

Research Article

Performance Evaluation of Linseed (*Linum usitatissimum* L.) Varieties in Buno Bedele Zone, South Western Oromia

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Abstract

Linseed (*Linum usitatissimum* L.) is one of the most important oil crops of Ethiopia and it is considered as the main food crop and the least expensive source of oil for the farmers in many highlands of the country. Even though numerous improved linseed varieties have been released in Ethiopia, the mean seed yield per unit area of the crop remains low due to poor access to improved varieties. To improve the crop's production and productivity, testing the performance of improved linseed varieties in potential agro ecologies where the varieties have never been grown before is an essential activity. A study was carried out with the objective of testing the performance of improved linseed varieties and their genetic variability for seed yield and related traits in Bedele, Dabo Hana and Didesa districts of Buno Bedele zone, south western Oromia, Ethiopia. This experiment was carried out using twelve linseed varieties were used for investigation (Bekoji-14, Kassa-2, Welen, Bekoji, Kuma, Yadano, Furtu, Bakalcha, Dibane, Horesoba & Jitu) and one local check were sown in randomized complete block design with three replications during the 2022/2023 and 2023/2024 main cropping seasons. Six (6) quantitative morphological traits were collected and analyzed by using R-software accordingly. Combined analysis of data from the three locations revealed that there is significant difference among varieties for days to flowering, days to maturity and grain yield, but non-significant for plant height (cm), number of primary branches per plant and number of capsules per plant. Significant effect of location was observed in plant height, number of primary branch per plant, number of capsule per plant and grain yield however non-significant in days to flowering and days to maturity. The interaction of Variety X location was significant for days to flowering, days to maturity, plant height and grain yield, however non-significant for number of primary branch per plant and number of capsule per plant. The maximum seed yield was recorded in varieties Kuma (1588.9 kg ha⁻¹) followed by Beokoji-14 (1476.7 kg ha⁻¹) and the lowest yield (978.9 kg/ha-1) was obtained from local check. The combine AMMI analysis for seed yield across environments revealed significantly affected by environments that hold 26.6% of the total variation. The genotype and genotype by environmental interaction were significant and accounted for 12.40% and 19.42% respectively. Principal component 1 and 2 accounted for 10.78 % and 6.13% of the GEI respectively with a total of 16.91% variation. In general, Kuma and Bekoji-14 varieties were identified as the best varieties for yielding ability, stability and recommended in the area and with similar agro-ecologies.

Keywords

Evaluation, Linseed, Varieties, Interactions and Significant

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1. Introductions

Oil crops occupy third position following cereal and pulse crops in the agricultural economy of Ethiopia. Among oil crops linseed (*Linum usitatissimum* L.) is one of the ancient oilseeds cultivated for oil, food and fiber [1]. Linseed (*Linum usitatissimum* L.) is an annual field crop that belongs to the family Linaceae. The haploid chromosome number of Linseed is 15 ($n=15$), and the diploid chromosome number is 30 ($2n=30$). It is an important oil crop cultivated worldwide for oil and fiber. Ethiopia's oilseed crop, which is quickly expanding to fulfill both domestic and international demand, is critical to the country's foreign exchange revenues and income. Oilseed exports account for about 11.5% of Ethiopia's total export profits. Oilseeds supplied 5.90% (766,167.66 ha) of grain crop area and 2.27% (7,774,444.17 quintals) of grain production to Ethiopia's national grain total [2]. Niger seed, sesame, and linseed accounted for 1.48% (19,766.00 ha), 2.85% (369,897.32 ha), and 0.61% (78,921.37 ha), respectively, of the grain crop area. These crops account for 0.63%, 0.76%, and 0.24% of grain crop production, respectively. Five countries (Canada, China, Russia, India, and USA) provide 72.50% of global linseed production. The European top producer is the Russian Federation (13.86%) [3]. The crop is largely grown in temperate climates and cool tropics, including the highlands (>2500 m above sea level) of Ethiopia. It thrives best at altitudes of 2200–2800 m above sea level in Ethiopia, but it can also be grown at 1200 m and 3420 m above sea level [4]. Linseed grows in cold weather ranging from 10–30 °C, but it produces the best harvests when temperatures are between 21–22 °C during the growth period. In fact, linseed is the second biggest oil plant in terms of acreage cultivated and yield in the highland areas of Ethiopia, after Niger seed [5]. In Ethiopia, linseed supplies 10.3% (78,921.37 ha) of the oilseed crop area and 10.35% (80,456.64 tons) of the production of the national oilseed total [2]. Despite its diverse uses for the local oil sector and foreign currency earnings, linseed productivity in Ethiopia is characterized by low yield, with an average yield of 10.2 qt ha⁻¹ [2], compared to more than 1.5 t/ha in developed countries [6]. In Oromia region linseed covered 27,661.60 hectares of cultivated land and has a production of about 310,824.57 quintals with average yield of 11.24 qt ha⁻¹ [2]. This indicates in the Oromia region linseed production potential is better. Even though there is no production status of the study area for this crop appropriate improved variety is crucial in order to increase the production. Some attempts have been done to improve the limitation of ideal linseed varieties for the area of Buno Bedele zone by Jimma Agricultural Research Center (JARC).

