varieties demonstrates the potential to improve productivity, enhance resilience to environmental variability, and increase adoption among smallholder farmers. By aligning varietal selection with farmer preferences and local agroecological conditions, PVS promotes efficient resource use, strengthens local seed systems, and supports the conservation of on-farm genetic diversity. The participatory approach further empowers farmers, encourages knowledge exchange, and fosters inclusive innovation, all of which are essential for sustainable development. Therefore, scaling up PVS based approaches and promoting the dissemination of preferred varieties can significantly enhance food security, improve climate resilience, and support sustainable rural livelihoods. Future research should focus on multi-season and multi-location validation to ensure the long-term stability and sustainability of these varieties under climate change conditions.

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Author contributions

Conceptualization, A.G, A.H.Y and A.S; Methodology, A.G, A.H.Y, and A.S; Writing Original draft preparation, A.G, A.H.Y, A.S., M.W and M.A.A; Writing review and editing, A.G, A.H.Y, A.S., M.W. and M.A.A. All authors contributed and approved the submitted version of the manuscript.

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Data availability

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Declarations

Ethics approval and consent to participate

The study protocol was reviewed and approved by the Institutional Review and Ethics Committee (IREC) of Mekdela Amba University, in accordance with Ethiopia's Higher Education Proclamation No. 1152/2019 governing research involving human participants.

Consent for publication

Not applicable.

Informed consent

Informed consent was obtained from all participants prior to their participation in the study. All participants were above 18 years of age and were fully informed about the objectives and procedures of the research. Participation was voluntary, and the privacy and anonymity of all participants were strictly protected throughout the study.

Competing interests

The authors declare no competing interests.

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