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# Association of linseed characters and its variability in different environments

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## SUMMARY

Associations of characters were studied in linseed using data of 60 accessions evaluated in a randomized complete block design with three replications under glasshouse and field conditions during 2000 and 2001. The main objectives were to determine the magnitude of correlations between yield and its components under variable environments, and identify stable and major yield attributes that could support further improvements of linseed productivity. The degree of character association varied considerably across years and locations, due mainly to climatic factors (e.g. temperature, moisture levels, etc.) and disease incidences. However, seed yield per plot was significantly ($P<0{\cdot}01$) and positively associated with seed yield per plant, 1000 seed weight and bolls per plant across environments. These three yield attributes were also strongly and positively correlated with plant height, branches per plant, days to flowering and maturity. Oil yield was significantly and positively associated with polyunsaturated (linoleic and linolenic) fatty acids, whereas it was negatively correlated with saturated (palmitic and stearic) fatty acids. Oil yield also had a weak positive relation with monounsaturated oleic acid. The quality of linseed oil, which is dependent on the levels of these fatty acids, can be influenced by the correlated responses of these variables in reaction to different environmental factors. Thus, knowledge on the causes and effects of these correlated responses are necessary to undertake sound and effective selection programmes.

## INTRODUCTION

Linseed (*Linum usitatissimum* L.) is largely a crop of temperate climates, including cooler parts of the tropics like the highlands of Africa. It is the second most important oil crop in the highlands of Ethiopia (Adefris *et al*. 1992), where small-scale farmers have been producing it organically, without applying any chemicals (fertilizers, herbicides, etc.) and with minimum inputs (Adugna 2000). It has been grown in Ethiopia primarily for food and to generate cash revenues for the farmers either on local markets or by exporting it abroad. For food, the seeds are usually roasted, ground and mixed with spices and some water to be served along with different cooked and boiled food products (Adugna 2000). Limited amounts of linseed are also locally pressed for their edible oils, which are often blended with oils of other oil crops that have high edible oil quality such as niger seed (*Guizotia abyssinica* Cass.), which contains about 75% linoleic fatty acid (Getinet & Adefris 1992).

Recent reports (Carter 1993; Cunnane *et al*. 1995; Payne 2000; Reinhardt-Martin 2001) indicate that consumption of linseed imparts numerous health benefits, including anti-hypercholesterolemic and anti-carcinogenic effects and is also beneficial in the development of brain and retinal tissues of infants. In order to maximize such benefits, one has to increase the productivity of the crop directly or indirectly via its yield components. According to Lafond (2001), the three major yield components in linseed are number of bolls per unit area, number of seeds per boll and seed weight. Moreover, recent studies (Hassan *et al*. 1999; Lafond 2001; Adugna & Labuschagne 2002) have shown that year, location, variety, seeding date, nitrogen fertility and seeding

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rate are the factors that have the greatest influence on the final seed yield of linseed, provided that proper weed control, crop establishment and other fertility conditions are fulfilled. Besides, correlations of characters with yield are useful in its breeding and provide the criteria for indirect selection of the characters (Mishra & Maheshwari 1975). Such studies can provide reliable information on the nature, extent and direction of selection. Thus, knowledge of interrelationships between different traits is important in breeding for direct and indirect selection of characters that are not easily measured and those with low heritability (Patil *et al*. 1981).

Several studies (Mishra & Maheshwari 1975; Agrawal *et al*. 1994; Muduli & Patnaik 1994; Kurt 1996; Mahto & Mahto 1998) were carried out on correlations of characters in linseed. Mahto & Mahto (1998) studied the variability and correlation for seven yield-related characters of linseed genotypes and found that seed yield per plant, bolls per plant, secondary branches and primary branches per plant had high correlations with yield. Kurt (1996) also showed significant positive correlations between seed yield per plant and bolls per plant, and between height of first branch and bolls per plant and seed yield per plant. Similar correlation analysis of divergent varieties of linseed indicated that seed yield had a high positive correlation with bolls per plant and moderate positive correlation with seeds per boll, but a significant negative correlation with 1000 seed weight (Muduli & Patnaik 1994). According to these workers, bolls per plant and seeds per boll were the major components determining yield. Rashid *et al*. (1998) also indicated that seed yield per plot had a positive and significant correlation with bolls per plant, seeds per boll, 1000 seed weight and oil content, whereas days to flowering and plant height had negative correlations with seed yield per plot. They also indicated that protein content and oleic acid had a negative association with seed yield per plot. They further suggested that bolls per plant and oil content could be a reliable selection index for maximum oil yield per unit area.

Nevertheless, data on correlation studies showing the influence of environments in the expression of correlated characters are generally lacking in linseed. But yield is a complex character determined by several components. It is quantitatively inherited and influenced by genotype, environment and their interactions (GEI). Hence, understanding of such important association of characters and their environments is necessary to conduct effective selection programmes. The identification of yield-contributing plant characters is also important as they improve breeding efficiency.

GEI results because individual genotypes differ in their responses to variations in soil fertility, soil moisture, temperature, day-length, light intensity, humidity, disease, cultural practices and other environmental factors (Poehlman 1987; Basford & Cooper 1998). GEI reduces association between phenotypic and genotypic values (Romagosa & Fox 1993), and may cause selections from one environment to perform poorly in another. Measurement of GEI is also important to determine an optimum breeding strategy for releasing genotypes with adequate adaptation to their target environments. Such a study of GEI is especially relevant for a country like Ethiopia that has a very diversified agro-ecology and challenging climatic conditions (Adugna 2000; Amsalu 2001). Thus, an attempt was made here to study the role of different testing environments in character association of diverse accessions of linseed. Its specific objective was to examine the magnitude of correlations between different characters of linseed under glasshouse and field conditions in order to identify major characters for achieving higher yield. The premise is that, by evaluating broad genetic genotypes of linseed in diverse environments, more reliable information could be generated for future breeding and development efforts of linseed.