However, that is not enough and satisfying the farmers demand regarding the option and accessibility of improved varieties. Hence, this study was conceived to evaluate the newly released linseed varieties to the agro-ecology of the Buno Bedele zones of south western Oromia region, Ethiopia and identify the most high yielders and stable varieties for the

farmers. One of the major production barriers affecting linseed productivity is a lack of access to improved varieties, which is why the majority (>90%) of Ethiopian farmers use unimproved seeds [7]. On the contrary, the Ethiopian Institute of Agricultural Research has released more than 19 improved linseed varieties [8] that, if properly assessed and produced by farmers, have the potential to increase crop output. Every crop improvement effort begins with a breeder looking into the existence of genetic variability for the desired traits [9]. According to Adugna [10], Ethiopia is believed to be the secondary place of variation, and it is the world's fifth largest linseed producer. Ethiopia's diverse agro climatic conditions may have led to the country's linseed crop diversification. However, having variance in a population is not enough to improve desired qualities and little or no research on the genetic variability of released linseed varieties has been conducted. As a result, breeders must evaluate the degree and distribution of genetic diversity in the genetic materials that are readily available.

The crop genotypes grown in different environments would frequently encounter significant fluctuations in yield performance, particularly when the growing environments are distinctly different, the test genotypes differentially respond to changes in the growing environments or both. AMMI is a multivariate tool, which was highly effective for the analysis of multi environment trials and in the recent years, this method has often been used by international agricultural development agencies [11]. The most recent method, the GGE (genotype main effect (G) plus G x E interaction) biplot model, provides breeders a more complete and visual evaluation of all aspects of the data by creating a biplot that simultaneously represents mean performance and stability, as well as identifying mega-environments (Ding et al., 2007; Yan and Kang, 2003).

In this study, we attempted to apply AMMI and sites regression GGE biplot statistical model for determination of the magnitude and pattern of G × E interaction effects and performance stability of seed yield of 12 linseed genotypes.

2. Materials and Methods

2.1. Description of the Study Areas

The field experiment was conducted during the 2022 – 2023 G.C main cropping seasons for two years at three districts of Buno Bedele Zone, South Western Oromia where agro ecology assumed to be conducive for Linseed production. The locations were Bedele, Dabo Hana and Didesa districts. The detailed agro-ecological conditions of the locations are presented below (Table 1).

2.2. Experimental Materials

Twelve linseed varieties from the Holetta, Kulumsa and

Sinana Agricultural Research Centers, as well as one local check from farmers, were collected and evaluated for performance and variability over seasons (Table 2).

Table 1. Agro-ecological features of the experimental Locations.

Locations	Altitude (m.a.s.l)	R/fall (mm)	Soil Type	Geographical Coordinates		Ave. Tem. (°C)	
				Latitude N	Longitude E	Max.	Min.
Bedele	1300-2200	1200-1800	Nitosols	8 °28'60.00"	36 °20'60.00"	28.5	12.5
Dabo Hana	1791-1990	1300-1945	Nitosols	8°55'60 20"	36 °26' 19.00"	25.8	12.9
Didessa	1945-2340	1250-2000	Nitosols	8 °04'60.00"	36 °39'59.99"	28	13

Source: Different literatures

Table 2. Description of Linseed Varieties used in this Study.

Varieties	Year of release	Releasing center/Maintainer	Seed Color
Bekoji-14	2014	HARC (EIAR)	Brown
Kassa-2	2012	HARC (EIAR)	Yellow
Welen	2019	KARC (EIAR)	Brown
Bekoji	-	SARC (EIAR)	Brown
Kuma	2016	KARC (EIAR)	Brown
Yadano	2015	KARC (EIAR)	Brown
Furtu	2013	KARC (EIAR)	Brown
Bakalcha	2010	KARC (EIAR)	Brown
Dibanne	2009	SARC (OARI)	Brown
Horesoba	2019	SARC (OARI)	Brown
Jitu	2012	SARC (OARI)	Brown
Local	-	-	Brown

Remark: HARC=Holeta Agricultural Research Center, KARC=Kulumsa Agricultural Research Center, SARC=Sinana Agricultural Research Center, EIAR=Ethiopia Institute of Agricultural Research, OARI=Oromia Agricultural Research Institute

2.3. Experimental Design and Field Work

The treatments were laid with a randomized completed block design (RCBD) with three replications was used in the study. The experimental plots were 1.5 m × 2 m (3m²) in size, with rows separated by 0.3 m. The distance between plots and blocks was 0.5 m and 1m, respectively. Each plot had five rows, with the middle three used for the collection of the data and the two outermost rows were used as border rows. The experimental sites were plowed three times with draught animals called oxen before planting, and 25 kg ha⁻¹ was used for planting. After weighing the seeds with a sensitive balance, they were assigned to each row, and drilling was used for planting. Planting oc-

curred during 2022 and 2023 main cropping seasons, following the onset of rain and when the locations received the moisture required for germination. Hand weeding was used three times during the experiment's growing seasons, and 30 kg ha⁻¹ of urea and 50 kg ha⁻¹ of NPS fertilizer were used according to crop recommendations. Harvesting begins in the last week of November of each cropping year, based on the maturity time of the varieties.

2.4. Data Collection

Data on flowering days, maturity days, number of primary branch/plant, capsule number/plant, plant height, and seed yield per plot were collected from the three middle rows. Data

for days to flowering, days to maturity, and seed yield were collected on a plot basis on three middle rows.

