ISSN : 1812-5379 (Print)
ISSN : 1812-5417 (Online)
http://ansijournals.com/ja

JOURNAL OF AGRONOMY

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

OPEN ACCESS
Journal of Agronomy
ISSN 1812-5379
DOI: 10.3923/ja.2026.11.23

Research Article
Flax Growth and Yield under Variable Nitrogen and Plant Density in Alluvial Soils

[1]Md. Faruque Hossain and [2]Houda A. Rabeh

[1]Department of Operations and Supply Chain Management, Faculty of Business Administration, American International University-Bangladesh, 408/1 Kuratoli Rd, Kuril, Dhaka 1229, Bangladesh
[2]Department of Agronomy, Faculty of Agriculture, Cairo University, Giza Governorate 3750210, Egypt

Abstract
Background and Objective: Appropriate nitrogen (N) fertilizer rate and plant density are important keys for optimizing flax fibers and seeds productivity. Therefore, this study aimed to determine how varying rates of N fertilizer and plant densities affect the productivity of different flax cultivars. **Materials and Methods:** Split-split plot field experiments with four replicates; three N fertilizer rates (67.5, 90 and 112.5 kg N/ha), three plant densities (1000, 1500 and 2000 seeds/m^2) and three cultivars (Giza12, Sakha3 and Lisette) were examined. Data were statistically analyzed using MSTAT-C software, and treatment means were compared using the LSD test at 5% significance level **Results:** Increasing N fertilizer rates and plant densities resulted in significant positive correlation with plant height, technical length, fiber length, seed oil, straw yield/ha. A negative significant correlation between plant densities and each primary branches, capsules/plant and seeds yield/plant. The superiority of Giza12 in capsules/plant (16.05), seed oil (38.62%), and seed yield (2.01 t/ha); Sakha3 in seeds/capsule (7.71) and fiber length (64.11 cm); Lisette stands out in fiber% (31.31%) and fiber yield (2.43 t/ha). The interaction of N rates, densities and cultivars showed that N at 112.5 kg N/ha with 2000 seeds/m^2 achieved the highest yield/ha of seed, oil and straw for Giza12 while, fiber yield/ha for Lisette. **Conclusion:** Following research findings, 112.5 kg N/ha with a density of 2000 seed/m^2 is suitable for increasing the flax seeds and fiber production in alluvial soil conditions. This helps flax plant growers increase their productivity and generate more revenue.

Key words: Flax (*Linum usitatissimum* L.) cultivars, dual purpose cultivars, winter growing seasons, maximum flax growth, straw and fiber yield, seed oil yield

Citation: Hossain M.F. and H.A. Rabeh, 2026. Flax growth and yield under variable nitrogen and plant density in alluvial soils. J. Agron., 25: 11-23.

Corresponding Author: Houda A. Rabeh, Department of Agronomy, Faculty of Agriculture, Cairo University, Giza Governorate 3750210, Egypt

Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Flax (*Linum usitatissimum* L.) is one of the oldest cultivated plants for its nature stem fibers and nutritious seeds, called flax seeds or linseed, from which linseed oil is obtained. Not only that, but it is also an important source of fiber that is used as a raw material for textiles, which is three-fold stronger than cotton[1,2]. It is cultivated as a food and fiber crop in temperate climate regions of the world and is used in the production of environmentally friendly durable composite materials[3-6] and paper with its non-fiber wastages[7]. Furthermore, dietary food products directly use flax seeds[8], industrial oil[9], extract oil for cooking and the remaining residues as a food supplement[10] and as animal feed[11]. Oil is used in the production of varnishes, paints, printing ink and soap because it quickly dries in the air[12]. In addition, flax considered the second important fiber crop after cotton which grown in Egypt as a dual purposes crop for its seed and fiber, especially imported flax varieties cultivated for fiber.

The cultivated area is extremely limited in Egypt; the total cultivated area of flax was 10,007 hectares in 2018-2019, with a total production of 105,509 tons of straw and 17,860 tons of seeds. However, it was approximately 8,609 hectares in the 2021 season, yielding 7601 tons of fiber[13].

This can be carried out by understanding the factors influencing and improving agronomic practices, including optimizing nitrogen fertilizer rates, planting more productive high-yielding varieties, and adjusting plant density which influences yield and quality[6].

Nitrogen fertilizer is essential for plant growth and rising productivity of all crops and its role in protein formation[14-16], which is an integrated part of the chlorophyll and involved in all processes associated with protoplasm, enzymatic reactions and photosynthesis that plays a key role in oil production[17]. Furthermore, soil fertility status of N is also a key factor to decide the rate of N fertilizer application for flax growing. Under the temperate climatic conditions of Egypt, proper N fertilizer application rates are important for the best-quality of maximum flax yield of fiber and seeds[18-20]. Increasing nitrogen fertilizer application level significantly increased fruiting zone length, capsules per plant, flax seed and straw yield per plant and fiber length, such as, from 70 to 140 kg/ha[21], 110 kg N/ha[22] and Egyptian Ministry of Agriculture recommended 180 kg N/ha in newly reclaimed land and 90 kg N/ha in Delta and valley land.

The plant density has a significant impact on the morphological parameters of stem fiber flax, therefore, it is important in flax cultivation to obtain a high yield of straw and fiber, suitable plants density increases fiber yield and quality[23], as well as the high densities had a significant effect on the fiber flax morphological parameters, while, the low plant densities, produced more branching and higher seeds per capsule[24]. The density of 2000 plant/m^2 was suitable for high fiber, straw and seed yield of fiber flax[2]. Increasing plant density significantly decreased capsules per plant but increased straw, fiber yield and fiber percentage, seed rates significantly affected seed and oil yield of flaxseed[4]. Therefore, this research aimed to examine the effect of different N fertilizer application rates and plant densities on different flax cultivars for maximum flax growth and yield production.

MATERIALS AND METHODS

Experimental site and design: A split-split plot distribution in a Randomized Complete Block Design (RCBD) experiment with four replications was carried out in alluvial soil at the Agricultural Research and Experimental Station, Faculty of Agriculture, Cairo University, Giza, Egypt (31°11'33.43' E, 30°1'36.16' N) during two consecutive winter growing seasons (2023/2024 and 2024/2025) to evaluate the productivity of three flax cultivars (*Linum usitatissimum* L.) under different N fertilizer application rates and plant densities.

Treatments and plot layout: The main plots received three nitrogen fertilizer rates (75, 100, and 125% of the Egyptian Ministry of Agriculture Recommended Fertilizer Dose (RFD), 90 kg N/ha). The sub-plots distributed three different plant densities, such as 1000, 1500, and 2000 seeds/m^2, and in sub-sub plots cultivars Giza12 (dual purpose, local, Egypt), Sakha 3 (Fiber, Local, Egypt) and Lisette (fiber, imported from Belgium). The sub-sub plot area was 9 m^2 (3 m length$\times$3 m width). Flax cultivars were sowing on 2nd November 2023 in the first growing season and 5th November 2024 in the second growing seasons.

