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Research Article

Genetic Variability and Heritability of Morpho-Agronomic Traits, Oil Yield and Fatty Acid Components in Linseed (*Linum usitatissimum* L.) Germplasm in Ethiopia

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Abstract

Comprehensive information on genetic variability and selection parameters is very crucial to design breeding strategies. However, very limited information is available in Ethiopian linseed germplasm. Therefore, the present study was conducted to estimate genetic variability, broad sense heritability and genetic advance; and determine selection for 19 quantitative traits using 126 genotypes (120 Ethiopian linseed accessions and six released varieties). The analysis of variance showed highly significant ($P < 0.01$) differences for all of the traits demonstrating the presence of high genetic diversity among the studied linseed genotypes. Higher differences between PCV and GCV estimates were observed for seed yield per plant and biological yield per plant, signifying the importance of environmental factors influence. High heritability coupled with high genetic advance was observed for seed yield per plant and biological yield per plant, indicating that this high heritability is due to additive gene effects and therefore, selection can be effective for the improvement of linseed for these traits. In addition, moderate heritability coupled with moderate genetic advance was recorded for oil yield per hectare, number of capsules, number of secondary branches, days to maturity, seed yield per hectare and plant height. These results indicated the existence of intermediate expression in these traits for both additive and dominance gene effect. In the present study, high heritability coupled with high GAM was observed for seed yield per plant and biological yield per plant, indicating greater contribution of additive gene action for the expression of these traits; and therefore, improvement can be achieved through selection in these traits.

Keywords: Additive Effect; Coefficient of Variation; Genetic Advance

Introduction

Linum usitatissimum is one of the nearly 230 species of the family Linaceae which comprises about 14 genera. *Linum usitatissimum* is an annual herbaceous whose genus *Linum* includes nearly two thirds of the total species of the Linaceae family. Despite this remarkable diversity, linseed is the only cultivated species in that family [1]. Flax is a self-pollinated species with a genome size approximately 370 Mb [2]. There is a general consensus that the species may have originated in the regions east of the Mediterranean Sea towards India (Mhiret and Heslop [3]; Vavilov [4]) and spread throughout Asia and Europe. Linseed was first domesticated in the region known as the Fertile Crescent (Hoque [5]; Adugna and Labuschagn [6]). Divergent selection applied over thousands of years has resulted in fiber and linseed types which are the same species but differ considerably in morphology, anatomy, physiology and agronomic performance (Mhiret and Heslop [3]; Worku [7]; Liu [8]). The linseed type, grown for oil extracted from the seed, is a relatively short plant which produces many secondary branches compared to the flax type, grown for the fiber extracted from the stem, which is taller and less branched (Zare [9]; Debelo [10]).

Flax has been a source of food, feed, fiber, and medicine for more than 8,000 years (van Zeist and Bakker-Heeres [11]). Linseed oil provides health benefits mainly due to its high content in omega-3 alpha linolenic acid (55-57%). Moreover, linseed oil has valuable attributes in paints and varnishes because of its unique drying properties that result from its distinctive fatty acid composition (De Silva and Alcorn [12]). The lignans contained in linseeds have been shown to have beneficial properties against breast, colon, prostate and thyroid cancer, and in lowering relative risk factors for heart disease (Adolphe [13]).

Linseed produced on 48285.56 hectares of land by 544606 farmers and produced 44398.432 tons in Ethiopia during 2021/22 Meher season. Linseed is the fourth largest produced oil crop in which it accounted 24.65, 9.25 and 8.2% of farmers, cultivated land and total production of oil crops, respectively. The average national yield was 0.919 t ha^{-1}(ESS, [14]). The low productivity in Ethiopia might be associated with the narrow genetic base and non-availability of high yielding varieties, cultivation in marginal lands and vulnerability to biotic and abiotic stresses (Debelo [10]).

Genetic variability plays the fundamental role in any plant breeding program. Quantifying genetic diversity present in crop species is of greatest importance as it provides the basis of selection for traits of interest (Hussain [15]; Kumar [16]; Tadele [17]). Additionally, reliable estimates of genetic and environmental variations are helpful in estimating the heritability and predicted genetic gain from selection (Debelo [10]; Mulusew [18,19]; Mhiret and Heslop [3]; Worku [7]; Adugna and Labuschagne [6]). Overall, comprehensive knowledge on genetic variability, heritability and genetic advance allows geneticists and breeders to design breeding strategies for the improvement of crop productivity and quality (Johnson [20]).

Heritability and genetic advance are important selection parameters (Rajannia [21]; Singh [22]). Heritability estimates can be grouped as broad sense heritability or narrow sense heritability (Debelo [10]; You [23]) Broad sense heritability provides information on the relative magnitude of genetic and environmental variation in specific population (Soroha [24]; Hussain [15]; Kumar [16]; Tadele [17]; Adugna and Labuschagne [6]). Genetic advance is the measure of genetic gain under selection and depends on genetic variability, heritability and selection intensity. Genetic advance also indicates the mode of gene action in the expression of traits and helps in choosing breeding methods (Rajanna [21]). Thus, heritability estimates coupled with genetic advance are more reliable and helpful in predicting the gain under selection than individual consideration of the parameters (Johnson [20]).

In linseed, genetic variability studies had been conducted by many researchers (Debelo [10]; Mhiret and Heslop [3]; Worku [7]; Mulusew [18,19]; Tadele [17]; Adugna and Labuschagne [6]) using quantitative traits and proved the presence of high genetic variation among studied genotypes. Heritability and genetic advance had also been estimated for yield and related traits by several authors (Ashok [25]; Hussain [15]; Kumar [16]; Tadele [17]; Adugna and Labuschagne [6] 2004). However, in Ethiopia large number of linseed genotypes (accessions) was collected by BID (Institute of Biodiversity) but, very limited research has been done in Ethiopian. Therefore, the present study was conducted to estimate genetic variability, heritability and genetic advance of morpho agronomic traits, oil yield and fatty acid components to determine selection in Ethiopian linseed accessions

Materials and Methods

Experimental sites

The study was conducted during 2019/20 in central Ethiopia in two locations, namely, Holeta (9^{0}03′41″N, 38^{o}30′44″ E) and Kulumsa (08^{0}01′10″N, 39^{o}09′11″ E). Holeta and Kulumsa are agricultural research stations of Ethiopian Institute of Agricultural Research (EIAR). These two sites represent agro-ecology of highland oil crops in Ethiopia. Holeta and Kulumsa are situated at an altitude of 2400 and 2200 m above sea level and receive a total rainfall of 976 and 820 mm, respectively. The mean minimum and maximum temperatures at Holeta site range from 6.1 to 22.4 °C. Kulumsa has an average minimum and maximum temperature of 10.5 and 22.8 °C. Holeta and Kulumsa has nitosol and luvisol soil types and soil PH 4.9 and 6, respectively [26,27].