## MATERIALS AND METHODS

### *Plant materials*

The accessions used in this study were selectively taken from the Highland Oil Crops Research Program of Holeta Research Centre in the Ethiopian Agricultural Research Organization to represent the apparent diversity of linseed germplasm in the country. A total of 60 accessions, including four released varieties (Chilalo, CI-1525, CI-1652 and Belay 96) were studied for their character association and variability across environments. Belay 96 was developed and released in 1996 out of a crossing programme undertaken between locally well-adapted and disease-resistant collections at Holeta Research Centre. Fifty-three accessions were collected from different regions of Ethiopia and Eritrea, the remaining seven being introductions from Europe, USA and Canada (Table 1).

### *Experimental environments and methods*

#### *Glasshouse*

The study at Bloemfontein was conducted in two different glasshouses during 2000 and 2001 at the University of the Free State (latitude 29°6′S, longitude 26°18′E, altitude 1351 m a.s.l.) in South Africa. The first glasshouse used in 2000 was warmer by about 10 °C (average) than the one used in 2001. The latter had a maximum temperature of up to 25 °C during the daytime and the minimum night temperatures ranged between 8 and 13 °C in both glasshouses. Daylight hours ranged from 10·1 in June to 13·9 in December; April to September had 11·3–11·8 hours

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Table 1. *List of the studied accessions along with their initial sources or collection areas*

| No. | Accession | Collection area/district | No. | Accession | Collection area/district |
|---|---|---|---|---|---|
| 1 | 10002 | Shewa/Ambo | 31 | 10169 | Gonder/Chera |
| 2 | 10005 | Sidamo/Bore | 32 | 10176 | Gojam/Guangua |
| 3 | 10007 | Kefa/Omonada | 33 | 10179 | Shewa/Alem-Gena |
| 4 | 10008 | Gonder/Fogera | 34 | 10185 | Shewa/Chelia |
| 5 | 10010 | Hararge/Chiro | 35 | 10192 | Shewa/Dendi |
| 6 | 10022 | Wello/Kalu | 36 | 10197 | Shewa/Ambo |
| 7 | 10026 | Gojam/Dambecha | 37 | 10204 | Wello/Bati |
| 8 | 10037 | Sidamo/Bore | 38 | 10006 | Ilubabor/Gore |
| 9 | 10039 | Eritrea/Mendefera | 39 | 10042 | Tigray/Lay-Machew |
| 10 | Chilalo | Arsi/n.a. | 40 | Belay 96 | Shewa/Holeta |
| 11 | 10041 | Bale/Adaba | 41 | 10047 | Ilubabor/Bedele |
| 12 | 10046 | Welega/Bedele | 42 | 10062 | Bale/Robe |
| 13 | 10060 | Gonder/Chera | 43 | 10235 | Gonder/n.a. |
| 14 | 10061 | Gamo-Gofa/Mirab-Abay | 44 | 10236 | Gonder/n.a. |
| 15 | 10068 | Gojam/Bahir-Dar | 45 | 10064 | Gamo-Gofa/BakoGazer |
| 16 | 10080 | Hararge/Habru | 46 | 10072 | Gojam/Dejen |
| 17 | 10085 | Hararge/Kuni | 47 | 10073 | Gojam/Maychekel |
| 18 | 10104 | Shewa/Dendi | 48 | 10246 | Ethiopia/n.a. |
| 19 | 10109 | Shewa/Tach-Bet | 49 | 10248 | Ethiopia/n.a. |
| 20 | CI-1525 | Europe/n.a. | 50 | 10250 | Ethiopia/n.a. |
| 21 | 10111 | Shewa/n.a. | 51 | 10252 | Ethiopia/n.a. |
| 22 | 10118 | Shewa/Ambo | 52 | 10254 | Ethiopia/n.a. |
| 23 | 10119 | Shewa/Chelia | 53 | 10256 | Ethiopia/n.a. |
| 24 | 10120 | Sidamo/Adola | 54 | 10258 | Ethiopia/n.a. |
| 25 | 10125 | Tigray/Inderta | 55 | 10260 | Ethiopia/n.a. |
| 26 | 10138 | Welega/Abe-Dongoro | 56 | Omega | USA/North Dakota |
| 27 | 10144 | Wello/Dese-Zuria | 57 | N1266 | Canada/Saskatoon |
| 28 | 10159 | Gonder/Dabat | 58 | M20G | Canada/Saskatoon |
| 29 | 10162 | Gonder/Dabat | 59 | CDC1747 | Canada/Saskatoon |
| 30 | CI-1652 | Europe/n.a. | 60 | CDCVG | Canada/Saskatoon |

n.a., information not available on specific collection regions/districts.

of daylight. The 60 accessions were evaluated in pots (2·5 litres) that were laid out in a randomized complete block design with three replications. Eight seeds were sown at a depth of about 2·5 cm and thinned to five plants per pot 3 weeks after planting. The seeds were sown in early September during the first year and in mid June during the second year. A mixture of nitrogen and phosphorus fertilizers of 3 g per pot was applied to red sandy-loam soil (pH = 5·8 in water) at sowing, 50% flowering and seed filling stages. The plants were irrigated almost every day from planting to maturity.