Fertilizer application: Then the basal fertilizers added to the soil, super phosphate fertilizer (15.5% P_2O_5) at the rate of 238 kg/ha (broadcasting before seed sowing during soil preparation for cultivation). Potassium sulfate fertilizer (48% K_2O) at the rate of 120 kg/ha and N fertilizer doses 75, 100 and 125% from RFD (67.5, 90 and 112.5 kg N/ha, respectively) as ammonium sulfate fertilizer (21% N) were partly split in two equal doses and applied before the first irrigation (21 days from the sowing date) and the second one was applied one month later. Others recommended cultural practices for growing flax done as usual in the area.

Table 1: Main physical and chemical parameter of the field experiment was soil in the two growing seasons 2023 (1st) and 2024 (2nd)

	Seasons	
Soil characteristics	1st	2nd
Particle size distribution (%)		
Coarse sand	3.85	4.30
Fine sand	33.20	35.85
Silt	28.45	25.85
Clay	34.50	34.00
Soil texture	Clay loam	Clay loam
Soil bulk density (g/cm^3)	1.25	1.24
pH*	7.55	7.62
EC (dS/m)**	1.89	2.07
Total carbonate (%)	3.15	2.99
Organic matter (%)	2.05	2.15
Available nutrient (mg/kg)		
N	27.85	24.65
P	9.75	8.55
K	254	268

*Measured in 1:2.5 soil water extraction and **Measured in saturated soil paste extract

Soil sampling and analysis: Before cultivation surface soil samples (0-30 cm) were collected and prepared for analysis. The analysis of the field experimental soil properties is shown in Table 1.

Morphological and yield measurements: Ten guarded plants at maturity stage were taken from each sub-sub plot for the recording morphological parameters such as, plant height, primary branches/plant, technical length (cm), fruiting zone length (cm) and fruiting zone branches /plant and seed yield technical length (cm), fruiting zone length (cm), and fruiting zone branches/plant, seed yield and its components (number of capsules/plant, number of seeds per capsule, 1000 seeds weight (g), seed yield (g/plant) and straw yield (g/plant). Seed and straw yield (t/ha) were measured according to seed and straw yield from square meter of each sub-sub plot.

Seed oil % was figured out by Soxhlet extraction device using solvent of petroleum ether and then the seed oil % was figured out on dry weight basis and oil yield (t/ha) calculated by multiplying seed oil %$\times$seed yield/ha.

Fiber extraction and measurement: After flax plants harvesting and removing the capsules, the retting process was done; straw was arranged in bundles, put and soaked in retting water for about 12 hrs then water was continuously changed to leach out all the soluble materials. The degree of water temperature during the retting processes ranged from 28 to 30°C, retting period was about 12 days in summer season. The retted straw was washed with water and finally dried in air. Thus, the fibers were easily extracted from above the woody part of the stem to figure out fiber percentage and fiber length (cm). Fiber yield (t/ha) was measured according to yield/m^2 of each sub-sub plot.

Statistical analysis: Data were analyzed statistically[25]. Least Significant Difference (LSD) test at 5% level of significance is used to compare treatment means. Computer software package "MSTAT-C" used for statistical analyses.

RESULTS AND DISCUSSION

Morphological characteristics: The main effects of N fertilizer rates (A), plant densities (B), flax cultivars (C) and their interactions on plant height, primary branches/plant, technical length, fruiting zone length and fruiting zone branches/plant are presented in Fig.1 and 2.

Main treatments effect: Nitrogen fertilizer rates, plant densities and flax cultivars exerted significant effects on all the morphological parameters investigated in both seasons (Fig. 1). Increasing N fertilizer rates (75, 100 and 125% RFD) significantly affected the examined morphological parameters in both growing seasons (Fig. 1). On average, rate of N 125% RFD achieved the highest increase as percentage of plant height (5.44 and 2.71%), primary branches/plant (16.85 and 7.56%) technical length (4.38 and 1.69%) and fruiting zone length (10.28 and 7.70%) in comparison with 75 and 100% RFD, respectively. A positive significant correlation was found between increasing N fertilizer rates with plant height ($r = 0.99^{**}$, $p<0.01$), primary branches/plant ($r = 0.97^{**}$, $p<0.01$), technical length ($r = 0.98^{**}$, $p<0.01$) and fruiting zone length ($r = 0.93^{**}$, $p<0.01$). This may be the role of nitrogen as