Descriptions of experimental materials

A total of 126 genotypes were evaluated of which the seeds of 120 accessions were obtained from Ethiopian Biodiversity Institute (EBI) collected from Tigray, Amhara, Oromia and SNNP administrative regions and different geographic regions and altitudes (1480 to 3440 m.a.s.l.) (Appendix Table 1). The seeds of six improved varieties were obtained from Holeta and Kulumsa Agricultural Research Centers. Belay-96, Berene and Chilalo (Kulumsa-1) released in 1997, 2001 and 2006, respectively, while Jeldu, Kasa-2 and Bekoji released in 2010, 2012 and 2014, respectively (Appendix Table 2) (EAA [28]). Seven altitude classes were made using the formulae: K = l + 3.32log10n and i = Range/K (Agarwal [29]); Where i = class interval width, K = number of classes and n = sample size.

	Weather variable					
	Minimum temperature (°C)		Maximum temperature (°C)		Precipitation (mm)	
Month	Holeta	Kulumsa	Holeta	Kulumsa	Holeta	Kulumsa
January	8	8.2	24	22.8	15.9	19
February	9	9.2	25	23.7	41.6	67
March	11	10.9	26	24.6	73.3	86
April	12	12	25	24.8	91.9	120
May	12	12.1	25	24.4	89.4	82
June	11	11.2	24	23.2	106.3	90
July	12	11.2	22	21.2	211	122
August	12	11	22	21	203.9	135
September	11	10.7	22	21.4	132.3	107
October	9	10.6	23	23	36.7	38
November	7	9	23	22.6	8	11
December	7	7.5	23	23	6	9
Mean	10.08	10.30	23.67	22.98	84.69	73.83

Table 1: Weather conditions of Holeta and Kulumsa Research Centers during cropping season 2019/20.

Source: Metrology Stations of Holeta and Kulumsa Agricultural Research Centers

Experimental design and management

The experiment was conducted under field conditions and laid out using alphalattice design (Patterson and Williams [30]), with two replications, at each location. In each replication there are 21 blocks and six plots in each block at each location. Each entry was planted in two rows plots of three meters in length, with an inter-row and intra-row spacing of 0.2 m and 0.1 m, respectively. The field management practices were practiced as the standard agronomic practices recommendation for linseed production by Holeta and Kulumsa Agricultural Research Centers [26,27].

Data collected

Data for days to 50% flowering and days to maturity were recorded from all plants at each plot. The growth traits and yield components viz. plant height(cm), primary branches, secondary branches, number of capsules, number of seeds per capsule, 1000 seed weight (g), biological yield per plant (g), harvest index (%), seed yield per plant and seed yield (kg/ha) data were collected from ten randomly taken plants at each plot. Carbohydrate (%), crude protein (%), oleic acid (%), linoleic acid (%), linolenic acid (%), oil yield per plant and oil yield per hectare (kg/ha)were determined from samples taken from seeds collected for each genotype at each location.

Data analysis

All the data were subjected to analysis using SAS software [3]. The combined analysis of variance (ANOVA) over two locations (Holeta and Kulumsa) was carried out according to the model:

Pijk = μ + gi + bk(j)(s) + rj(s) + ls + (gl)is + eijks

Where: Pijks = phenotypic value of i^{th} genotype under j^{th}replication at s^{th} location and k^{th} incomplete block within replication j and location s; μ = grand mean; g_i = the effect of i^{th} genotype; $b_{k(j)(s)}$ = the effect of incomplete block k within replication j and location s; $rj_{(s)}$ = the effect of replication j within location s; ls = the effect of location s; $(gl)_{is}$ = the interaction effects between genotype and location; and e_{ijks} = the residual or effect.

Estimation of genetic parameters

Phenotypic and genotypic variances and coefficients of variation

Estimates of variance components were computed using the formula suggested by Burton and De Vane [32] as follows.

- Genetic variance $\sigma_g^2 = \frac{MS_g - MS_{gl}}{lr}$ at combined over two locations
- Variance due to genotype by environment interaction

$= \sigma_{gl}^2 = \frac{MS_{gl} - MS_e}{r}$

- Intrablock error variance (σ_e^2)=MS_e
- Phenotypic variance (σ_p^2)=$\sigma_g^2+\sigma_g l^2+\sigma_e^2$

Where, σ^2gl = variance due to genotype by environment interaction, l = location, σ^2e = combined intra block error variance.

Estimation of phenotypic and genotypic coefficient of variations

$$\text{Phenotypic coefficient variation, PCV} = \frac{\sqrt{\sigma_p^2}}{\bar{x}} \times 100\%$$

$$\text{Genotypic coefficient of variation, GCV} = \frac{\sqrt{\sigma_g^2}}{\bar{x}} \times 100\%$$

$\bar{x}$ = Population mean of the character being evaluated

Heritability in broad sense

Heritability in the broad sense for quantitative traits will be computed using the formula suggested by Singh and Chaudhary [33]:

$$H = \frac{\sigma_g^2}{\sigma_p^2} \times 100\%$$

Where,

H = Heritability in broad sense.

σ_g^2 = Genotypc variance

σ_p^2 = Phenotypic variance

Expected genetic advance

Absolute genetic advance and as percent of mean at 5% selection intensity (k) will be calculated as suggested by Allard [34] as follows:

$$GA = k * \sigma_p * H$$

Where,

GA = Expected genetic advance,

σ_p = Phenotypic standard deviation on mean basis,

H = Heritability in broad sense,

k = Selection differential (k = 2.06 at 5% selection intensity)

Genetic advance as percent of mean (GAM) will be computed to compare the extent of predicted genetic advance of different traits under selection using the formula:

$$GAM = \frac{GA}{\bar{x}} * 100\%$$

Where,

GA = Expected genetic advance,

GAM = Genetic advance as percentage of mean

Results and Discussion

Coefficient of variation (CV)

The coefficient of variation (CV) over the entire genotypes (Table 2) showed the least CV was from Linolenic acid (5.22%) whereas the highest CV from biological yield per plant (26.32%). Although the CV for precision varies greatly with the characters measured and type of plant, the above CV for linseed showed high precision in the measure of linolenic acid (Gomez and Gomez [35]).