*Field experiments*

The field trials were conducted at Holeta Research Centre (latitude 9°3′N, longitude 38°30′E, altitude 2400 m a.s.l.) during the 2000 and 2001 main cropping seasons in Ethiopia. Monthly temperature ranged between 2–22 °C during the growing seasons (June–November), while total rainfall varied between 900–1000 mm per annum during the 2 growing years. The minimum temperature (2 °C) occurred during nights in November after the crop had already matured. The accessions were evaluated in two rows (5 m long spaced at 20 cm = 2 m²) that were laid out in a randomized complete block design with three replications. The seeds were planted at a seeding depth of about 2·5 cm on June 26 during both years. The recommended fertilizers of both nitrogen (N) in the form of urea and phosphorus ($P_2O_5$) in the form of diammonium phosphate (DAP) were manually drilled and incorporated with the red clay (eutric Nitosol) soil at planting, both at a rate of 23 kg/ha. The seeds were also drilled by hand at a rate of 25 kg/ha. Weeds were controlled by hand weeding and no herbicide or insecticide was applied. The plants of each accession were separately harvested and dried for about 15 to 30 days, threshed and cleaned manually. Seed yield data were taken at about 8% seed moisture level. Seed was oven dried to about 1% seed moisture level for oil analysis.

*Data recording*

Data on the agronomical and morphological characters were collected from three and five randomly

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selected plants in the glasshouses and in the field, respectively, and their means were recorded for all observations. Except for days to flower initiation, 50% flowering, diseases scores and similar observations, most of the data were recorded at maturity and thereafter. Scores for powdery mildew (*Odium* spp.) and pasmo (*Septoria lini*) diseases were recorded on 0–5 scales (0 = nil; 5 = very severe) under normal field conditions without any artificial inoculation. Days to flowering and maturity represent the number of days from sowing to 50% blooming and physiological ripening, respectively. The unit of measurement for plant height was centimetres (cm), while that of seed yield and 1000 seed weight was in grams (g). Oil yield (g/m²) was estimated by multiplying the mean values of oil content (%) and seed yield (g/m²) for each accession. Most of the evaluation was undertaken based on the major phenological and morphological quantitative descriptors (Diederichsen 2001).

### *Analysis of oil content and fatty acids*

Oil contents were determined by a wide line nuclear magnetic resonance (NMR) and solvent extraction method (SEM). About 25 g of oven-dried seeds were analysed by NMR (Newport Analyser) with reference to a standard of extracted linseed oil at Holeta Research Centre in Ethiopia. In South Africa, however, oils were extracted for fatty acid analysis from about 0·5 g of ground seed of linseed, following the organic solvent extraction method (Folch *et al*. 1957) in the laboratories of Food Science at the University of the Free State. Fatty acid methyl esters were prepared following the method of Slover & Lanza (1979). Fatty acids were quantified using a Varian GX 3400 flame ionization gas chromatograph, with a fused silica capillary column, Chrompack CPSIL 88 (100 m length, 0·25 μm ID, 0·2 μm film thickness). Column temperature was 40–230 °C (hold 2 min; 4 °C/min; hold 10 min). Fatty acid methyl esters in hexane (1 μl) were injected into the column using a Varian 8200 CX Autosampler with a split ratio of 100:1. The injection port and detector were both maintained at 250 °C. Hydrogen was used as the carrier gas at 45 psi and nitrogen was the makeup gas. Chromatograms were recorded with Varian Star Chromatography Software. Identification of sample fatty acids was made by comparing the relative retention times of fatty acid methyl ester peaks from samples with those of standards obtained from SIGMA (Cat. No. 189-19).

### *Statistical analysis*

The mean values of all observations for the measured characters were first screened for normality and outliers by using the Number Cruncher Statistical System, NCSS 2000 (Hintze 1998) statistical system for Windows. Then, data that showed non-normal distribution were transformed by a square root system and analysed for their correlations and significance using the same statistical software. The total observations for each location and year were separately analysed at first and then their combined data were analysed to investigate their correlations across environments, locations and years. The agronomic traits were also computed for their combined analyses using AGROBASE 98 software (Agronomix Software, Inc., Winnipeg, Canada).

## RESULTS

### *Separate analyses*

#### *Glasshouse experiment*

The analyses of correlations between the evaluated characters for the separate years of 2000 and 2001 are presented in Table 2. Seed yield (g/m²) was significantly ($P < 0{\cdot}01$) and positively correlated with plant height and seeds per boll in 2000, while it was strongly associated with only seed yield per plant ($r = 0{\cdot}8998$) in 2001. Likewise, seed yield per plant was significantly and positively correlated with plant height and number of primary and secondary branches per plant in 2000 but this performance was not repeated in the succeeding year, showing fluctuations in character associations due to environmental variables, specifically temperature differences between the two glasshouses.

Seed yield per plant was negatively correlated with days to flowering and maturity during both years. However, bolls per plant were strongly correlated with primary and secondary branches in both years, and it was also significantly associated with plant height in 2001. Similarly, 1000-seed weight was strongly associated with yield per plant, seed yield (g/m²), plant height and bolls per plant in 2000 and it was also significantly correlated with the former two traits in 2001.

#### *Field experiment*

Under the Holeta field conditions of Ethiopia, seed yield (g/m²) was significantly ($P < 0{\cdot}01$) and positively correlated with plant height, days to flowering, days to maturity, seed yield per plant and 1000-seed weight in 2000 and the first three characters repeated their performance in the year 2001 (Table 3). Moreover, primary branches per plant and bolls per plant significantly contributed to seed yield (g/m²) in 2001 unlike their non-significant effects in the previous year.