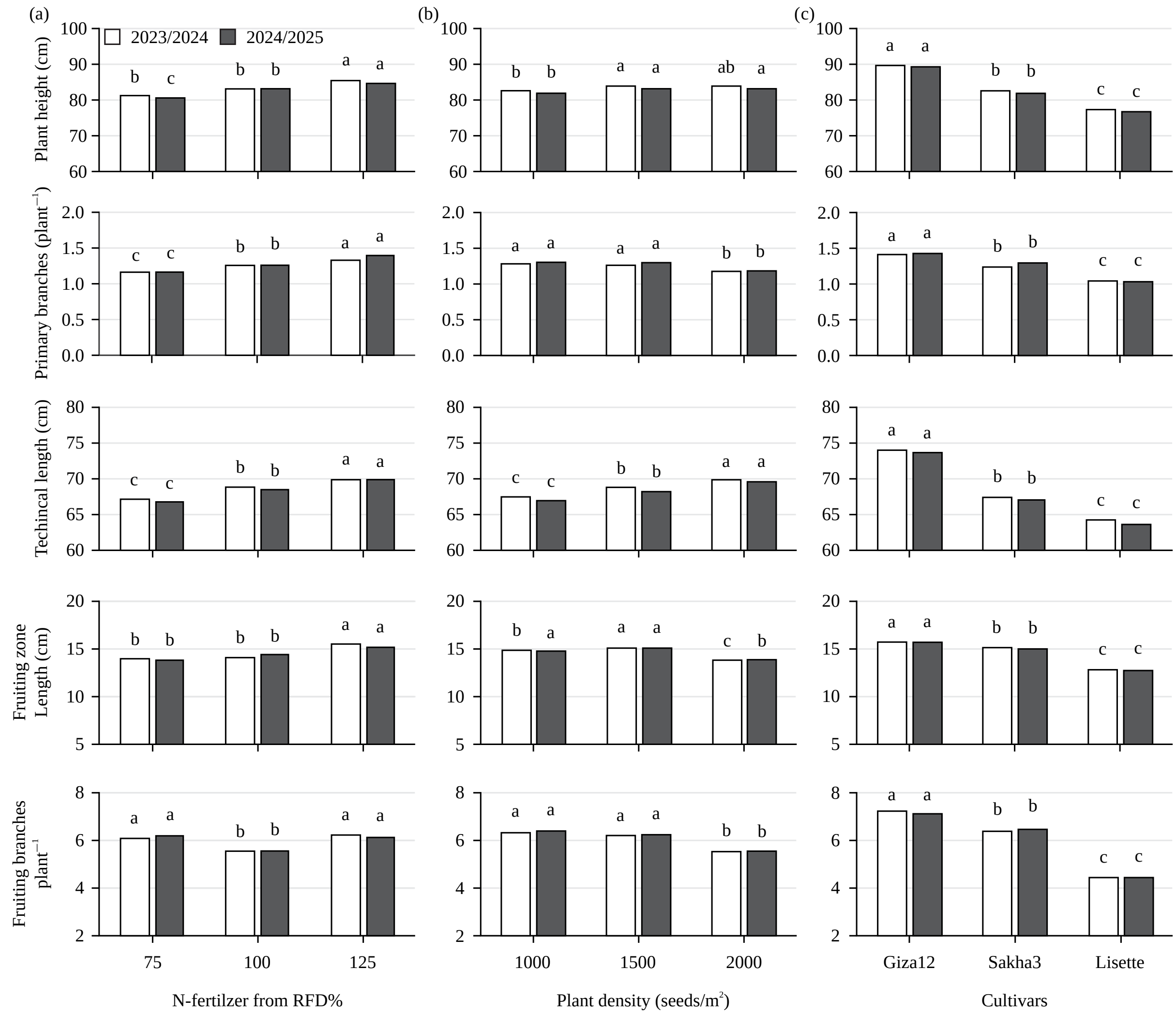

Fig. 1(a-c): (a) Main effects of nitrogen (N) fertilizer application rates as a percentage of the Recommended Fertilizer Dose, (b) Plant densities, and (c) Flax cultivars on morphological characteristics (plant height, number of primary branches/plant, technical length, fruiting zone length, and number of fruiting branches/plant) of flax over two consecutive growing seasons (2023/2024 and 2024/2025)

Bars sharing the same lowercase letters do not differ significantly according to the LSD test at ($p \leq 0.05$)

an essential nutrient for plant growth to build up protoplasm and protein, which is very important for cell division and meristematic activity. Findings of this research has well agreement with several research works[9] as they recorded a statistically significant increase in flax plant height and technical length as nitrogen rates increased.

Plant densities of 1000, 1500 and 2000 seeds/m^2 were statistically significant for inspected morphological characters in both seasons (Fig. 1). The density of 2000 seeds/m^2 gave the highest plant height (83.51 cm) and technical length (69.63 cm) that represent an increase of 1.79 and 3.66%, respectively in comparison with 1000 seeds/m^2. While plant height and technical length at 1500 close to 2000 seeds/m^2. Even though, density at 2000 seeds/m^2 recorded the lowest primary branches 1.19/plant, fruiting zone length 13.82 cm and fruiting zone branches 5.51/plant, these were decreased 8.85 and 7.75 % for primary branches/plant, 6.69 and 9.10% for fruiting zone length and 13.01 and 11.22% for fruiting zone branches/plant in comparing with 1000 and 1500 seeds/m^2, respectively. Plant densities resulted a positive significant correlation with plant height ($r = 0.794^*$, $p<0.05$), technical length ($r = 0.98^{**}$, $p<0.01$), but a negative significant correlation with number of primary branches ($r = -0.88^{**}$, $p<0.01$), fruiting zone length ($r = -0.69^*$, $p<0.05$) and fruiting zone branches/plant ($r = -0.93^{**}$, $p<0.01$). These may be due to low plant density increases the vegetative growth of the

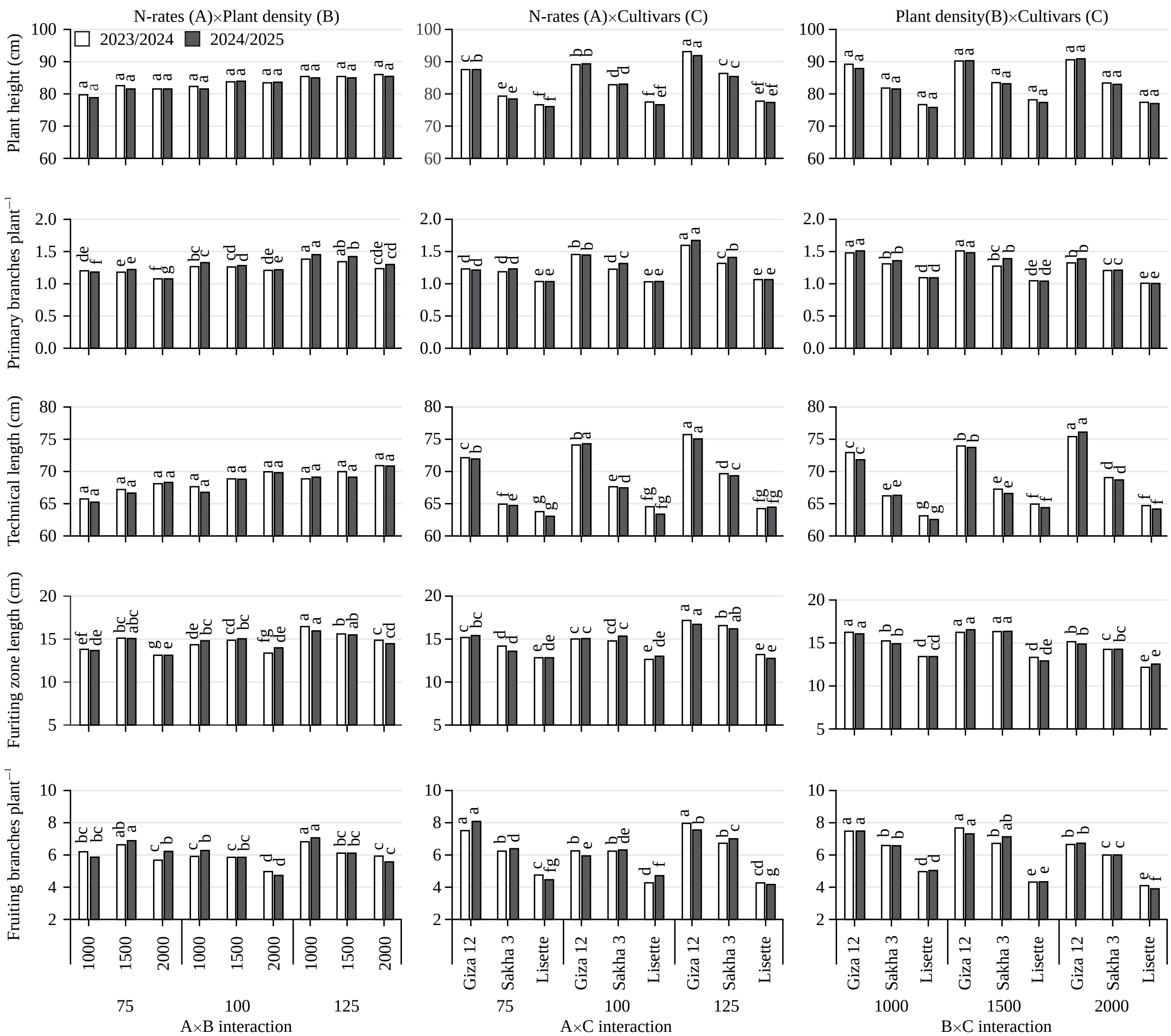

Fig. 2: Effects of two-factor interactions nitrogen rates×plant density (A×B), nitrogen rates×cultivars (A×C), and plant density×cultivars (B×C) on morphological properties of flax during the 2023/2024 and 2024/2025 growing seasons

Bars sharing the same lowercase letters do not differ significantly according to the LSD test at ($p \le 0.05$)

individual plant which support producing more dry matter, as a result, increases primary branches per plant. However, high plant density produces fewer primary branches per plant that has well agreement with other researchers found that flax at low plant density produced more branches per plant[24].