Accessions collected from SNNP and commercial varieties were with the least CVs (Table 3) for about 52.63% and 10.53% of morpho-agronomic traits, oil yield and fatty acid components, respectively. That is accessions from SNNP and commercial varieties were less variable.

Comparisons among altitudinal classes of accessions for CVs (Table 4) showed that accessions from altitude class I (1480-1700 m) were with the highest CV for number of secondary branches followed by biological yield per plant, but least CVs for linolenic acid oleic acid, days to 50% flowering, 1000-seed weight and linoleic acid. Accessions from altitude class II (1730-1970 m) showed the highest CVs for biological yield per plant followed by number of secondary branches, but with least CVs for oleic acid and linolenic acid. Accessions from altitude class III (1980-2210 m) were with the highest CV for biological yield per plant and number of secondary branches, but least CVs for linolenic acid and crude protien. Accessions from altitude class IV (2220-2460m) were with the highest CVs for biological yield per plant, number of secondary branches, number of capsules, oil yield per plant and oil yield per hectare, but least CVs for linolenic acid and crude protein.

Accessions from altitude class V (2480-2700 m) were with the highest CVs for biological yield per plant, number of capsules, number of secondary branches, and oil yield per plant, seed yield per plant, oil yield and seed yield per hectare. Accessions from altitude class VI (2710-2950 m) were with the highest CVs for number of capsules, biological yield per plant, days to maturity, oil yield per plant, seed yield per plant, oil yield and seed yield per hectare but with least CVs for oleic acid and linolenic acid. Accessions from altitude class VII (3040-3440 m) were with the highest CVs for biological yield per plant, number of capsules, oil yield per plant and oil yield per hectare but with least CVs for oleic acid and linolenic acid. This indicates that linseed accessions tend to be highly variable towards the higher altitude classes than the lowest altitude classes. This finding disagreed with the findings of Work [7] who reported as linseed accessions tend to be highly variable towards the lowest altitude classes than to the highest altitude classes.

Mean value

Accessions collected from Oromia showed the highest mean value (Table 3) for plant height, number of primary branches, number of secondary branches, and number of seeds per capsule, 1000-seed weight, biological yield per plant, oil yield per plant, seed yield per plant, oil and seed yield per hectare. Accessions collected from Tigray showed the highest mean values for days to maturity and harvest index. The highest mean values for number of capsules, crude protein, oleic acid, linoleic acid and linoleneic acid were from accessions collected from SNNP. In contrary, as Worku [7] and Mulusew [18,19]) reported, low days to maturity and oleic acid showed from linseed accessions collected from Tigray, respectively. Accessions from Tigray showed the highest mean value for days to maturity but the least mean value for plant height. Oromia and SNNP were similar with the results reported by Mhret and Heslop [3] for number of capsules and linolenic acid. The highest mean value for crude protein and oleic acid were from accessions collected from Tigray and SNNP (Worku [7]). Commercial varieties revealed high mean values for days to 50% flowering and carbohydrate content.

Accessions collected from altitude class I (1480-1700 m) (Table 4) showed the least mean values for days to maturity, oleic acid and linolenic acid, but the highest mean values for plant height, number of primary branches, number of capsules, 1000-seed weight, harvest index, carbohydrate content and seed yield per plant. This indicates that linseed accessions from low altitudes adapt to mature early using the available short cycle of rain fall. This is in agreement with the reports of Worku [7] and Mulusew [18,19]) on linseed accessions.

Accessions collected from altitude class II (1730-1970 m) were with the least mean value for days to 50% flowering and linoleic acid, but with highest mean value for biological yield, oil yield per plant and oil yield per hectare. Accessions collected from altitude class III (1980-2210 m) showed the least mean value for crude protein and maximum mean value for number of seeds per capsule. Accessions collected from altitude class IV (2220-2460 m) showed least mean value for plant height, number of primary branches, and number of seeds per capsule, 1000-seeds weight, biological yield, and oil yield per plant, seed yield per plant, oil yield and seed yield per hectare. Accessions collected from altitude class V (2480-2700 m) were with least mean values of number of capsules and harvest index. Accessions collected from altitude class VI (2710-2950 m) showed least mean value only for number of secondary branches.

Accessions collected from altitude class VII (3040-3440 m) were with the highest mean value for days to 50% flowering, days to maturity, number of secondary branches, crude protein, oleic acid, linolenic acid and seed yield per hectare, but with least mean value for carbohydrate content. This is in agreement with the finding by Worku [7] that the number of secondary branches tends to be inversly correlated with 1000-seed weight, and the smallest seeds are found in areas with the high rainfall.

Mulusew [18,19] and Worku [7]) reported that mean values are useful to determine variations within and between populations. Therefore, linseed accessions from Oromia and those from the high altitude class VII (3040-3440 m) are relatively high productive than the accessions from other regions and altitude classes, respectively. Accessions from lowest altitude class took 51and 50, and from highest altitude class, 61 and 63 days to flowering, and from flowering to maturity, respectively. This could be due to positive effect of longer growing season on growth. Maturing in the rainy season decreases the oil yield and seed yield per hectare and causes seed decay in linseed. This also agrees with the report of Worku [7]). Therefore, adapting to longer flowering and maturity time in higher altitudes characterized with longer rainy season is advantageous for linseed to flower and mature towards the end of the rainy season.