The incidence of powdery mildew negatively affected the yield, unlike pasmo score that had non-significant effects on the seed yield. Both diseases had

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Table 2. *Separate analysis of correlation* (r) *between 11 quantitative traits of 60 linseed accessions evaluated in 2000* (*bold and upper diagonal*) *and in 2001* (*lower diagonal*) *at the University of the Free State, South Africa*

| Trait | PH | IDF | DF | DM | PB/P | SB/P | B/P | S/B | SY/P | SY/PT | TSW |
|---|---|---|---|---|---|---|---|---|---|---|---|
| PH | | **0·3992**** | **0·3464**** | **0·1893*** | **0·0991** | **0·1819*** | **0·1247** | **−0·0152** | **0·2664**** | **0·2430**** | **0·2043**** |
| IDF | 0·2090** | | **0·8530**** | **0·5266**** | **−0·0066** | **0·0338** | **0·0275** | **0·0581** | **0·0099** | **−0·1596*** | **−0·2637**** |
| DF | 0·2277** | 0·7960** | | **0·5645**** | **−0·0703** | **0·0007** | **−0·0156** | **0·0435** | **−0·0067** | **−0·2312**** | **−0·3662**** |
| DM | 0·1070 | 0·3327** | 0·4471** | | **−0·0444** | **0·0457** | **0·1411** | **−0·1160** | **0·1721**** | **−0·4262**** | **−0·1430** |
| PB/P | 0·0713 | 0·1249 | 0·0784 | −0·0724 | | **0·3927**** | **0·4430**** | **0·0079** | **0·2913**** | **0·0794** | **0·1355** |
| SB/P | 0·3663** | −0·0529 | 0·0107 | −0·0257 | 0·3034** | | **0·6709**** | **−0·1435** | **0·4895**** | **0·0412** | **0·0321** |
| B/P | 0·2350** | −0·0498 | −0·0004 | −0·0487 | 0·3316** | 0·5127** | | **−0·1199** | **0·6076**** | **0·0722** | **0·1488*** |
| S/B | −0·0639 | 0·1180 | 0·1356 | 0·0055** | −0·0045 | −0·0968 | 0·0092 | | **−0·2725**** | **0·3612**** | **−0·2196**** |
| SY/P | 0·0608 | −0·0769 | −0·1838* | −0·4262** | 0·0650 | 0·0737 | 0·1034 | −0·0279 | | **0·0793** | **0·2542**** |
| SY/PT | 0·0597 | −0·0793 | −0·1866* | −0·4255** | 0·0657 | 0·0720 | 0·1040 | −0·0296 | 0·8998** | | **0·3612**** |
| TSW | −0·1822 | 0·0809 | −0·1130 | −0·0919 | −0·0359 | −0·4200** | −0·2764** | −0·1125 | 0·1476* | 0·1476* | |

*, **, significant at $P<0·05$, 0·01, respectively; PH, plant height at maturity; IDF, initial days of flowering; DF, days to 50% flowering; DM, days to maturity; PB/P, primary branches/plant; SB/P, secondary branches/plant; B/P, bolls/plant; S/B, seeds/bolls; SY/P, seed yield/plant; SY/PT, seed yield/pot; TSW, thousand seed weight; *n*, 180.

Table 3. *Separate analysis of correlation* (r) *between 11 traits of 60 linseed accessions evaluated in 2000* (*bold and upper diagonal*) *and in 2001* (*lower diagonal*) *at Holeta, Ethiopia*

| Trait | PH | DF | DM | PM | PS | PB/P | SB/P | B/P | S/B | SY/P | SY/PT | TSW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PH | | **0·0501** | **0·5127**** | **−0·1469*** | **0·0165** | **0·1132** | **−0·0511** | **0·2086**** | **0·1073** | **0·4635**** | **0·6222**** | **0·1868**** |
| DF | 0·0168 | | **01467*** | **0·0078** | **−0·2469**** | **0·0817** | **−0·0172** | **−0·1520*** | **0·2027**** | **−0·0808** | **0·1680*** | **−0·1097** |
| DM | 0·3817** | 0·4051** | | **−0·0250** | **−0·1903*** | **−0·0037** | **0·0222** | **0·0140** | **0·0523** | **0·1455*** | **0·2773**** | **0·0138** |
| PM | −0·5245** | −0·1990** | −0·4086** | | **−0·0129** | **−0·1506*** | **0·0226** | **−0·0382** | **−0·0547** | **−0·0936** | **−0·0479** | **−0·0989** |
| PS | −0·1144 | −0·3430** | −0·2195** | 0·2206** | | **−0·0353** | **−0·2173**** | **0·0507** | **−0·0700** | **0·0286** | **0·1198** | **0·1210** |
| PB/P | 0·1477* | 0·1810* | 0·1081 | −0·1156 | 0·0585 | | **0·5318**** | **0·3807**** | **0·1687**** | **0·2114**** | **0·0679** | **0·0979** |
| SB/P | −0·1472* | 0·0093 | −0·1054 | 0·2154** | −0·0629 | 0·4381** | | **0·4177**** | **0·0931** | **0·1523*** | **−0·0607** | **0·0110** |
| B/P | 0·2535** | −0·1396 | 0·0151 | −0·1327 | 0·1447 | 0·4015** | 0·2952** | | **0·0182** | **0·6918**** | **0·0764** | **0·0531** |
| S/B | −0·0277 | 0·0384 | 0·0015 | 0·0495 | −0·1125 | −0·0743 | −0·2099** | −0·2058** | | **0·1433** | **0·0798** | **−0·0739** |
| SY/P | 0·3269** | −0·2037** | −0·1657* | 0·0043 | −0·0235 | 0·0687 | 0·0500 | 0·4827** | 0·3153 | | **0·2232**** | **0·1698*** |
| SY/PT | 0·4186** | 0·0286 | 0·2358** | −0·4114** | 0·1072 | 0·2438** | −0·0686 | 0·2703** | 0·0082 | 0·0301 | | **0·1458*** |
| TSW | 0·5568** | −0·2905** | 0·0173 | −0·2532** | 0·0890 | −0·0947 | −0·1152 | 0·1600* | −0·1477* | 0·4547** | 0·1255 | |

*, **, significant at $P<0·05$, 0·01, respectively; PH, plant height at maturity; IDF, initial days of flowering; DF, days to 50% flowering; DM, days to maturity; PB/P, primary branches/plant; SB/P, secondary branches/plant; B/P, bolls/plant; S/B, seeds/bolls; SY/P, seed yield/plant; SY/PT, seed yield/pot; TSW, thousand seed weight; *n*, 180.