Regarding to cultivars (Fig. 1), Giza12 gave the highest increase compared with Sakha3 and Lisette for plant height (8.76 and 16.56%), primary branches/plant (11.91 and 37.39%), technical length (9.74 and 15.45%), fruiting zone length (4.49 and 22.34 %) and fruiting zone branches/plant (11.34 and 62.83%), respectively. These differences could be attributed to genetic background of cultivars and their response to the environmental conditions, obtained results have partially agreed with[26,27].

Effects of the interactions

Two factors interaction: The interaction of N fertilizer rates and plant densities (AB) showed a significant difference in primary branches/plant, fruiting zone length and fruiting zone branches/plant (Fig. 2). On average, both seasons, N 125% RFD with plant density at 1000 seeds/m^2 produced the highest primary branches (1.42/plant), fruiting zone length (16.19 cm) and fruiting zone b ranches (6.93/plant). However, N 75% RFD at 2000 seeds/m^2 recorded the lowest primary branches (1.08/plant) and fruiting zone length (13.20 cm) while, the lowest fruiting zone branches (4.84/plant) was at N 100% RFD. Other research used different levels of nitrogen fertilizer and reported that the

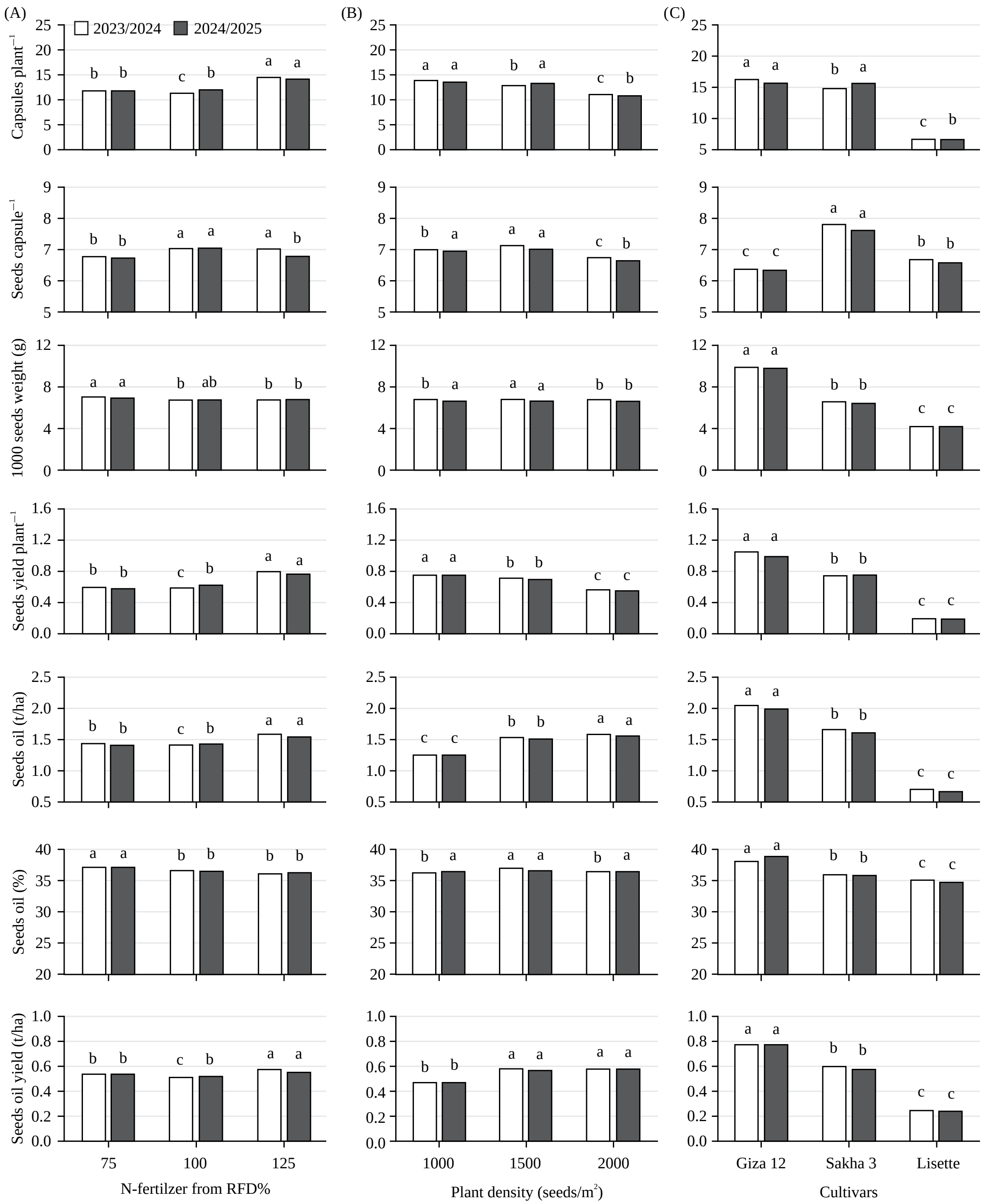

Fig. 3: Main effects and three-factor interactions (A×B×C), of nitrogen fertilizer rates, plant densities, and flax cultivars on flaxseed yield and its components (number of capsules/plant, number of seeds/capsule, 1000-seed weight, seed yield/plant, seed yield/ha, seed oil percentage, and seed oil yield/ha) across two growing seasons

Means with the same lowercase letters are not significantly different ($p \leq 0.05$)

highest dose exceeding 60 kg N/ha was the best which produced more branches for plant of flax[24]. Significant differences for N fertilizer rates and flax cultivars interaction (AC) were seen in the studied morphological characteristics (Fig. 2). As an average, the highest plant height (92.33 cm), primary branches/plant (1.63), technical length (75.33 cm) and fruiting zone length (17.01 cm) resulted from N at 125% RFD with Giza 12 cultivar. While N at 75% RFD registered the during both seasons lowest value of plant height (76.33 cm), primary branches (1.03/plant), technical length (63.47 cm) and fruiting zone length (12.86 cm) of Lisette cultivar. Other research reported that the interaction between N fertilizer rates and cultivars were significant and increasing N level from 30 to 60 kg/fed significantly increased some flax morphological parameters[28]. The interaction among plant densities with flax cultivars (BC) was significant during both seasons for per plant, technical length, fruiting zone length and fruiting zone per plant (Fig. 2). Plant density at 1000 seeds/m^2 with Giza 12 cultivar recorded a higher value of primary branches (1.48/plant), fruiting zone length (16.13 cm) and fruiting zone branches (7.46/plant) than the same density of other cultivars. Plant density at 2000 seeds/m^2 with lisette cultivar achieved the lowest value of primary branches (1.0/plant), fruiting zone length (12.34 cm) and fruiting zone branches (3.97/plant). Another research found that the interaction between plant density and cultivars was significant on fruiting zone length[28].