Parameter	Character									
	DF	DM	PH	PB	SB	NC	NSC	TSW	BYP	HI
Mean	52.73	106.53	59.91	8.51	18.56	46.58	7.11	6.91	14.97	32.76
Std	5.6	18.09	8.54	1.13	4.46	9.85	0.89	0.79	3.94	4.02
Min	41	87.65	43.73	6.04	10.78	23.15	5.73	4.97	7.89	22.63
Max	66.26	151.2	76.51	11.2	25.87	69.68	9.48	8.15	28.67	44.92
CV%	10.63	16.98	14.26	13.31	24.02	21.14	12.53	11.49	26.32	12.28
Parameter	**Character**									
	CRB	PRT	OA	LN	LNN	OYP	SYP	OYD	SYD	
Mean	26.27	19	22.07	9.26	50.52	190.69	4.68	953.47	2341.47	
Std	3.56	1.38	1.6	1.33	2.64	36.7	0.78	183.5	391.06	
Min	12.57	16.07	16.67	7.61	43.78	119.06	3.11	595.3	1555	
Max	33.03	24.82	25.71	14.7	58.03	313.64	6.43	1568.2	3215	
CV%	13.56	7.26	7.25	14.39	5.22	19.25	16.71	19.25	16.7	

Table 2: Mean, Std., Min., Max and CV for entire linseed genotypes (120 accessions and six commercial varieties).

DH= Days to heading, DM= Days to maturity, PH (cm) = Plant height, PB= Primary branches, SB= Secondary branches, NC= Number of capsules, NSC= Number of seeds per capsule, TGW=1000-grain weight, BYP=Biological yield per plant, HI= Harvest index, CRB= Carbohydrate PRT= crude protein, OA=Oleic acid, LN= Linoleic acid, LNN= Linolenic acid, OYP=Oil yield per plant, SYP=Seed yield Per plant, OYD= Oil yield and SYD= Seed yield.

Adm. Reg	Parameter	DF	DM	PH	PB	SB	NC	NSC	TSW	BYP	HI
TIGRAY	mean	53.29	111.5	57.21	8.04	18.77	41.91	6.78	6.53	13.82	33.6
(30 accessions)	Std	6.52	20.93	9.15	1.12	4.4	10.24	0.8	0.85	4.16	4.77
	CV%	12.24	18.77	15.99	13.99	23.45	24.44	11.73	13.05	30.06	14.19
	Range	25.26	63.55	32.78	5.06	14.83	36.95	3.65	2.86	20.78	22.29
AMHARA	MEAN	52.88	105.71	60.15	8.53	18.73	47.42	7.19	6.99	15.15	32.41
(46 accessions)	Std	5.37	17.08	8.31	1.08	4.46	9.21	0.9	0.72	3.69	3.71
	CV%	10.15	16.16	13.82	12.67	23.79	19.41	12.46	10.35	24.34	11.45
	Range	23.08	61.63	31.45	4.96	14.94	44.36	3.69	3.07	18.28	21.06
OROMIA	MEAN	50.75	101.68	63.07	9.09	19.02	50.25	7.41	7.22	16.29	32.62
(39 accessions)	Std	5.2	16.88	8.56	1.21	4.46	9.23	1	0.78	4.58	4.48
	CV%	10.24	16.6	13.57	13.32	23.45	18.37	13.45	10.8	28.1	13.73
	Range	20.89	54.97	28.71	3.94	13.71	39.9	3.15	2.69	17.56	19.35
SNNP	MEAN	53.54	101.56	61.42	8.48	15.29	51.06	7.16	7.11	14.33	33.25
(5 accessions)	Std	0.17	6.99	0.43	0.4	0.62	7.07	0.11	0.13	0.95	1.53
	CV%	0.32	6.89	0.7	4.67	4.02	13.85	1.58	1.79	6.66	4.59
	Range	0.24	9.89	0.61	0.56	0.87	10	0.16	0.18	1.35	2.16
COMM. VAR	MEAN	55.61	110.74	58.26	8.47	14.97	45.24	6.81	6.83	13.86	32.74
(6 varieties)	Std	4.51	18.61	6.27	0.69	4.61	11.55	0.52	0.89	1.83	1.31

	CV%	8.12	16.8	10.77	8.17	30.78	25.54	7.62	13.03	13.18	3.99
	Range	11.67	49.49	16.36	1.86	12.75	31.56	1.46	2.28	5.5	3.51

Adm. Reg	Parameter	CRB	PRT	OA	LN	LNN	OYP	SYP	OYD	SYD
TIGRAY	Mean	26.46	19.04	22.27	9.53	50.55	175.9	4.37	879.5	2186.33
(30 accessions)	Std	3.15	1.09	1.34	1.74	2.61	33.99	0.82	170	410.4
	CV%	11.9	5.72	6.01	18.21	5.16	19.32	18.77	19.32	18.77
	Range	15.86	4.91	4.78	7.07	11.8	132.58	3.32	662.9	1660
AMHARA	Mean	26.19	19.03	21.96	9.21	50.6	192.98	4.72	964.9	2358.85
(46 accessions)	Std	3.34	1.31	1.73	1.07	2.53	35.8	0.73	179	366.19
	CV%	12.77	6.88	7.88	11.63	5.01	18.55	15.52	18.55	15.52
	Range	17.61	6.92	9.04	5.48	11.66	194.58	3.22	972.9	1610
OROMIA	Mean	25.79	18.98	22.01	8.61	50.61	208.15	5.05	1041	2522.61
(39 accessions)	Std	3.55	1.25	1.51	0.74	2.87	37.32	0.81	186.6	407.23
	CV%	13.77	6.57	6.86	8.62	5.66	17.93	16.14	17.93	16.14
	Range	17.1	6.89	6.11	2.35	12.02	139.31	2.74	696.5	1370
SNNP	Mean	22.03	21.08	23.9	10.56	51.99	200.98	4.7	1005	2350
(5 accessions)	Std	13.37	5.29	0.56	4.16	6.75	48.8	0.1	244	49.5
	CV%	60.71	25.09	2.34	39.46	12.99	24.28	2.12	24.28	2.11
	Range	18.91	7.48	0.79	5.89	9.55	69.01	0.14	345	70
COMM. VAR	Mean	29.47	17.93	21.92	10.44	48.68	169.55	4.46	847.7	2231.67
(6 varieties)	Std	2.07	1.79	1.87	1.23	1.42	24.45	0.59	122.3	293.22
	CV%	7.04	9.98	8.54	11.83	2.92	14.42	13.14	14.42	13.14
	Range	4.47	4.96	4.68	3.68	4.41	68.6	1.62	343	810

Table 3: Mean, Std, CV and Range of morpho-aronomic traits, oil yield and fatty acid components by Administrative Regions. For character codes see Table 2.