Table 4. *Correlation between combined data of different traits of 60 linseed accessions evaluated under glasshouse conditions in South Africa (bold and upper diagonal) and under field environment in Ethiopia (lower diagonal), 2000–2001*

| Trait | PH | DF | DM | PM | PS | PB/P | SB/P | B/P | S/B | SY/P | SY/PT | TSW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PH | | **0·7734**** | **0·7424**** | – | – | **0·1858**** | **0·3347**** | **0·3565**** | **−0·0094** | **0·7010**** | **0·0660** | **0·3616**** |
| DF | 0·0642 | | **0·8766**** | – | – | **0·1719**** | **0·1808**** | **0·2597**** | **0·0632** | **0·7144**** | **−0·0925** | **0·4209**** |
| DM | 0·5667** | 0·2746** | | – | – | **0·1319**** | **0·1846**** | **0·2768**** | **−0·0077** | **0·7055**** | **−0·1851**** | **0·4509**** |
| PM | −0·3946** | −0·1230* | −0·3195** | | – | – | – | – | – | – | – | – |
| PS | 0·0419 | −0·2789** | −0·0985 | 0·0837 | | – | – | – | – | – | – | – |
| PB/P | 0·1810** | 0·1374** | 0·1117* | −0·1601** | 0·0409 | | **0·3480**** | **0·3904**** | **0·0041** | **0·2040**** | **0·0684** | **0·0866** |
| SB/P | −0·1381** | −0·0132 | −0·0917 | 0·1579** | −0·1520** | 0·4180** | | **0·5810**** | **−0·1131**** | **0·2600**** | **0·0580** | **0·1261**** |
| B/P | 0·2631** | −0·1339* | 0·0765 | −0·1151* | 0·1173* | 0·4014** | 0·3389** | | **−0·0319**** | **0·3411**** | **0·0898** | **−0·0025** |
| S/B | −0·0249 | 0·0968 | −0·0359 | 0·0435 | −0·1164* | 0·0130 | −0·0624 | −0·1105* | | **−0·0291** | **0·0368** | **−0·0889** |
| SY/P | 0·2556** | −0·1529** | −0·0996 | 0·0152 | −0·0365 | 0·1074* | 0·1192* | 0·5477** | 0·2592** | | **0·4058**** | **0·5286**** |
| SY/PT | 0·6649** | 0·1364** | 0·4389** | −0·2770** | 0·1058 | 0·1815** | −0·1195* | 0·1840** | −0·0323 | 0·0086 | | **0·1495**** |
| TSW | 0·3070** | −0·1983** | 0·0139 | −0·1804** | 0·1012 | 0·0059 | −0·0506 | 0·0984 | −0·1144* | 0·3068** | 0·1093* | |

*, **, significant at $P<0·05$, 0·01, respectively; PH, plant height at maturity; DF, days to 50% flowering; DM, days to maturity; PM, powdery mildew score; PS, pasmo score; –, not available; PB/P, primary branches/plant; SB/P, secondary branches/plant; B/P, bolls/plant; S/B, seeds/boll; SY/P, seed yield/plant; SY/PT, total seed yield/pot; TSW, thousand seed weight; *n*, 360.

a significant ($P<0·01$) negative correlation with plant height, days to flowering and maturity, suggesting that shorter and early maturing genotypes were susceptible to these diseases. The two diseases also showed significant positive association with each other, indicating similar reactions of the genotypes to these diseases.

The other yield component of linseed, bolls per plant, was significantly and positively associated with plant height, primary branches and secondary branches during both years. Likewise, 1000-seed weight was positively correlated with plant height, but it was negatively associated with days to flowering, powdery mildew and seeds per boll during both years. Nevertheless, the relationship of 1000-seed weight with seed yield was highly significant ($P<0·05$), and this confirmed its positive contribution to the seed yield. Similarly, plant height was consistently and strongly correlated with days to maturity, bolls per plant, yield per plant, seed yield (g/m²) and 1000-seed weight, reflecting the important contribution of taller genotypes to seed yield and its components. Primary branches were positively associated with yield per plant, and secondary branches and plant height were strongly correlated with bolls per plant during both years.

### *Combined analyses*

#### *Across locations*

The combined data analysis across locations revealed that seed yield (g/m²) was significantly ($P<0·01$) and positively correlated with seed yield per plant and 1000-seed weight under glasshouse conditions. It was also strongly associated with plant height, days to flowering and maturity, primary branches per plant, bolls per plant and 1000-seed weight under field conditions (Table 4). That means the association between seed yield (g/m²) and 1000-seed weight was significantly correlated under both glasshouse and field environments.

On the other hand, seed yield (g/m²) was significantly ($P<0·01$) and negatively correlated with powdery mildew under field conditions. In contrast, seed yield per plant was positively correlated with plant height, days to flowering and maturity, primary and secondary branches per plant and bolls per plant in the glasshouses, and it had the same relationship with plant height, primary branches, secondary branches, bolls and seeds per boll under field conditions. In other words, plant height, primary branches per plant, secondary branches per plant and bolls per plant were significantly correlated with yield per plant under both environments.