1. Days to flowering- were calculated from the date of planting when 75% of the crop stand produced the first flower.
2. Days to maturity- The number of days from planting to physiological maturity of the plants was used to compute the days to maturity.
3. Plant height- the average height of five randomly selected plants, measured from the base to the tip of the plant.
4. The number of primary branch/plant- was recorded as the average number of primary branch from five randomly sampled plants taken from the three middle rows of the plots.
5. The number of capsules per plant- It was calculated as the mean number of capsules collected from five randomly selected from the three middle rows of the plots.
6. Seed yield (kg plot⁻¹) - It was calculated as the entire seed yield produced from the plants harvested and threshed and converted into seed yield per hectare.

2.5. Analysis of Variance

The ANOVA was run for the three locations separately and combined over the three locations for all characters using R software. Analysis of variance was carried out to partition the variance due to genotype, environment and genotype by environment interaction, replication within environment and block within replication. The combined analysis of variance was carried out to estimate the additive effects of the environment, genotype and GEI. Analysis of variance was done using R-Software after testing the ANOVA assumptions. Mean separations were estimated using Least Significant Difference (LSD) for the comparison among the experimental varieties at 0.05 probability level.

ANOVA model for a single location as:

$$Y_{ijk} = \mu + G_i + R_j + B_{kj} + E_{ijk}$$

ANOVA model for the combined over locations as:

$$Y_{ijk} = \mu + G_i + L_j + R_k(L_j) + Br(L_j R_k) + G_i L_j + E_{ijk}$$

Where Y is the performance of genotype i in jth location, kth replication and rth incomplete block, μ is the mean effect, L_j is the effect of jth location, $R_k(L_j)$ the effect of the kth replication in location J, $Br(L_j R_k)$ is the effect of rth incomplete block in jth location and kth replication, $G_i L_j$ is the interaction effect of genotype i and location j and e_{ijk} is the error associated with the ith genotype, jth location, kth replication, rth incomplete block.

2.6. Stability Analysis

Yield stability of the genotypes was evaluated using

different models: Yield stability index (YSI), AMMI Stability Value (ASV), Additive Main Effect and Multiplicative Interaction (AMMI) model and Genotype Main Effect and Genotype x Environment Interaction Effect (GGE) biplot analysis were used to determine the effects of GEI on yields. These analyses also were performed using R software.

2.6.1. Yield Stability Index (YSI)

This measurement was developed by [17]. Stability by itself should not be the only measurement for selection, because the most stable genotypes would not necessarily give the best yield performance. This method is vital to measure and rank genotypes based on grain yield stability. The summation of rank of ASV and rank of yield are used to calculate YSI. The genotype with least YSI is considered as the most stable with high grain yield [18].

YSI was calculated as:

$$YSI = RASV + RY$$

Where: RASV is the rank of AMMI stability value, RY is the rank of mean yield of genotypes across environments.

2.6.2. AMMI Stability Value

The ASV is the distance from the coordinate point to the origin in a two dimensional scatter length of IPCA1 scores against IPCA2 scores in the AMMI model [16]. AMMI Stability Value (ASV), length of genotype and environment markers of the origin in a two dimensional plot of IPCA1 scores against IPCA2 scores was calculated as follow [16]

$$ASV = \sqrt{\left[\frac{IPCA1 \text{ Sum Squares}}{IPCA2 \text{ Sum Squares}} (IPCA1 \text{ Score}) \right]^2 + [IPCA2 \text{ Score}]^2}$$

Where: IPCA1= interaction principal component axis 1; IPCA2 = interaction principal component, axis 2. Genotypes with lower values of the ASV are considered to be more stable.

2.6.3. Additive Main Effect and Multiplicative Interaction (AMMI) Model

Additive Main Effect and Multiplicative Interaction (AMMI) is one of most widely used model to explain G×E interaction of multi-environment genotype trial and categorizing the genotypes into narrow or wider adaptation [19]. The AMMI analysis uses analysis of variance (ANOVA) followed by a principal component analysis applied to the sums of squares allocated by the ANOVA to the GEI [20].

The AMMI Model Equation is:

$$\bar{Y}_{ijk} = \mu + G_i + E_j + \sum_{m=1}^M \lambda_m \alpha_{im} \gamma_{jm} + P_{ij}$$

Where: \bar{Y}_{ijk} = the yield of the ith genotype in the jth environment, G_i = the mean of the ith genotype minus the grand

mean, E_j = the mean of the j^{th} environment minus the grand mean, λ_k = the square root of the Eigen value of the k^{th} IPCA axis, α_{ik} and γ_{jk} = the principal component scores for IPCA axis k of the i^{th} genotypes and the j^{th} environment, P_{ij} = the deviation from the model.

2.6.4. Genotype Main Effect and Genotype by Environment Interaction (GGE) Biplot

The GGE biplot [18] model is: $Y_{ij} - \mu - \beta_j = \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \epsilon_{ij}$ where: Y_{ij} = the performance of the i^{th} genotype in the j^{th} environment; μ = the grand mean; β_j = The main effect of the environment j ; λ_1 and λ_2 = Singular value for IPCA1 and IPCA2 respectively;

ξ_{i1} and ξ_{i2} = Eigen vectors of genotype i IPCA1 and IPCA2 respectively; η_{j1} and η_{j2} = Eigen vectors of environment j for IPCA1 and IPCA2 respectively; ϵ_{ij} = Residual associated with genotype i and environment j .