Altitude	Parameter	DF	DM	PH	PB	SB	NC	NSC	TSW	BYP	HI
class I	Mean	51.36	99.30	63.54	8.73	18.66	50.53	7.14	7.22	14.89	33.98
(1480-1700)	Std	2.64	7.11	5.70	0.73	5.62	7.28	0.48	0.39	2.79	3.61
(9 accessions)	CV%	5.13	7.16	8.98	8.30	30.13	14.40	6.71	5.43	18.71	10.62
	Range	8.48	19.67	17.19	2.46	14.43	22.27	1.51	1.34	7.97	11.74
class II	Mean	50.80	101.98	61.71	8.67	17.40	45.76	7.16	7.04	15.64	32.39
(1730-1970)	Std	4.83	13.67	7.29	1.09	4.15	8.17	0.90	0.69	4.37	4.20
(25 accessions)	CV%	9.51	13.41	11.81	12.59	23.87	17.85	12.51	9.80	27.96	12.97
	Range	20.89	55.43	28.71	3.73	14.97	30.33	3.37	2.51	19.15	21.38
class III	Mean	53.42	107.37	59.48	8.53	19.13	48.20	7.19	6.93	14.68	33.28
(1980-2210)	Std	5.32	18.72	8.46	1.10	4.28	8.36	0.86	0.75	3.55	3.63
(27 accessions)	CV%	9.95	17.43	14.22	12.87	22.38	17.35	11.93	10.83	24.18	10.92
	Range	19.26	55.65	28.19	3.54	14.83	27.52	3.03	2.53	11.72	13.07

class IV	Mean	53.82	109.10	57.19	8.04	19.58	46.07	7.03	6.78	14.67	32.38
(2220-2460)	Std	5.84	19.95	7.83	1.06	4.96	10.49	1.04	0.88	4.00	3.98
(19 accessions)	CV%	10.85	18.29	13.69	13.24	25.35	22.76	14.75	13.02	27.27	12.29
	Range	18.33	56.40	26.95	4.56	14.63	37.56	3.25	2.99	13.46	13.84
class V	Mean	52.84	108.67	58.77	8.65	19.18	44.55	7.14	6.79	15.29	32.06
(2480-2700)	Std	6.74	21.44	10.11	1.37	4.41	11.98	1.06	0.92	5.05	5.08
(23 accessions)	CV%	12.76	19.73	17.20	15.81	22.98	26.90	14.79	13.51	33.05	15.85
	Range	24.36	63.55	32.48	4.61	14.62	43.27	3.75	2.86	20.78	22.29
class VI	Mean	53.22	108.85	61.05	8.50	16.77	45.93	7.10	6.85	14.76	32.70
(2710-2950)	Std	7.48	23.15	11.33	1.43	3.27	13.34	1.06	1.07	3.96	3.20
(9 accessions)	CV%	14.05	21.27	18.55	16.88	19.51	29.04	14.89	15.68	26.83	9.78
	Range	21.70	61.62	31.31	4.66	11.28	42.77	2.87	3.06	13.25	11.55
class VII	Mean	61.74	124.82	61.42	8.44	20.70	47.98	7.05	6.95	14.76	33.83
(3040-3440)	Std	5.51	17.74	10.26	1.20	3.06	9.92	0.75	0.74	3.24	4.80
(8 accessions)	CV%	10.53	16.43	16.70	14.23	14.78	20.67	10.57	10.69	21.95	14.20
	Range	14.46	50.72	25.05	2.85	10.05	28.82	1.84	2.08	7.58	14.97

Altitude	**Parameter**	**CRB**	**PRT**	**OA**	**LN**	**LNN**	**OYP**	**SYP**	**OYD**	**SYD**
class I	Mean	28.23	18.67	21.15	9.33	49.44	192.2	4.9	961.02	2385
(1480-1700)	Std	2.18	1.22	1.08	0.54	2.34	20.09	0.47	100.47	235.4
(9 accessions)	CV%	7.71	6.54	5.12	5.76	4.74	10.45	9.6	10.45	9.6
	Range	6.49	3.98	2.68	1.3	7.89	63.61	1.38	318.08	690
class II	Mean	24.99	19.42	22.18	8.92	50.96	200.65	4.82	1003.27	2408.6
(1730-1970)	Std	4.85	1.63	1.32	1.27	3.03	39.62	0.77	198.13	383.59
(25 accessions)	CV%	19.42	8.38	5.93	14.23	5.94	19.75	15.93	19.75	15.93
	Range	17.7	6.92	4.83	5.88	10.98	174	2.74	869.98	1370
class III	Mean	26.8	18.63	22.28	9.25	49.79	190.14	4.71	950.68	2355.37
(1980-2210)	Std	2.59	1.02	1.82	1.38	2.62	33.17	0.76	165.83	381.92
(27 accessions)	CV%	9.67	5.49	8.16	14.96	5.26	17.44	16.21	17.44	16.21
	Range	7.8	4.91	6.42	5.95	10.42	109.45	2.44	547.21	1220
class IV	Mean	26.62	18.97	22.1	9.48	50.89	183.45	4.54	917.24	2269.21
(2220-2460)	Std	2.48	0.86	2.05	1.57	2.22	38.87	0.79	194.38	397.61
(19 accessions)	CV%	9.32	4.55	9.28	16.53	4.36	21.19	17.52	21.19	17.52
	Range	9.41	3.88	9.04	7.04	8.54	132.61	2.69	663.09	1345
class V	Mean	25.44	19.12	21.81	9.1	51.09	190.22	4.58	951.12	2288.04
(2480-2700)	Std	3.76	1.49	1.69	1.61	2.51	41.71	0.93	208.55	464.37
(23 accessions)	CV%	14.77	7.8	7.73	17.71	4.92	21.93	20.29	21.93	20.3
	Range	18.82	7.51	6.5	5.59	11.43	144.89	3.32	724.46	1660
class VI	Mean	26.86	19.02	22.25	9.18	50.36	186.36	4.65	931.83	2326.11
(2710-2950)	Std	2.22	1.43	0.77	0.7	2.55	38.98	0.97	194.92	485.93
(9 accessions)	CV%	8.26	7.54	3.48	7.63	5.06	20.92	20.89	20.92	20.89
	Range	7.15	4.9	2.19	2.09	7.04	113.41	2.86	567.01	1430

class VII	Mean	24.8	19.88	22.65	9.37	51.87	199.04	4.77	995.22	2452.22
(3040-3440)	Std	4.51	1.61	1.15	0.86	3.02	40.17	0.74	200.85	369.86
(8 accessions)	CV%	18.18	8.07	5.09	9.13	5.83	20.18	15.51	20.18	15.51
	Range	13.26	4.22	3.53	2.38	9.69	122.08	1.82	610.39	910

Table 4: Mean, Std, CV and Range of morpho-aronomic trais, oil yield and fatty acid components by altitude classes.