Three factors' interactions: Data illustrated a significant interaction between N fertilizer rates, plant densities and cultivars (ABC) for primary branches/plant in 2nd season, technical length in 1st season while fruiting zone length, and fruiting zone branches/plant in both seasons (Fig. 2). As an average the application of N 125% RFD with the Giza 12 cultivar recorded the highest primary branches (1.68/plant) at 1500 seeds/m^2, fruiting zone length (17.63 cm) and fruiting zone branches (8.15/plant) at 1000 seeds/m^2 and technical length (77.08 cm) at 2000 seeds/m^2. While Lisette cultivar at N 125% RFD with 2000 seeds/m^2 recorded the lowest number of branches (1.0/plant), fruiting zone length (12.18 cm) and fruiting zone branches (3.83/plant). The same trend was reported as a significant interaction between nitrogen rates, densities and cultivars for flax technical and fruiting zone length[28].

Seed yield and its parameters

Main treatments effect: The results showed that the main effects of nitrogen fertilizing rates (A), densities (B) and cultivars (C) had a significant impact on investigated flaxseed yield and its related parameters in both growing seasons (Fig. 3). Results cleared that N at 125% RFD increased capsules 14.41/plant, seed yield 0.77 g/plant, seed yield 1.54 t/ha, seed oil yield 0 .57 t/ha on average in both seasons. A positive significant correlation was found between N fertilizer rates with capsules/plant ($r = 0.80^*$, $p<0.05$), seed yield/plant ($r = 0.85^*$, $p<0.05$) and seed yield t/ha ($r = 0.83^*$, $p<0.05$). The increase in capsules per plant and flax seed yield due to the increase in nitrogen fertilizer rate was confirmed by different researches[29,30]. Either weight of 1000 seeds or seed oil% increased at N 75% RFD, the increase in 1000 seeds may because that treatment gave less capsules with less competition between them, so the capsule obtained its nutritional needs and fullness, and thus the weight of the capsule increased. The decrease in seed oil% with the increasing N fertilizer rate could be explained by dilution effect because of accumulating more protein in the seed. On the contrary, the increase in oil yield could be explained by the increase in seed yield. These results harmonize with those obtained from several research works[29,31] and they revealed that oil content reduction with high N take place because of a "dilution effect". Whereas, application of N encourages vegetative growth, delaying seed fill and maturity, other components such as protein and starch are accumulated in the seed diluting the oil that increasing rates of N reduced flax seed oil content[32].

Increasing plant density to 2000 seeds/m^2 led to a decrease in the number of plant/capsules (10.97), seeds/ capsule (6.67), weight of 1000 seeds (6.71 g) and seed yield/ plant (0.544 g) as an average. A negative significant correlation was found between plant densities and capsules/plant ($r = -0.94^{**}$, $p<0.01$), seed yield/plant ($r = -0.97^{**}$, $p<0.01$). Also, results cleared that there was a positive significant correlation ($r = 0.96^{**}$, $p<0.01$) between the number of primary branches and capsules/plant. This may be due to the low plant density which encouraged the plant to branch from the lower parts of plant which increase the number of capsules. These results agree with another research by Berti *et al.*[33] they found that increase plant density reduced capsules and so seeds/plant. On the other hand, increase plant density to 2000 seeds/m^2 caused an increase in seed yield 1.57 t/ha ($r = 0.917^{**}$, $p<0.01$) and flaxseed oil yield 0.576 t/ha ($r = 0.878^{**}$, $p<0.01$).

Among the flax cultivars, Giza12 gave the highest values for most of flaxseed yield and its related parameters comparing with Sakha3 and Lisette, the number increasing times are as follows; 1.05 and 2.39 for capsules/plant, 1.53 and 2.34 for 1000 seeds weight, 1.37 and 4.99 for seed yield/ plant, 1.22 and 2.88 for seed yield/ha, 1.07 and 1.10 for seed oil% and 1.31, 3.16 for seed oil yield/ha, respectively as an average. Whereas, Lisette recorded the lowest ones. These varietal differences could be attributed to genetic background of varieties.