Similarly, bolls per plant were significantly ($P<0·01$) correlated with plant height, days to flowering and maturity, and primary and secondary

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Table 5. *Correlation between the combined data of different characters of 60 linseed accessions evaluated in four environments of South Africa and Ethiopia, 2000–2001*

| Trait | PH | DF | DM | PB/P | SB/P | B/P | S/B | SY/P | SY/PT |
|---|---|---|---|---|---|---|---|---|---|
| DF | 0·7709** | | | | | | | | |
| DM | 0·7397** | 0·8930** | | | | | | | |
| PB/P | 0·1854** | 0·1719** | 0·1319** | | | | | | |
| SB/P | 0·3341** | 0·1808** | 0·1846** | 0·3480** | | | | | |
| B/P | 0·3534** | 0·2590** | 0·2762** | 0·3913** | 0·5822** | | | | |
| S/B | −0·0091 | 0·0632 | −0·0077 | 0·0041 | −0·1131** | −0·0322 | | | |
| SY/P | 0·4009** | 0·3530** | 0·3168** | 0·1328** | 0·1567** | 0·2174** | −0·0020 | | |
| SY/PT | 0·0700 | −0·0902* | −0·1835** | 0·0695 | 0·0552 | 0·0888* | 0·0387 | 0·5512** | |
| TSW | 0·3691** | 0·4210** | 0·4507** | 0·0867* | −0·1264* | −0·0035 | −0·0884* | 0·3342** | 0·1515** |

*, **, significant at $P<0·05$, 0·01, respectively; PH, plant height at maturity; DF, days to 50% flowering; DM, days to maturity; PB/P, primary branches/plant; SB/P, secondary branches/plant; B/P, bolls/plant; S/B, seeds/bolls; SY/P, seed yield/plant; SY/PT, total seed yield/pot; TSW, thousand seed weight; *n*, 720.

branches per plant in the glasshouses. This character was also strongly associated with plant height, primary and secondary branches per plant under field conditions. Plant height and primary and secondary branches per plant therefore had a strong positive association with bolls per plant, while the remaining relationships were varied under both glasshouse and field environments. This variability was also confirmed by the occurrence of significant interactions of characters with their environments (Table 7). In this regard, the minimum, maximum and mean values of the studied characters (Table 8) showed a broad spectrum of variation. Almost all of the studied traits showed significant ($P<0·05$) differences among accessions, and more than double values of ranges were observed between their minimum and maximum values.

Thousand seed weight had a strong and positive correlation with days to flowering, days to maturity, primary branches per plant, plant height, yield per plant and seed yield (g/m²) in glasshouses and the last three characters repeated the same performance under field conditions (Table 4). However, 1000-seed weight was negatively correlated with days to flowering, powdery mildew and seeds per boll under the field environment.

*Across locations and years*

The combined data analysis across sites and years revealed that seed yield (g/m²) was positively correlated with seed yield per plant, 1000-seed weight and bolls per plant, while it was negatively correlated with days to flowering and maturity, indicating that early maturing genotypes gave relatively poor yields (Table 5). Seed yield per plant was also significantly ($P<0·05$) and positively correlated with plant height, days to flowering and maturity, primary and secondary branches per plant and bolls per plant. Similarly, 1000-seed weight was strongly associated with plant height, days to flowering and maturity, primary branches per plant and with seed yield; however, it was negatively correlated with secondary branches, bolls per plant and seeds per boll.

*Oil yield and fatty acid composition*

Oil yield (g/m²), which is the product of seed yield and oil content, was significantly ($P<0·01$) and positively correlated with polyunsaturated (linoleic and linolenic) fatty acids, while negatively associated with saturated (palmitic and stearic) fatty acids (Table 6). It also showed a weak correlation with monounsaturated (oleic) fatty acid.

The mean of oil content was only positively correlated with the total unsaturated fatty acids, and with the solvent extraction and nuclear magnetic resonance, indicating both oil extraction methods were good enough to measure the oil contents of linseed. Oil yield was also significantly ($P<0·01$) and positively associated with both methods of oil extraction (Table 6). There was a strong negative association between the total saturated fatty acids and the unsaturated fatty acids. Linolenic fatty acid was strongly correlated ($r=0·6534$) with linoleic acid.

## DISCUSSION

Studies of character association across environments may supply more reliable information on the nature and level of interrelationships of linseed yield with its yield components. Economic characters, such as seed and oil yields are controlled by many genes, and have a complex type of inheritance (Poehlman 1987). They are much influenced by the environment. The

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Table 6. *Coefficients of correlation* (r) *between different oil contents and fatty acids of the 60 linseed accessions analysed at the University of the Free State* (*South Africa*), *2001*

| Trait | Palmitic ($C_{16:0}$) | Stearic ($C_{18:0}$) | Total saturated | Oleic ($C_{18:1}$) | Linoleic ($C_{18:2}$) | Linolenic ($C_{18:3}$) | Total unsaturated | Oil % (SEM) | Oil % (NMR) | Oil % (Mean) |
|---|---|---|---|---|---|---|---|---|---|---|
| $C_{18:0}$ | 0·3505** | | | | | | | | | |
| TS | 0·7219** | 0·9011** | | | | | | | | |
| $C_{18:1}$ | 0·2276* | 0·2929* | 0·3218* | | | | | | | |
| $C_{18:2}$ | −0·4611** | −0·4258** | −0·5281** | −0·7637** | | | | | | |
| $C_{18:3}$ | −0·3092* | −0·4078** | −0·4445** | −0·9610** | 0·6534** | | | | | |
| TU | −0·7615** | −0·7909** | −0·9369** | −0·2611* | 0·4733** | 0·4118** | | | | |
| SEM | −0·4154** | 0·0403 | 0·1626 | 0·2162* | −0·0364 | −0·1867 | 0·1897 | | | |
| NMR | −0·3280* | −0·3478** | −0·4088** | 0·0408 | 0·3549** | −0·0728 | 0·3873** | 0·2977* | | |
| Oil % (M) | −0·4675** | −0·1335 | −0·3150* | 0·1822 | 0·1398 | −0·1751 | 0·3254* | 0·8934** | 0·6949** | |
| Oil yield | −0·3028* | −0·3413** | −0·3924** | 0·0067 | 0·3094* | 0·8586** | 0·3587** | 0·5537** | 0·6584** | 0·7271** |

*, **, significant at $P<0·05$, 0·01, respectively; TS, total saturated fatty acids; TU, total unsaturated fatty acids; oil contents determined by SEM (solvent extraction method) and NMR (nuclear magnetic resonance); *n*, 60.