For character codes see Table 2.

Analysis of variance (ANOVA)

The analysis of variance (ANOVA) computed for each location for 19 quantitative traits of linseed genotypes revealed the presence of highly significant differences among genotypes for all traits (Appendix Table 3). Combined analysis of variance across locations (Holeta and Kulumsa) for the different characters is presented in Table 5. The location variance showed non-significant differences for all traits except days to 50% flowering, days to maturity, plant height, seed yield per plant and seed yield per hectare (kg ha^{-1}). The interaction variance between genotypes x location was found non-significant for all the traits indicating consistence performance of the genotypes across locations. Mean square due to genotype showed highly significant differences (P<0.01) for all traits, indicating that presence of genotypic variation among the tested linseed genotypes. Mulusew [18,19]) and Worku [7]) also reported variations among on linseed landraces and commercial varieties for morpho-agronomic and biochemical traits evaluated at different locations in Ethiopia. Many other authors also reported significant variations among linseed genotypes for morpho-agronomic traits, oil yield and fatty acid composition in Ethiopia (Gemechu and Gudeta [36]; Worku [3]; Mulusew [18,19]).

Estimates of variances and genetic parameters

Estimates of variances

Estimates of genotypic (σ^2g), genotype by environment interaction (σ^2g*l), pooled error (environmental) (σ^2e) and phenotypic (σ^2p) variances were estimated for the studied traits (Table 6). Phenotypic variance was relatively high for the traits like seed yield per hectare, days to maturity and number of capsules. This indicated that the phenotypic expression of these traits was greatly influenced by environmental factors; and selection on phenotypic bases of these traits may not be effective for genetic improvement unless the environmental conditions are optimized. Similarly, in another studies, relatively higher phenotypic variance for days to 50% flowering, days to maturity, number of primary branches, seed yield per plot, oleic acid, linoleic acid, linolenic acid and crude protein content were reported (Mulusew [18,19]). On the contrary, degree of difference between phenotypic variance and genotypic variance was relatively low for number of seeds per capsule, 1000-seed weight and number of primary branches. This shows that the phenotypic expression of these traits was relatively less affected by environmental factors; and selection on phenotypic bases of these traits will be effective. Gemechu and Gudeta [35] also indicated lower degree of difference between phenotypic and genotypic variances for days to 50% flowering and biomass. However, the same authors reported relatively high and low degree of differences between phenotypic and genotypic variances for days to maturity and harvest index, respectively. This variation of phenotypic expression of the two traits between studies might be mainly due to differences in environmental conditions of the two research sites.

Coefficients of variation

Genetic (GCV) and phenotypic (PCV) coefficients of variability values for 19 traits varied from 1.32% to 3.52% for oil yield per plant and 28.02% to 34.98% for seedl yield per plant, respectively (Table 6). Estimates of GCV and PCV had been reported for the same traits of linseed by previous investigators (Gemechu and Gudeta [36]; Debelo [10]; Tadele [17]; Adugna [6]). It has been reported that GCV and PCV values, > 20%, 10-20% and < 10% are regarded as high, moderate and low, respectively (Deshmukh [37]).

High GCV value was obtained for traits seed yield per plant and biological yield per plant (Table 6). This indicated the existence of considerable genotypic variability among linseed genotypes for these traits and greater influence of genetic factors for the expression of this trait. High GCV estimate for seed yield per plant and biological yield per plant was reported by several authors (Kumar [16]; Tadele [17]). Moderate GCV value was obtained for traits like number of secondary branches, number of capsules, seed yield per hectare and days to maturity (Table 6). In line with the present results, moderate GCV was reported by Kumar [16] for number of secondary branches; and by Tadele [17] for seed yield per hectare and days to maturity.

Low GCV value was obtained for traits like linoleic acid, plant height, carbohydrate content, number of primary branches, number of seeds per capsule, harvest index, days to 50% flowering, 1000-seed weight, oil yield per hectare, oleic acid, crude protein, lenolenic acid and oil yield per plant (Table 6). Similarly, low GCV estimates were reported by Gemechu and Gudeta [36] for days to 50% flowering, days to maturity and number of seeds per capsule; and Debelo [10]) for plant height, days to maturity, days to flowering and oil content. However, on the contrary, low GCV estimate was reported by Dhirhi [38] for number of secondary branches; and by Debelo [10]) for days to maturity. These differences might be due to differences between sets of accessions used for the studies or environmental conditions of research sites where genotypes were grown for characterization.

High PCV was revealed for seed yield per plant (34.98%), biological yield per plant (33.27%), number of secondary branches (23.37%) and number of capsules (20.87%) (Table 6). These results reflected the presence of considerable phenotypic variation among linseed genotypes for these traits. The high PCV estimates for seed yield per plant, biological yield per plant, number of secondary branches and number of capsules were in harmony with the previous reports by several authors (Kumar [16]; Dhirhi [38]; Tadele [17]).

In the present study, moderate PCV values were exhibited for traits like seed yield per hectare, days to maturity, linoleic acid, carbohydrate content, plant height, number of primary branches, harvest index, number of seeds per capsule, 1000-seed weight and days to 50% flowering. On the hand, low PCV was observed for oil yield per hectare, crude protein content, oleic acid, linolenic acid and oil yield per plant, indicating existence of lesser phenotypic variability among linseed genotypes that might be due to higher influence of environmental factors for the expression of the traits. In agreement with the present result, low PCV estimate for oil yield per plant and moderate PCV for harvest index was reported by Fekadu [39]. However, in contrast to the present study, low PCV estimate was reported by Rajanna [21] for traits like days to 50% flowering, plant height and number of seeds per capsule; and by Dhirhi [38] for plant height. These differences might be due to differences in genetic bases of the studied materials for these traits or higher influence of environmental factors for their expression.