3. Results and Discussions

3.1. Analysis of Variance

The ANOVA revealed highly significant differences ($p < 0.01$) for seed yield at Bedeele-2023 only and significance differences ($p < 0.05$) at Dabo Hana-2022, Dabo hana-2023, Bedele-2022 and Didesa-2023.

3.1.1. Seed Yield

The average environmental seed yield across varieties ranged from the lowest of 1088.7 kg ha^{-1} at Didesa -2023 to the highest of 1662.9 kg ha^{-1} at Dabo Hana-2023), with a grand mean of 1294.6 kg ha^{-1} (Table 4). The varieties average seed yield across environments ranged from the lowest of 978.9 kg ha^{-1} for local check to the highest of 1588.9 kg ha^{-1} for Kuma (Table 3). This difference could be due to their genetic potential of the varieties, and also environment explained large variation indicated the existence of diverse mega environments.

Table 3. Mean seed yield (kg ha^{-1}) of twelve (12) linseed varieties evaluated at six environments.

Mean of seed yield of 12 linseed varieties across environment						
Varieties	D/Hana-2022	D/Hana-2023	Bedele-2022	Bedele-2023	Didesa-2023	Mean
Bekoji 14	2288.89 ^a	1400.00 ^{bc}	1233.33 ^{abc}	1444.4 ^a	1016.7 ^{bc}	1476.7 ^{ab}
Kassa-2	1633.33 ^{bcd}	1434.44 ^{abc}	1177.78 ^{bc}	1077.8 ^{abc}	1000.0 ^{bc}	1260.2 ^{bc}
Welen	1511.11 ^{bcd}	1544.44 ^{ab}	1144.44 ^{bc}	1400.0 ^a	1066.7 ^{bc}	1333.3 ^{abc}
Bekoji	1633.33 ^{bcd}	1355.56 ^{bcd}	1033.33 ^c	773.3 ^{cd}	1225.6 ^{ab}	1204.2 ^{cd}
Kuma	1788.89 ^b	1527.78 ^{abc}	1566.67 ^a	1627.8 ^a	1433.3 ^a	1588.9 ^a
Yadano	1322.22 ^{cd}	1722.22 ^a	1077.78 ^c	1244.4 ^{abc}	1277.8 ^{ab}	1328.9 ^{bc}
Furtu	1755.56 ^{bc}	1416.67 ^{bc}	1455.56 ^{ab}	788.9 ^{bcd}	1233.3 ^{ab}	1330.0 ^{abc}
Bakalcha	1577.78 ^{bcd}	1090.00 ^d	1146.67 ^{bc}	1264.4 ^{abc}	794.4 ^c	1174.7 ^{cd}
Dibanne	1744.44 ^{bcd}	1473.33 ^{abc}	1077.78 ^c	1466.7 ^a	983.3 ^{bc}	1349.1 ^{abc}
Horesoba	1725.00 ^{bcd}	1296.67 ^{bcd}	1250.00 ^{abc}	1373.3 ^{ab}	1058.3 ^{bc}	1319.3 ^{bc}
Jitu	1750.00 ^{bcd}	1368.33 ^{bcd}	1000.00 ^c	694.4 ^{cd}	950.0 ^{bc}	1191.3 ^{cd}
Local	1255.56 ^d	1244.44 ^{cd}	1066.67 ^c	338.9 ^d	988.9 ^{bc}	978.9 ^d
Mean	1662.96	1404.17	1192.78	1124.5	1088.7	1294.6
LSD (0.05)	440.23	291.80	378.56	590.61	322.2	259.8
CV %	16.08	12.16	17.87	31.02	16.95	27.8
P-value	*	*	*	**	*	**

3.1.2. Yield Related Traits

The results of the combined analysis of variance are depicted in Table 4. The combined analysis of variance over the five sites for two seasons revealed a significant ($P < 0.01$) difference in flowering days and maturity days however, non-significant for plant height, number of primary branch and number of capsule per plant between the studied varieties.

Accordingly, the tested linseed varieties shows statistically significant variation that ranged from 47.1 (Kassa-2) and 85.0 (Local check) for days to flowering and 127.8 (Kassa-2) to 153.4 (local check) for days to maturity. From this result kassa-2 was the earliest to maturity whereas local check was the late maturing variety. A similar result was reported by (F. Amsalu *et al.*, 2020).

Table 4. Combined mean yield and other parameters of linseed variety adaptation trial across the three locations.