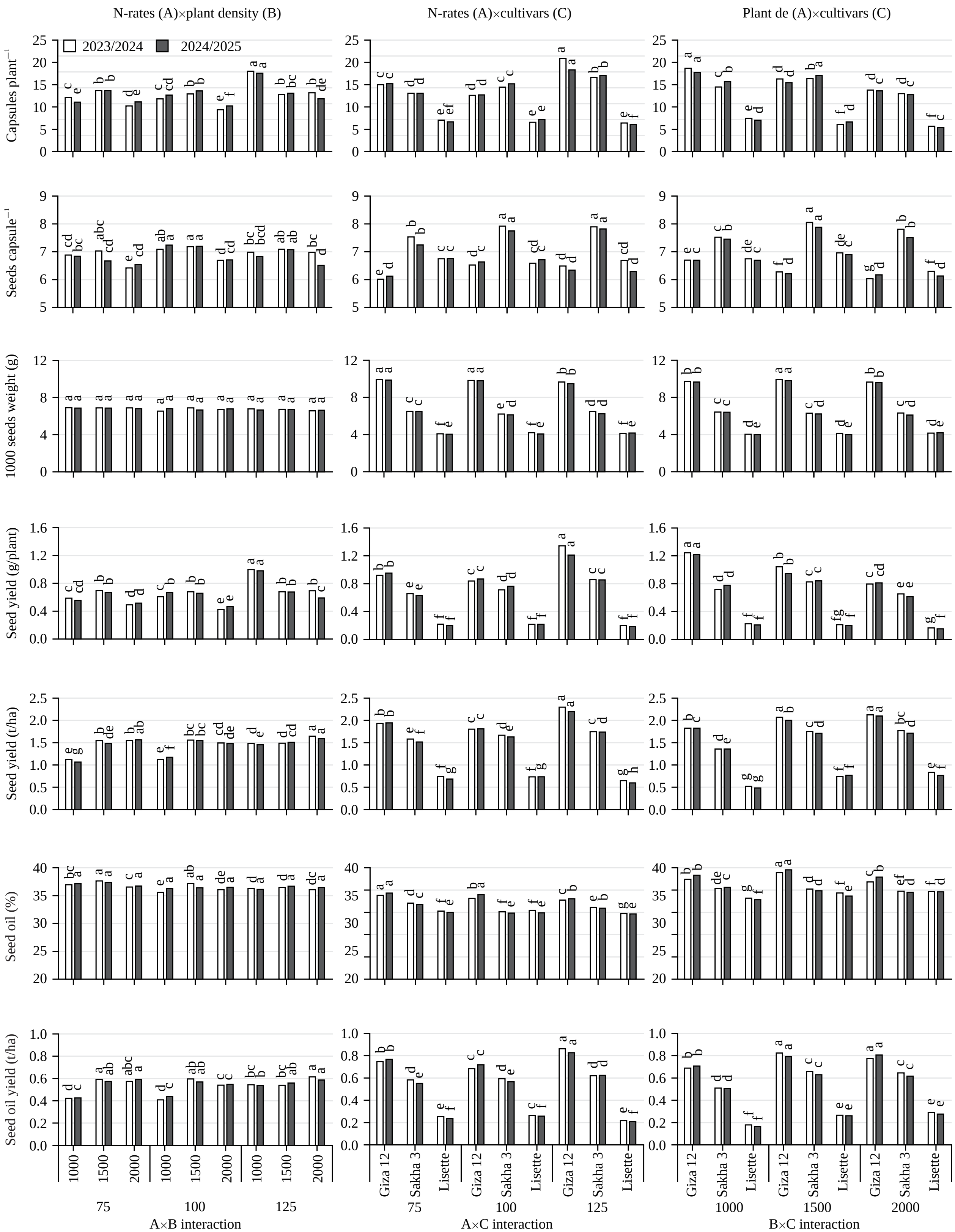

Fig. 4: Effects of two-factor interactions (A×B), (A×C), (B×C) between nitrogen fertilizer rates, plant densities, and different cultivars on flaxseed yield metrics and oil yield during the 2023/2024 and 2024/2025 experimental seasons

Different lowercase letters indicate significant differences at ($p \leq 0.05$)

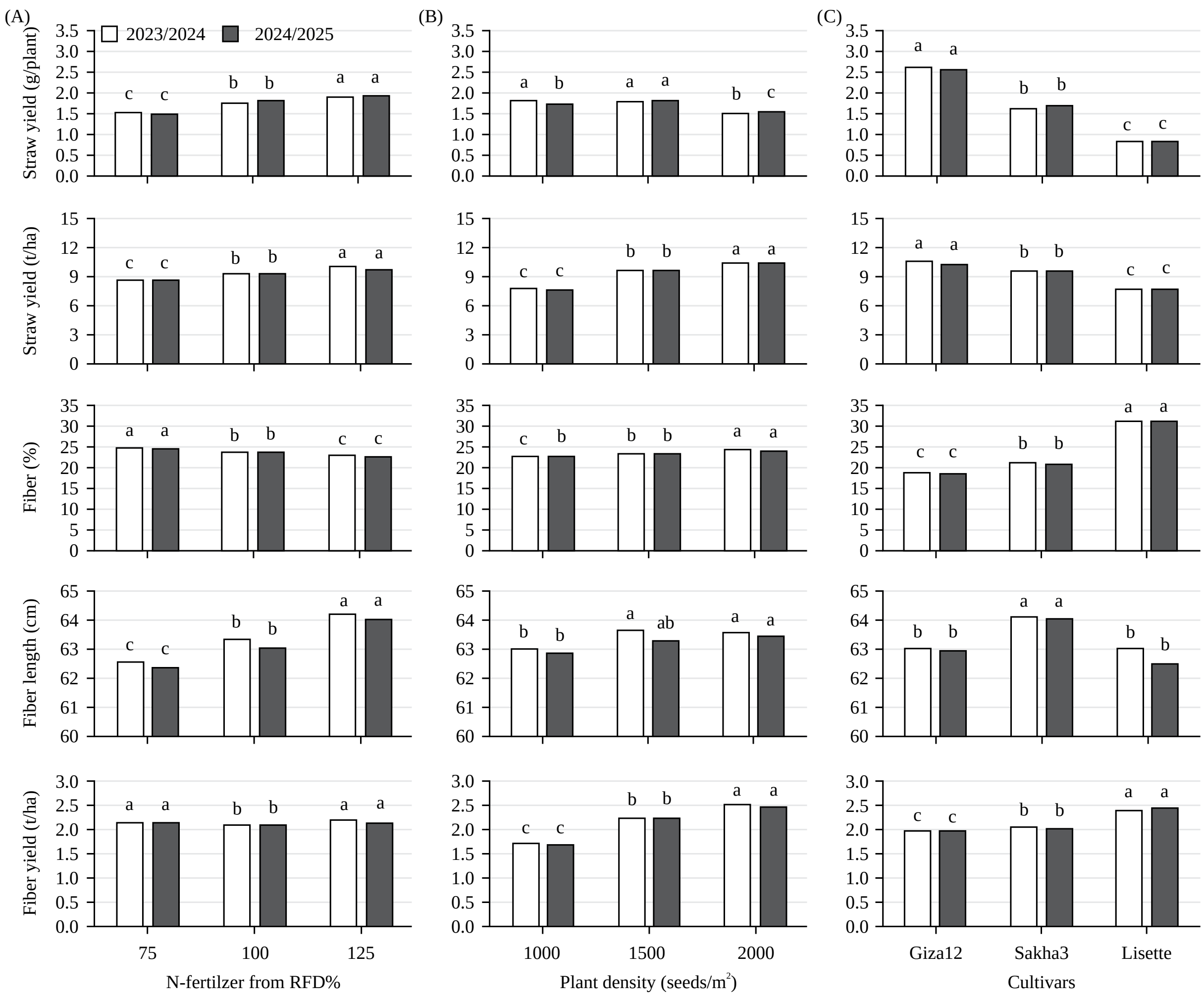

Fig. 5: Main effects of varying nitrogen fertilizer rates, plant stand densities, and flax cultivars on straw yield, fiber percentage, fiber length, and total fiber yield/ha over two winter growing seasons

Bars designated with identical letters do not vary significantly according to the LSD test at ($p \leq 0.05$)