	LOC	REP	REP(LOC)	BLOC(REP)	GEN	GEN*LOC	ERROR	CV%
S.V	(d.f=1)	(d.f=1)	(d.f=1)	(d.f=40)	(d.f=125)	(d.f=125)	(d.f=210)	
Days to 50% flowering	2.14**	38.12ns	25.52ns	9.05ns	68.84**	20.47ns	15.26	7.41
Days to maturity	2.41**	38.11ns	25.51ns	131.54ns	718.36**	187.77ns	161.94	11.95
Plant height (cm)	2.47**	38.12ns	25.52ns	32.03ns	153.93**	55.59ns	36.27	10.05
Number of primary branches	0.31ns	38.11ns	25.51ns	0.71ns	2.58**	0.93ns	0.74	10.08
Number of secondary branches	0.15ns	38.12ns	25.52ns	8.57ns	40.44**	15.49ns	9.66	16.75
Number of capsules per plant	0.24ns	38.11ns	25.51ns	35.62ns	209.72**	68.17ns	49.98	15.18
Number of seeds per capsule	0.51ns	38.11ns	25.52ns	0.52ns	1.64**	0.58ns	0.42	9.12
1000 seeds weight (g)	0.11ns	38.12ns	25.52ns	0.85ns	1.34**	0.54ns	0.34	8.42
Biological yield per plant (g)	0.73ns	38.11ns	25.51ns	8.34ns	72.05**	11.78ns	7.71	18.55
Harvest index (%)	0.83ns	38.12ns	25.52ns	8.54ns	38.4**	16.77ns	7.5	8.36
Carbohydrate (%)	0.58ns	38.11ns	25.51ns	3.36ns	31.62**	15.08ns	5.41	8.85
Crudeprotein (%)	0.25ns	38.11ns	25.52ns	0.93ns	4.24**	1.92ns	0.92	5.04
Oleic acid (%)	0.52ns	38.25ns	25.51ns	1.12ns	5.45**	1.93ns	1.39	5.35
Linoleic acid (%)	0.15ns	38.11ns	25.57ns	0.48ns	4.16**	1.77ns	0.83	9.84
Linolenic acid (%)	0.85ns	38.11ns	25.55ns	2.38ns	16.36**	3.88ns	2.98	3.41
Oil yield per plant (g $plant^{-1}$)	0.42ns	37.85ns	23.75ns	8.32ns	65.35**	39.92ns	37.47	3.21
Seed yield per plant (g $plant^{-1}$)	1.26**	36.83ns	22.57ns	7.01ns	8.05**	1.17ns	0.74	18.38

Oil yield (kg ha^{-1})	0.62ns	21629.41ns	14479.5ns	13793.53ns	74197.99**	18711.63ns	17681.47	13.95
Seed yield (kg ha^{-1})	2.21**	38.12ns	25.51ns	80171.48ns	321226.5**	85662.7ns	81946.74	12.23

Table 5: Mean squares from combined analysis of variance for 19 morpho-agronomic traits and seed biochemical contents of 126 linseed genotypes evaluated at Holeta and Kulumsa during 2019/20 main cropping season.

ns and **, non-significant and significant at P<0.01, respectively. Loc = Location, Gen = Genotype, Gen*Loc = Genotype by location interaction and CV (%) = Percentage of coefficient of variation. Number in parenthesis indicates the degree of freedom.

TRAIT	σ^2g	σ^2g*l	σ^2e	σ^2p	GCV (%)	PCV (%)	H^2 (%)	GA (5%)	GAM (5%)
Days to 50% flowering	12.09	2.61	15.26	29.96	6.59	10.38	40.35	4.55	8.63
Days to maturity	132.65	12.92	161.94	307.5	10.81	16.46	43.14	15.58	14.63
Plant height (cm)	24.59	9.66	36.27	70.52	8.28	14.02	34.87	6.03	10.07
Number of primary branches	0.41	0.1	0.74	1.25	7.55	13.12	32.8	0.76	8.88
Number of secondary branches	6.24	2.92	9.66	18.81	13.46	23.37	33.17	2.96	15.97
Number of capsules per plant	35.39	9.1	49.98	94.46	12.77	20.87	37.47	7.5	16.11
Number of seeds per capsule	0.27	0.08	0.42	0.77	7.24	12.3	35.06	0.63	8.91
1000 seeds weight (g)	0.2	0.1	0.34	0.64	6.47	11.58	31.25	0.52	7.45
Biological yield per plant (g)	15.07	2.04	7.71	24.81	25.93	33.27	60.72	6.23	41.62
Harvest index (%)	5.41	4.64	7.5	17.54	7.1	12.79	30.84	2.66	8.12
Carbohydrate (%)	4.14	4.84	5.41	14.38	7.74	14.44	28.79	2.25	8.56
Crudeprotein (%)	0.58	0.5	0.92	2	4.01	7.44	29	0.84	4.45
Oleic acid (%)	0.88	0.27	1.39	2.54	4.25	7.22	34.65	1.14	5.15
Linoleic acid (%)	0.6	0.47	0.83	1.9	8.35	14.88	31.58	0.9	9.68
Linolenic acid (%)	3.12	0.45	2.98	6.55	3.5	5.07	47.63	2.51	4.97
Oil yield per plant (g plant^{-1})	6.36	1.23	37.47	45.05	1.32	3.52	14.11	1.95	1.02
Seed yield per plant (g plant^{-1})	1.72	0.22	0.74	2.68	28.02	34.98	64.18	2.16	46.25
Oil yield (kg ha^{-1})	4.41	1.35	4.29	10.05	5.16	7.79	43.26	159.58	16.74
Seed yield (kg ha^{-1})	13872	515.08	17681	32068	12.35	18.78	41.27	321.15	13.72

Table 6: Estimates of coefficients of variation, heritability and genetic advance for 19 Morpho agronomic traits, oil yield and fatty acid components in 126 (120 accessions and 6 commercial varieties) linseed genotypes (2019/20).

Higher differences between PCV and GCV estimates were observed for number of secondary branches, number of capsules and biological yield per plant, (Table 6) indicating the complexity of these traits and the importance of environmental factors in influencing the expression of these traits. High differences between PCV and GCV were also reported in linseed by previous authors (Gemechu and Gudeta [36]; Debelo [10]) for biological yield per plant, number of secondary branches and number of capsules. Similar results were reported by Fekadu [39] for number of capsules and biological yield per plant. However, difference between PCV and GCV estimates was relatively very slight in the case of linolenic acid and oil yield per plant, signifying minimal influence of environment and a reasonable effect of genotypic factors on the expression of these traits.