Varieties	DTF (days)	DTM (days)	PLH (cm)	NPB/PL	NC/PL	Dis. Reac.
Bekoji-14	59.2 ^{cd}	144.9 ^b	80.4	5.2	27.6	0
Kassa-2	47.1 ^g	127.8 ^f	81.2	5.7	27.9	0
Welen	52.9 ^f	131.5 ^e	74.7	4.4	23.8	0
Bekoji	56.9 ^{de}	142.9 ^{bcd}	80.1	4.9	26.9	0
Kuma	62.8 ^{bc}	142.0 ^d	79.4	5.2	27.3	0
Yadano	56.9 ^{de}	144.3 ^{bc}	70.9	4.2	23.3	0
Furtu	63.7 ^b	131.7 ^e	77.9	4.4	22.1	0
Bakalcha	54.0 ^{ef}	130.0 ^e	73.8	4.4	21.6	0
Dibanne	57.3 ^{de}	142.8 ^{bcd}	78.3	4.0	23.8	0
Horesoba	57.2 ^{de}	142.2 ^{cd}	76.5	4.6	23.5	0
Jitu	56.6 ^{de}	142.6 ^{cd}	79.3	4.4	25.1	0
Local	85.0 ^a	153.4 ^a	78.4	4.5	22.7	0
Grand Mean	59.1	139.68	77.6	4.7	24.6	
LSD (0.05)	3.6	2.15	6.9	1.0	6.2	
CV %	8.5	2.14	12.3	9.6	14.7	
P-value	***	***	NS	NS	NS	

3.2. Combined Analysis of Variance for Seed Yield and Yield-Related Traits

The combined analysis of variance showed that significant differences were recorded across location for most of parameters except number of primary branch per plant and number of capsule per plant. After testing the homogeneity of error vari-

ances of the test locations, the combined analysis of variance was conducted for each trait with special focus on grain yield and other agronomic traits in order to examine the presence of significant effect of locations, varieties and varieties x location interactions. The mean square of analysis of variance (ANOVA) is presented in Table 5. Significant differences were detected among the main and the interaction effects at ($p \leq 0.05$) and ($p < 0.001$) for most of the parameters.

Table 5. Mean square value of combined Analysis of Variance (ANOVA) for seed yield and yield related traits of twelve (12) Linseed varieties tested at three locations for two years.

SOV	DF	DTF (days)	DTM (days)	PLH (cm)	NPB/PL (no)	NC/PL (no)	SY (kg ha ⁻¹)
Loc.	4	11.07 ^{ns}	9.20 ^{ns}	1947.41 ^{***}	15.22 ^{***}	1222.38 ^{**}	2064407 ^{**}
Rep.	2	0.71 ^{ns}	21.05 [*]	37.44 ^{ns}	0.3098 ^{ns}	26.87 ^{ns}	3895 ^{ns}

SOV	DF	DTF (days)	DTM (days)	PLH (cm)	NPB/PL (no)	NC/PL (no)	SY (kg ha ⁻¹)
Yr.	1	18.78 ^{ns}	1.00 ^{ns}	2557.94***	56.94***	1047.82***	962579***
Var.	11	1278.28***	877.47***	141.46***	2.86*	76.42 ^{ns}	356370**
Var.*Loc.	22	151.33***	28.26***	69.06**	2.17 ^{ns}	51.63 ^{ns}	104936*
Var.*yr.	11	4.54 ^{ns}	10.44*	90.67*	1.35 ^{ns}	71.10 ^{ns}	166036**
Loc.*yr.	2	2.35 ^{ns}	3.55 ^{ns}	40.30 ^{ns}	0.04 ^{ns}	1205***	163402*
Var.*Loc.*yr.	22	1.17 ^{ns}	3.37 ^{ns}	13.10 ^{ns}	0.89 ^{ns}	18.51 ^{ns}	182392**
Pooled error	118	6.19	5.42	38.56	1.52	41.73	60645
CV		8.50	2.14	12.30	9.60	14.70	27.80

Remark: SOV=source of variations, DF=degree of freedom, DTF=days to flowering, DTM=days to maturity, PLH=plant height, NPBPL=number of primary branch per plant, NCPPL=number of capsule per plant, GY=grain yield, Loc.=Location, Rep=replication, yr.=year, Var.=variety, CV=coefficient of variations, *=significant 0.05 probability level, **=significant at 0.01 probability level, ***=significant at 0.001 probability level

3.3. Stability Analysis

3.3.1. Yield Stability Index (YSI)

Yield stability index incorporates both mean yield and stability in a single criterion. The minimum values of YSI desirable genotypes with high mean yield and stability.

3.3.2. AMMI Stability Value (ASV)

The ASV measure was proposed to cope up the fact that the AMMI model does not make a provision for a quantitative

stability measure [14]. Depending on this method, genotype with least ASV score is the stable, accordingly, variety Kassa-2 followed by Kuma and Horesoba were the most stable respectively. While local, Bekoji-4, Furtu, Dibanne and Jitu were unstable varieties (Table 6). The greater the IPCA scores (Negative or Positive), the more specifically adapted variety is to certain environment. The closer the IPCA scores to zero, the more stable the genotype over the tested locations. The further away from zero the IPCA score for the environments is the more interaction the environment has with the genotypes, thus making difficult to choose genotypes for that environment.

Table 6. The first and second IPCA, Grain Mean yield and different yield stability statistics investigated in linseed varieties over locations.