Effects of the interactions

Two factors interaction: The interaction between N fertilizer rates and plant densities (AB) showed a significant positive effect on the flaxseed yield and its related parameters in both seasons (Fig. 4). As an average, the treatment that was fertilized with N at 125% RFD and planted with 1000 seeds/m^2 achieved the highest capsules/plant (17.83) and seed yield/plant (0.99 g), while at N 125% RFD with 2000 seeds/m^2 represented the highest seed yield/ha (1.64 t) and seed oil yield/ha (0.60 t). A significant interaction between N fertilizer rates and flax cultivars (AC) was seen in the flaxseed yield and its components in both growing seasons (Fig. 4). As an average of both seasons, N at 125% RFD with Giza 12 achieved the highest capsules/plant (19.83), seed yield/plant (1.28 g), seed yield t/ha (2.25), seed oil yield t/ha (0.85). While both Sakha3 gave the highest seeds/capsule (7.89) and Lisette recorded the lowest values for capsules/plant (6.35), seed yield/plant (0.19 g), seed yield t/ha (0.63), seed oil t/ha (0.22) at the earlier nitrogen rate. However, other researchers[21,22] reported that high N fertilizer application produced high capsules per plant, flax seed yield per plant such as, from 110 to 140 kg/ha. The interaction between plant densities and cultivars (BC) significantly affected seed yield and its related parameters in both growing seasons (Fig. 4). The cultivar of Giza 12 recorded the highest capsules/plant (18.35) and seed yield/plant (1.24 g) resulted from plant density 1000 seeds/m^2 in comparing with other cultivars and densities, a high seed yield/ha (2.13 t) and seed oil yield/ha (0.81 t) at 2000 seeds/m^2. The highest seeds/capsule (7.98) was produced from 1500 seeds/m^2 for Sakha3. The lowest values were recorded from Lisette cultivar for number of capsules/plant (5.78), 1000 seeds weight (4.20 g) and seed

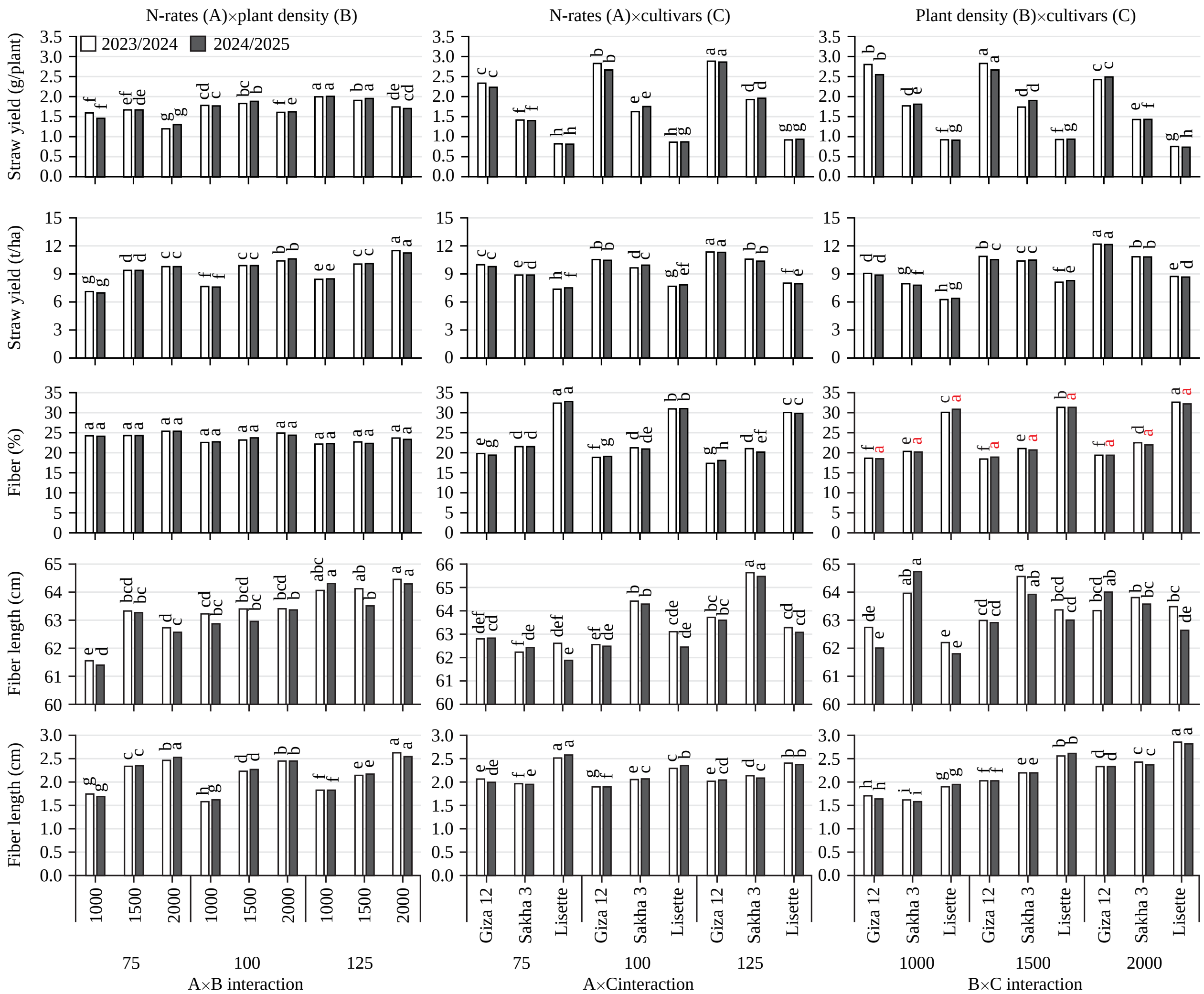

Fig. 6: Interaction effects of nitrogen fertilizer rates, plant densities, and cultivars (A×B), (A×C), (B×C) on the harvested straw properties and extracted fiber quality indicators (fiber yield, percentage, and length) of flax

Bars sharing the same lowercase letters do not differ significantly ($p \leq 0.05$)

yield/plant (0.17 g) at 2000 seeds/m^2 and seed yield/ha (0.52 t), seed oil yield/ha (0.18 t) at 1000 seeds/m^2. However, several researchers reported that the flax density of 2000 plant/m^2 was the best suitable for high seed and oil yield[2,4].

Three factors interaction: The interaction between N fertilizer rates, plant densities and cultivars significantly affected the flaxseed yield and its related parameters in both seasons (Fig. 3). Giza 12 cultivar produced the highest number of capsules/plant (24.70), seed yield/plant (1.70 g) as a result of plant density 1000 plants/m^2 at N 125% RFD, seed yield/ha (2.31 t) and seed oil yield 0.860 t/ha resulted from 2000 plants/m^2 at N 125% RFD, while the highest 1000 seed weight (10.05 g) and seed oil% (40.25%) were achieved from 1500 plants/m^2 with N 100% RFD. N 125% RFD with 1500 plants/m^2 gave the highest flaxseeds/capsule (8.16) in Sakha3. Lisette cultivar recorded the lowest capsules/plant (5.05), 1000 seeds weight (4.15 g), seed yield/plant (0.15 g) because of 2000 plant/m^2 with N 125% RFD. Another researcher mentioned that capsules per plant and seed yield significantly affected by the interaction between N rates×plant density×cultivars[28].