In general, coefficients of genotypic and phenotypic variation suggest that there is good scope for improvement through selection for seed yield per plant and biological yield per plant. Similar results were reported for traits like number of capsules, seed yield per plant and biological yield per plant in linseed accessions (Gemechu and Gudeta [36]; Debelo [10]).

Broad sense heritability

Heritability estimates for traits under study varied from 14.11% for oil yield per plant to 64.18% for seed yield per plant (Table 3). According to Johnson [20], these heritability estimates can be classified as low (< 30%), moderate (30-60%) and high (> 60%) levels. Hence, high heritability estimate was recorded for seed yield per plant and biological yield per plant. This result indicated that expression of these traits were least influenced by the environmental factors, signifying a close correspondence between genotype and phenotype due to a relatively smaller contribution of environment to phenotypic expression. However, selection may not be useful for these traits, because broad sense heritability is based on total genetic variance which includes both fixable (additive) and non-fixable (dominance and epistatic) variances (Singh and Narayanan [40]). Similarly, Dhirhi [38] reported high heritability estimates for seed yield per plant and biological yield per plant.

Traits like harvest index, 1000-seed weight, linoleic acid, number of primary branches, number of secondary branches, oleic acid, plant height, number of seeds per capsule, number of capsules, days to 50% flowering, seed yield per hectare, days to maturity, oil yield per hectare and linolenic acid revealed moderate level of heritability. For such traits, phenotypic expression is influenced by environmental factors and the non-additive gene effects; and hence, genetic improvement through selection is difficult due to masking effects of the environment on the genotypic effects (Johnson [20]). Further, the lowest heritability estimate was recorded for oil yield per plant (14.11%), carbohydrate content (28.75%) and crude protein (29%); these indicated that a small proportion of the phenotypic variation is caused by variation in genotypes, signifying that the phenotypic expression of this trait was highly influenced by environmental factors with less contribution of genetic factors. In agreement with the present results, moderate level of heritability was reported by Gemechu and Gudeta [36] for plant height and number of primary branches and Debelo [10]) reported moderate level of heritability for number of primary branches.

Genetic advance

In present study, genetic advance as a percent mean (GAM) ranged from 1.02% oil yield per plant to 46.25% for seed yield per plant (Table 6). These results indicated that selecting the top 5% of the accessions could result in an advance of 1.02% to 46.25% over the respective population mean. As suggested by Johnson [20], estimates of genetic advance can be classified as low (< 10%), moderate (10-20%) and high (> 20%).

High GAM was recorded for seed yield per plant and biological yield per plant. These results indicated that the expressions of these traits are mainly governed by additive gene effects; and therefore, improvement of such trait can be achieved through selection. In harmony to the present findings, Gemechu and Gudeta [36] reported high GAM for number of capsules per plant, seed yield per plant and biological yield per plant. Similarly, Rajanna [21] reported high GAM for linoleic acid, linolenic acid, number of capsules and seed yield per plant.

On the contrary, oil yield per hectare, number of capsules, number of secondary branches, days to maturity, seed yield per hectare and plant height revealed moderate level of GAM. In addition, low genetic advance was recorded for traits like linoleic acid, number of seeds per capsule, number of primary branches, days to 50% flowering, carbohydrate content, harvest index, 1000-seed weight, oleic acid, linolenic acid, crude protein and oil yield per plant. This indicated that expression of these traits is governed by non-additive gene effects; and hence, heterosis breeding may be useful for the improvement of these traits than selection. Similarly, Gemechu and Gudeta [36] reported low GAM for number of seeds per capsule in linseed accessions. However, in contrast to the present results, Gemechu and Gudeta [36] reported moderate level of GAM for days to maturity, number of secondary branches and plant height. Additionally, Rajanna [21] reported moderate level of GAM for days to maturity and 1000 seed weight. These differences might be due to difference in magnitude of the different gene effects or the influence of environmental factors.

Scope of selection

In the present study, high heritability coupled with high GAM was observed for seed yield per plant and biological yield per plant (Table 6), indicating greater contribution of additive gene action for the expression of these traits; and therefore, improvement can be achieved through selection in these traits. Similarly, Gemechu and Gudeta [36] reported high heritability coupled with high GAM for seed yield per plant and biological yield per plant. However, it is not necessary for a trait showing high heritability to exhibit high GAM or the vise-versa (Johnson [20]).

In addition, moderate heritability coupled with moderate genetic advance was recorded for oil yield per hectare, number of capsules, number of secondary branches, days to maturity, seed yield per hectare and plant height. These results indicated the existence of intermediate expression in these traits for both additive and dominance gene effect. Similar results were reported for days to maturity (Debelo [10]; Rajanna [21]). Furthermore, moderate heritability coupled with low GAM was recorded for linoleic acid, number of seeds per capsule, number of primary branches, days to 50% flowering, harvest index, 1000-seed weight, oleic acid and linolenic acid, suggesting that the expression of these traits is governed by non-additive gene action. However, the exhibited moderate heritability might be mostly due to favorable influence of the environment rather than the genetic factors. Additionally, low heritability and low GAM were recorded for carbohydrate content, crude protein and oil yield per plant, indicating that the expression of these traits is governed by non-additive gene effects; and inf1uenced negatively by environmental effects. In general, these results indicate the predominance of non-additive gene action in the inheritance of carbohydrate content, crude protein and oil yield per plant, suggesting that selection may not be effective for the improvement of these traits, and rather heterosis breeding may be useful. Similar suggestion was given for the traits exhibiting non-additive gene action (Singh and Narayanan [40]).

Conclusions

In conclusion, the analysis of variance showed the presence of high genetic diversity among the studied linseed genotypes. Traits like number of secondary branches and number of capsules were highly influenced by the environment factors compared to other traits. The role of additive gene action was high for seed yield per plant and biological yield per plant; and therefore, selection can do improvement on these traits. High heritability coupled with high GAM was observed for seed yield per plant and biological yield per plant showing that the high heritability is most likely due to additive gene effects; and the importance of selection for the improvement of linseed for these traits. On the contrary, the role of additive gene effects was low for carbohydrate content, crude protein and oil yield per plant indicating limited scope of selection for improvement for these traits; rather heterosis breeding may be useful.

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