Code	Varieties	Yield (kg ha ⁻¹)	rY	PCA1	PCA2	ASV	rASV	YSI
1	Bekoji-14	1476.7	2	9.72	-16.40	23.69	11	13
2	Kassa-2	1260.2	8	-0.29	0.68	0.85	1	9
3	Welen	1333.3	4	6.44	8.88	14.38	4	8
4	Bekoji	1204.2	9	-9.45	-1.37	16.67	5	14
5	Kuma	1588.9	1	5.04	5.01	10.74	2	3
6	Yadano	1328.9	6	-1.48	17.55	17.74	6	12
7	Furtu	1330.0	5	-12.22	-5.04	22.06	10	15
8	Bakalcha	1174.7	11	10.04	-2.98	17.90	7	18
9	Dibanne	1349.1	3	10.5	1.01	18.47	9	12
10	Horesoba	1319.3	7	7.85	-0.22	13.80	3	10
11	Jitu	1191.3	10	-9.02	-9.02	18.25	8	18
12	Local	978.9	12	-17.49	1.91	30.79	12	24

Remark: rY=rank in yield, PCA=principal component Axis, ASV=AMMI stability value, rASV=rank in AMMI stability value, YSI=yield stability value

3.3.3. Additive Main Effects and Multiple Interaction (AMMI) Model

The mean squares for all varieties evaluated under different environmental condition for seed yield are presented below (Table 7). The result indicated that differences among all varieties were significant ($P \leq 0.01$). Variation due to genotypes by environments interaction was significant for the studied traits, indicated that genotypes differ genetically in

their response to different environment. The genotypes by environments interaction was significant effect on the seed yield, which explained 19.42% of the total variation while the genotypes, contributed 12.40% of the variation. However, large portion (26.11%) of the total variation was attributed to the environmental effect. The environment explains a major amount of the yield differential, showing that the environments were different, according to AMMI.

Table 7. Additive main effect and multiplicative interaction analysis of variances (AMMI) for seed yield of twelve Linseed varieties.

Source	D.F.	S.S.	EX.SS %	M.S.
Environments	4	8257629	26.11	2064407**
Block	10	467602	1.48	46760 ^{ns}
Genotypes	11	3920071	12.40	356370*
Interactions (G x E)	44	6141309	19.42	139575**
PCA1	14	3408677	10.78	243477*
PCA2	12	1939471	6.13	161623*
PCA3	10	642666	2.03	64267 ^{ns}
PCA4	8	150494	0.48	18812 ^{ns}
Residuals	110	6696354	21.17	60876
Total	223	31624273	100	141813

Remark: DF=degree of freedom, SS=sum of square, EXSS=explained sum of square, MS=mean sum of square, PCA= = Interaction Principal Component Axis

(i). AMMI 1 Biplot

In AMMI biplot 1 showing main effects means on the abscissa and principal component (IPCA) values as the ordinates, genotypes (environments) that appear almost on a perpendicular line have similar means and those that fall on the almost horizontal line have similar interaction patterns. Genotypes that group together have similar adaptation while environments which group together influences the genotypes in the same way. Genotypes (environments) with large IPCA1 scores (either positive or negative) have high interactions whereas genotypes (environments) with IPCA1 score near zero have small interactions.

AMMI-I consider genotype and locations main effects plus the PCA1 to interpret the residual matrix and represented genotype productivity. It is further stated that any genotype with PCA1 value close to zero shows general adaptation to the tested locations whereas a large genotypic PCA1 score reflects more specific adaptation to location with PCA1 scores of the same size. Genotypes and locations with IPCA1 scores of the same

sign produce positive interaction suggesting adaptation of genotypes in those locations whereas the reverse sign of PCA value of genotypes and locations depicts negative interaction i.e., poor performance of genotypes in such locations. In summary, a stable genotype might not be the highest yielding. Genotypes having a zero IPCA1 score are less influenced by the locations and adapted to all locations. The closer the IPCA score to zero, the more stable the genotypes over the tested locations. Since IPCA1 scores of soybean varieties Welen, Horesoba and Kassa-2, were close to zero, they were more stable varieties that across these locations. However, the mean yield of Kassa-2 had a mean yield below average, therefore, they are least preferable. A variety showing high positive interaction in location has the ability to exploit the agro ecological and agro-management conditions of the specific location and is therefore best suited to that location. In this case, Kuma and Bekoji-14 linseed varieties are suited for Dabo Hana. Furtu is suited for Dabo Hana-2023, Bakalcha is suited for Bedele-2023 & Jitu variety is suite for Bedele-2022.

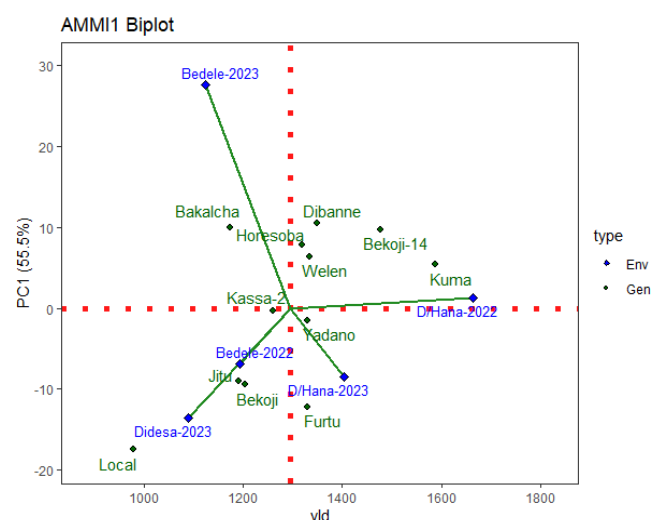


Figure 1. AMMI bi plot of IPCA 1 against grain yield of 12 linseed varieties across locations.