Table 7. *Mean squares of the combined analysis of variance for the major characters of 60 accessions* (*entries*) *of linseed across four environments, indicating various interactions of characters*

| | | Traits | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Source | D.F. | PH | DF | DM | PB/P | SB/P | B/P | S/B | SY/P | SY/PT | TSW |
| Year (Y) | 1 | 29594** | 42504** | 52275** | 3·70* | 48·57** | 130·05* | 8·45* | 1·49** | 776970** | 287·94** |
| Location (L) | 1 | 984·67** | 8750** | 51461** | 2·22* | 75·40** | 11297** | 62·42** | 0·12 | 303·65 | 6·21 |
| Y × L | 1 | 97767** | 48478** | 104040** | 11·25** | 1·70 | 1105·09** | 6·42* | 0·08 | 314·66 | 287·94** |
| Entry (E) | 59 | 783·88** | 371·68** | 193·44** | 1·03** | 4·67** | 65·50** | 2·78** | 0·18** | 3807** | 5·41** |
| E × Y | 59 | 83·27** | 29·62 | 84·19** | 0·29 | 0·87 | 19·53 | 0·61 | 0·07* | 2928** | 1·49 |
| E × L | 59 | 147·19** | 80·72** | 67·95** | 0·71* | 4·43** | 32·75* | 1·58 | 0·07 | 2301** | 2·46 |
| E × Y × L | 59 | 165·11** | 47·55** | 101·71** | 0·53 | 1·02 | 20·72 | 0·61 | 0·06 | 1125 | 2·30 |
| Rep (Y × L) | 8 | 1929·60 | 39·68 | 423·63** | 5·11 | 35·26** | 356·76** | 4·61** | 0·30** | 29223** | 79·82** |
| Residual | 472 | 49·98 | 27·08 | 54·20 | 0·47 | 1·89 | 23·84 | 1·54 | 0·05 | 1079·80 | 1·97 |

*, **, significant at $P<0·05$, 0·01, respectively; PH, plant height; DF, days to 50% flowering; DM, days to maturity; PB/P, primary branches/plant; SB/P, secondary branches/plant; B/P, bolls/plant; S/B, seeds/boll; SY/P, seed yield/plant; SY/PT, seed yield/plot; TSW, thousand seed weight.

Table 8. *Overall mean performance of the 60 accessions of linseed evaluated under glasshouse and field conditions in South Africa and Ethiopia, respectively, 2000–2001*

| Character | Minimum | Maximum | Mean | CD 0·05 | CV |
|---|---|---|---|---|---|
| Plant height (cm) | 56 | 88 | 70·08 | 9·53 | 10·09 |
| Days to flowering | 70 | 92 | 82·07 | 7·02 | 6·34 |
| Days to maturity | 135 | 153 | 144·00 | 9·93 | 5·13 |
| Primary braches/plant | 3 | 5 | 4·20 | 0·92 | 16·36 |
| Secondary branches/plant | 4 | 8 | 6·17 | 1·85 | 17·31 |
| Bolls/plant | 13 | 25 | 17·40 | 6·58 | 18·07 |
| Seeds/boll | 7 | 10 | 9·11 | 1·67 | 13·63 |
| Seed yield/plant (g) | 0·51 | 1·08 | 0·70 | 0·30 | 22·14 |
| Total seed yield (g/m²) | 51 | 127 | 86·14 | 22·16 | 10·29 |
| 1000-seed weight (g) | 5 | 9 | 8·20 | 1·89 | 12·10 |
| Oil content (g/kg) | 29·13 | 35·88 | 32·06 | 0·35 | 5·05 |
| Total oil yield (g/m²) | 1443 | 3276 | 2243 | 79·39 | 0·08 |
| Palmitic acid (g/kg) | 5·19 | 6·57 | 6·03 | 6·33 | 4·87 |
| Stearic acid (g/kg) | 2·86 | 5·70 | 4·88 | 10·11 | 9·62 |
| Oleic acid (g/kg) | 14·76 | 29·33 | 22·56 | 0·74 | 0·15 |
| Linoleic acid (g/kg) | 10·88 | 16·14 | 13·36 | 0·23 | 8·16 |
| Linlenic acid (g/kg) | 47·00 | 59·06 | 51·86 | 0·62 | 5·53 |

CD, critical difference; CV, coefficient of variability.

progress of breeding for such economic traits is thus determined by the magnitude and nature of their genotypic and environmental variability. In order to utilize the available variability through different selection methods, the estimates of correlations of yield with its components are very important. Taking these facts into account, association of linseed characters and their variability in different environments was conducted to detect consistent and major yield attributes on which future genetic improvement should be based.

The results of both glasshouse and field experiments have shown variable degrees of correlations among the different characters analysed (Tables 2–6). There were significant variations across the years and localities. These results were also substantiated by the combined analysis of variance (Table 7) that revealed highly significant differences for genotypes, years, locations and their interactions for most of the characters. This indicates the very high differential expressions of the genotypes and their quantitative traits in response to the variable environmental factors. In other words, since quantitative traits are greatly influenced by environmental factors and show continuous variation, their results from single environments (one year or one locality) were less reliable than those of four environments as shown in the present study. That is why multi-environment tests are preferred to the single ones in many breeding and agronomic experiments. This is specifically true for countries like Ethiopia, which is characterized by a diversity of climate, physiography, soils, vegetation, farming systems and socio-economic conditions (Amsalu 2001).