(ii). AMMI 2 Biplot

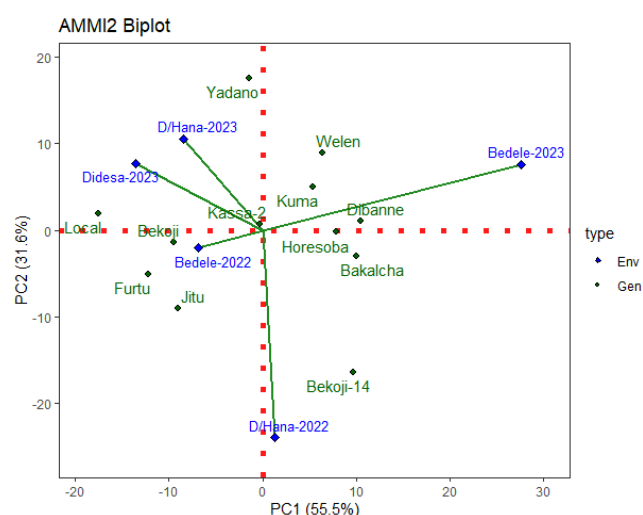


Figure 2. AMMI bi plot of IPCA 1 against PCA2 of 12 linseed varieties across locations.

In AMMI2 biplot, the distances from the biplot origin are indicative of the amount of interaction exhibited by genotypes over environments or environments over genotypes. Genotypes located near the biplot origin are less responsive than the vertex genotypes indicating general adaptability to all environments. Environments with longer vectors are very interactive and discriminate the differences among genotypes more than environments with shorter vectors. Shorter vectors are less interactive and provide little or no information about the differences among genotypes' performances [15]. In this study local check, Yadano, Furtu and Bekoji-14 linseed varieties placed farthest away from the biplot origin & expressed a highly interactive behavior (positively or negatively) whereas Kassa-2, Kuma and Horesoba placed relatively close to the

biplot origin expressed less interaction and more adaptable to all locations. In AMMI 2 biplot, those environments having shorter length of arrow do not create strong interaction while those with long length of arrow has strong interaction and they are not favorable to all genotypes. In the present study, Bedele-2022 and Dabo Hana-2023 having shorter spokes interact less with the genotypes whereas Bedele-2023, Dabo Hana-2022 and Didesa-2023 having longer spokes or length of the arrow line exerts high interaction with the genotypes (Figure 2).

3.3.4. GGE Bi-plot Analysis for Grain Yield

(i). Ranking of Genotypes

Stability can be identified using concentric circles and also ideal genotypes are at the center of the concentric circle. The ideal genotype is the one that with the highest mean performance and absolutely stable [12]. The genotypes that are closer to the ideal genotypes are the best performing genotypes. Hence, the GGE bi plots shows that Kuma is an ideal variety, with other varieties, like Dibane, Horesoba, Welen and Bekoji-14 are desirable varieties as they are closer to the ideal variety on the bi plot. The varieties local and Jitu are the most undesirable varieties as they are too far to the ideal variety on the bi plot.

(ii). Ranking of Environments

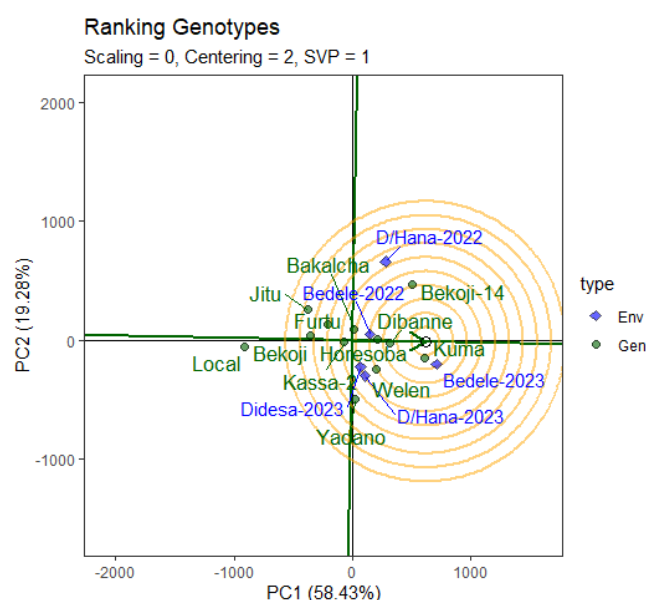


Figure 3. Ranking of the genotypes based on the ideal genotype.

The most representative of the locations (ability to represent the megaenvironment) and the most powerful to discriminate varieties reported that the ideal environment is the one located at the center of the concentric circles, and it is possible to identify desirable environments based on their

closeness to the ideal environment [15] reported that a testing location has less power to discriminate genotypes when located far away from the center of the concentric circle or to an ideal location. Therefore, among the test locations, location Bedele which fell into the center of concentric circles was an ideal test location in terms of being the most representative of the overall locations and the most powerful to discriminate the performance of the tested genotypes. Next to the first concentric circle location, locations Dabo Hana-2022 is close to the ideal location while, Didesa is detected as the weakest locations to discriminate varieties.

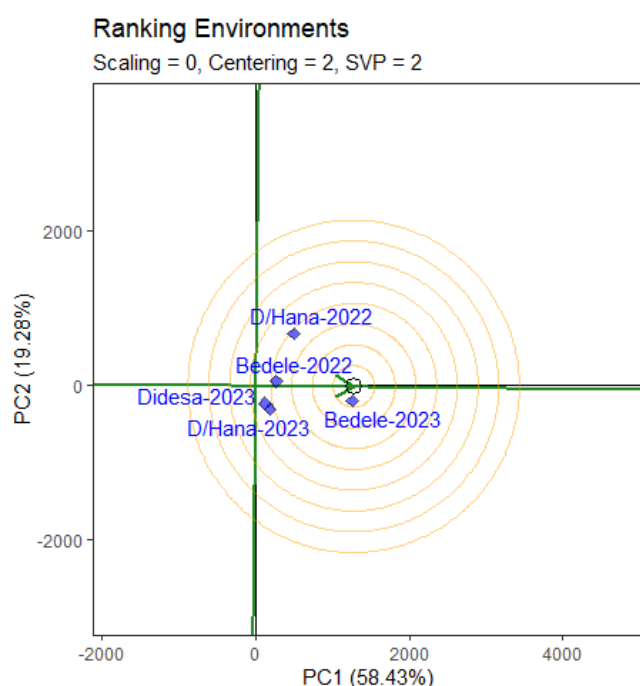


Figure 4. Ranking of the locations based on the ideal locations.

(iii). Which-Won-Where Pattern

The polygon view of GGE bi plot indicates the best genotypes in each environment and group of environments [13]. In this situation, the polygon is formed by connecting the genotypes that are farthest away from the bi plot origin, such that all the other genotypes are contained in the polygon. In this case, the polygon connects all the farthest genotypes and perpendicular lines divide the polygon into sectors. Sectors help to visualize the mega-environments. This means that winning genotypes for each sector are placed at the vertex. Polygon view of the linseed varieties tested at three locations presented in (figure 5). The genotypes found at the vertex of the polygon perform best in the environments within the sector [14]. Six rays divide the bi plot in to six sector and the locations fall in to three different mega-environments (Figure 5).

Accordingly, Yadano, Kuma, Bekoji-14, Jitu and local varieties were the vertex varieties. From this figure, Yadano

variety best performer at Didesa and Dabo Hana 2023 in mega environment. The second environment containing the higher yielding environment Bedele-2023, with winner variety Kuma. The third environment includes Dabo Hana-2022 with a winner variety Bekoji-14. From the figure, Jitu and local had no environment on the vertex. This indicates that varieties in the vertex without environment performed poorly in all the locations.

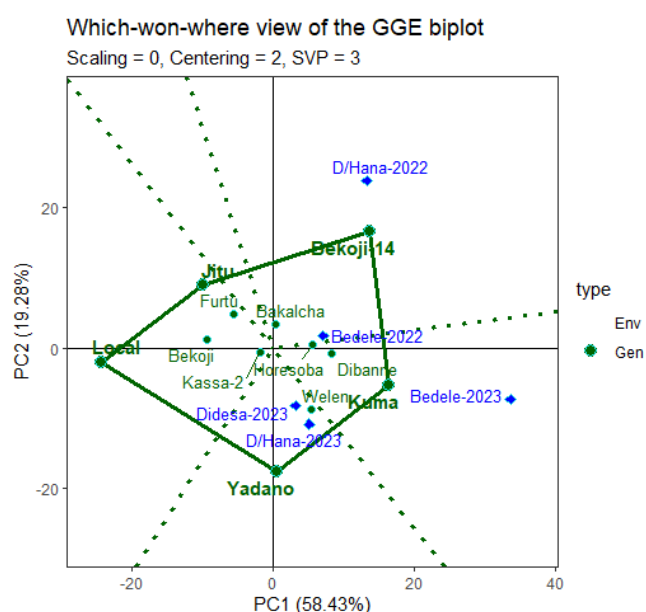


Figure 5. Which won where pattern.

4. Conclusion and Recommendation

Combined analysis of variance (ANOVA) result revealed significant difference of seed yield and most of yield contributing traits among evaluated Linseed varieties across locations, years and the interactions. This indicated that, the location and fluctuation of weather condition over the cropping season had affected performance of varieties. Although the GEI of grain yield partitioned in to different IPCAs using AMMI model analysis, the first principal component axis for interaction alone explains most of the interaction sum of squares. The sign and magnitude of IPCA scores showed the relative contribution of each genotype and environment for the genotype and environment interactions.

This helps to summarize the pattern and magnitude of GEI and main effects that reveal clear insight into the adaptation of genotypes to environments. This shows that, Kuma and Bekoji-14 varieties are fewer contributors to the interaction effect and have consistent performances across locations. Therefore, Kuma and Bekoji-14 were identified as the best varieties in terms of yielding ability, stability and better agronomic performance.

Abbreviations

ANOVA	Analysis of Variance
GGE	Genotype, Genotype by Environment Interaction
JARC	Jimma Agricultural Research Center
LSD	Least Significant Difference
IPCA	Interactive Principal Component Axis
RCBD	Randomized Complete Block Design

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Author Contributions

Mohammed Tesiso: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing

Garoma Firdisa: Conceptualization, Resources, Supervision

Conflicts of Interest

The authors declare no conflicts of interest.

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