Among the major environmental components, temperature was reported to be the most important factor influencing yield, oil content, maturity period, plant height, fatty acid levels and diseases of linseed (Kenaschuk 1975; Green 1986; Adugna & Adefris 1995; Adugna 2000). High temperature at flowering stage was reported to be deleterious for boll setting, depress seeds per boll and seed weight (Green 1986). Luhs & Friedt (1994) indicated that higher temperatures and drought during the sensitive seed-filling periods accelerate maturity, and thus reduce seed size and oil content. Green (1986) also reported the decline of oil content by 4% as temperature increased from 15–27 °C (day) and 10–22 °C (night). This author also found that increased temperature increased saturated fatty acids, while decreasing the unsaturated ones, particularly linoleic and linolenic acids. Getinet & Nigussie (1992) reported that a range of about 12–18 °C was suitable for normal growth and development of linseed in Ethiopia and extreme temperatures outside of this range could negatively affect the performance of the crop.

The other environmental factor that greatly affects the yield of linseed was moisture deficit (Kenaschuk 1975; Luhs & Friedt 1994), especially during the first 2–5 weeks after flowering. Kenaschuk (1975) indicated that boll setting, seeds per boll and seed weight were reduced in the flowers formed later in the season due to moisture stress. Likewise, a very high

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flower abortion rate was also reported (Adugna 2000) at Holeta in Ethiopia when dry spells occurred during flowering periods. Thus drought and temperature are the most important environmental factors observed to affect the yield of linseed by influencing its correlated yield components. Therefore, linseed growers need to have adequate information on these environmental factors in order to make better decisions in selecting appropriate varieties, localities, seasons and for managing cultural practices, e.g. coping with drought through supplemental irrigations or moisture conserving techniques.

The pooled data analysis across the four environments showed that seed yield was positively associated with seed yield per plant, 1000-seed weight and bolls per plant (Table 5). Mishra & Yadav (1999) also found a significant positive correlation between seed yield and bolls per plant, seeds per boll and branches per plant. Hence, the improvement of linseed yield could be done by selecting for individual yield components like bolls per plant, seeds per boll and 1000-seed weight. Thus, these traits need to be well considered in the future cultivar improvement programmes besides other traits such as tillering and lodging that are much influenced by plant density and nitrogen supply (Luhs & Friedt 1994). These authors have estimated the yield of modern linseed cultivars can reach up to 3 ton/ha under optimum conditions though realization of this potential is often limited by economic and ecological conditions. In a similar study, Patil *et al*. (1981) found that yield per plant of linseed was positively correlated with bolls per plant and seeds per boll, whereas Kurt (1996) reported a negative association between yield per plant and 1000-seed weight, bolls per plant and seeds per boll. Similarly, a significant negative association was also reported between days to maturity and 1000-seed weight (Satapathi *et al*. 1987). These observations indicate that there could not be an improvement in total seed yield simply by increasing only seeds per boll, as it reduces the seed weight and consequently the yield. So, one has to deal with the other major yield components, such as yield per plant, 1000-seed weight and bolls per plant that were significantly, positively and consistently associated with seed and oil yield of linseed.

Oil yield was significantly and positively correlated with polyunsaturated (linoleic and linolenic) fatty acids, but negatively associated with the saturated (palmitic and stearic) ones (Table 6). Similarly, Mishra & Maheshwari (1975) reported that seed yield was positively correlated with oil content, seeds per boll and 1000-seed weight, indicating that these characters contribute significantly to the total oil yield of linseed. Since the association between seed yield and oil content was positive, the improvement for seed yield or oil content can enhance the other character and simultaneous improvement of both traits could be possible. The strong negative association between the total saturated fatty acids and the unsaturated fatty acids indicates the desaturating processes from palmitic to linolenic fatty acids during their biosynthesis (i.e. palmitic→stearic→oleic→linoleic→linolenic), as reported by several researchers (Batta *et al*. 1985; Green 1986; Nigussie 2001).

Linolenic fatty acid was strongly correlated ($r = 0{\cdot}6534$) with linoleic acid. This result did not agree with that of Green (1986), which indicated a complete inverse correlation between linoleic and linolenic. Batta *et al*. (1985) also reported a weak correlation between linoleic and linolenic fatty acids. This shows that correlation results can be variable depending on genotypes, environments, GEI and other factors, such as extraction processes (i.e. methods, timing, storage conditions, etc.). Therefore, it is very important to take into consideration all the factors that could affect the oil yield and its quality to obtain more reliable results. Linoleic acid was negatively associated with all the saturated fatty acids and oleic acid, and this latter monounsaturated fatty acid was positively correlated ($P < 0{\cdot}05$) with saturated fatty acids (Table 6). The saturated fatty acid was observed to be associated positively only with its close components, particularly with stearic acid. Since the quality of linseed oil is dependent on its fatty acid composition and they are influenced by various factors, e.g. genotypes, environments and correlated responses of different fatty acids, all of these components should be considered to achieve the targeted oil quality. Moreover, since yield of linseed is dependent on a number of related traits, understanding of such interrelationship of characters under different environments is essential in formulating selection criteria, which could enhance breeding progress in linseed. This joint analysis of different characters under four environments has also led to better understanding and more gains from selection. Atlin *et al*. (2001) reported that by increasing environments (i.e. replications, testing sites and years), selection responses and gains could be increased. This, in turn, can improve the productivity of linseed yield as it offers more opportunities to improve the productivity by manipulating both genotypic and environmental aspects at a time.

In summary, the magnitude of character associations showed a wide range of variation across years and locations, due mainly to environmental factors such as temperature levels, moisture regimes and disease incidences. Seed yield of linseed per unit area was significantly and positively associated with seed yield per plant, 1000-seed weight and bolls per plant across the four environments. Therefore, focusing on these three traits could improve breeding efficiency of linseed in future breeding efforts. Such study could also provide options of selecting for broad and/or

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specific adaptations through in-depth understanding of genetic and environmental variability and thus can enhance the effectiveness of crop improvement programmes.

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