Straw, fiber yield and its characteristics

Main effects: The main effects of N fertilizer rates (A), plant densities (B) and flax cultivars (C) recorded significant differences in straw yield, fiber%, fiber length and fiber yield (Fig. 5). As an average in both seasons, with increasing N fertilizer rates straw yield and fiber length increased, on the other hand, fiber% decreased. The highest straw yield 1.91 g/plant, 9.95 t/ha and fiber length 64.16 cm were at N rate of 125% RFD, which increased by 27.08 and 8.08% for straw yield/plant, 13.51 and 6.46% for straw yield/ha, 2.67 and 1.46% for fiber length compared with N rate of 75 and 100% RFD, respectively. Insignificant difference between N rate at 75 and 125% RFD on fiber yield/ha because the lower N rate gave the highest fiber%, while the higher N rate gave the highest straw yield. These results were strongly supported by another research[34], who mentioned that increase application rates of NPK fertilizers increased fiber yield resulting from the increased straw yield, although the fiber% decreased. A positive significant correlation was found as increasing N fertilizer rates with straw yield/plant ($r = 0.985^{**}$, $p<0.01$), straw yield/ha ($r = 0.997^{**}$, $p<0.01$) and fiber length ($r = 0.988^{**}$, $p<0.01$), while a negative significant correlation with fiber% ($r = -0.998^{**}$, $p<0.01$). Obtained results are harmony with several reseaches[9,35] and they reported that the flax fiber length increased as N fertilizer rate increased.

By increasing plant densities, the straw and fiber yield/ha, fiber% and fiber length directly increased, while straw yield/plant decreased (Fig. 5). Plant density at 2000 seeds/m^2 achieved the highest straw yield (10.56 t/ha), fiber% (24.54%), fiber length (63.49 cm) and fiber yield (2.50 t/ha), however the lowest values were recorded at 1000 seeds/m^2. In addition with plant densities increase then a positive significant correlation was observed with straw yield t/ha ($r = 0.97^{**}$, $p<0.01$), fiber % ($r = 0.98^{**}$, $p<0.01$), fiber length ($r = 0.81^{**}$, $p<0.01$) and fiber yield t/ha ($r = 0.98^{**}$, $p<0.01$), while a negative significant correlation was observed with straw yield/plant ($r = -0.76^{*}$, $p<0.05$). The similar trends reported by other researchers who recorded that 2000 plant/m^2 were proper for flax cultivation to get high straw and fiber yield[2]. Also, another research by Andruszczak *et al.*[36] reported that straw yield, fiber yield, fiber% and fiber length significantly increased by increasing plant density to 2500 seeds/m^2, and straw yield/plant inversely increased.

Giza12 cultivar achieved higher values for straw yield/plant (2.63 g) and straw yield/ha (10.60 t) than Sakha3 by 1.56 and 1.09 times and Lisette cultivar by 3.05 and 1.37 times, respectively. While Lisette cultivar recorded the highest value of fiber% (31.31%) and fiber yield/ha (2.43 t) and Sakha3 cultivar achieved the highest value in fiber length (64.10 cm). These results have well agreement with[36] who found that Sakha3 cultivar significantly produced higher fiber length than Giza 12.

Effects of the interactions

Two factors interaction: The interaction of N fertilization rates and plant density (AB) showed a significant difference in straw and fiber properties in both seasons (Fig. 6). Nitrogen with the rate of 125% RFD achieved the highest value of straw yield (2.03 g/plant) at density of 1000 seeds/m^2 and the highest value of straw yield (11.32 t/ha), fiber length (64.41 cm) and fiber yield (2.57 t/ha) at density of 2000 seeds/m^2 as an average of both seasons. Flax cultivated at 2500 seeds/m^2 and received high N rate (70 kg N/fed) gave the highest straw and fiber yield/fed[36]. Interaction of N fertilizer rates and flax cultivars (AC) has a significant effect on straw and fiber parameters in both seasons (Fig. 6). On average, at N 125% RFD treatment Giza12 produced the highest value of straw yield (2.87 g/plant), Straw yield (11.33 t/ha) and Sakha 3 gave the highest fiber length (65.58 cm). On the other hand, Lisette cultivar recorded a high fiber% (32.80%) and fiber yield (2.55 t/ha) because of adding Nitrogen at a rate of 75% RFD. Results are strongly supported by several researchers[36] and they found under the highest N rate (70 kg N/fed) flax cultivar Giza 12 gave the highest straw yield and Sakha 3 produced the longest fiber. A significant interaction among plant densities and flax cultivars (BC) investigated straw and fiber parameters in both growing seasons (Fig. 6). The density of 2000 seeds/m^2 resulted the highest straw yield (12.14 t/ha) with Giza12 cultivar, and the highest fiber% (32.34%) and fiber yield (2.82 t/ha) with Lisette cultivar. The highest straw yield (2.77 g/plant) was seen at 1500 plant/m^2 was for Giza 12.

Three factors interaction: Interaction of N fertilizer rates, densities and Flax cultivars (ABC) significantly effected on the studied straw and fiber characters in both seasons. On average, the maximum straw yield of 2.93 g/plant was obtained from Giza12 cultivar because of planting 1500 seeds/m^2 with adding N rate of 125% RFD. The minimum straw yield 0.72 g/plant was produced from Lisette cultivar resulted from 2000 seeds/m^2 with 75% N from RFD. N 125% RFD at density 2000 seeds/m^2 recorded the highest straw yield 13.34 t/ha for Giza 12. While, the lowest straw yield 6.06 t/ha had resulted due to addition of N at 75% RFD and plant density 1000/m^2 for Lisette cultivar. The most effective interaction treatment produced the highest fiber yield 2.88 t/ha was Lisette resulted of planting 2000 seeds/m^2 and adding N rate 125% RFD, and the lowest fiber yield 1.38 t/ha was for Sakha3 resulted from 1000 seeds/m^2 and N 75% RFD. Sakha3 recorded the longest fiber length 66.50 cm from plant density 1000 seeds/m^2 and N 125% RFD, however Lisette cultivar gave the shortest one 60.47 cm resulted from planting

1000 seeds/m^2 and adding N at a rate of 75% RFD. However, research on flax seed production shows that both fertilizer rates and plant densities have significant impact on yield, but best levels vary depending on soil type, climate and flax verities. Eventually, higher N fertilizer rates can increase flax seed and oil yield, while plant density also plays a crucial role here, with different densities affecting straw and seed yields individuals. Research results agree with[28] who revealed that the interaction between nitrogen levels×seeding rates×cultivar significantly effected fiber length and fiber yield.

CONCLUSION

The study evaluated the effects of N fertilizer rates application and plant densities on different flax cultivars (*Linum usitatissimum* L.) productivity because flax is grown to get natural fibers which are used in the production of textiles, as well as seeds that supply a source of oil and some human nutritious products. Both best N fertilizer rates and plant densities are among the important agricultural practices that help flax growers to improve their productivity. Based on the two seasons experimental results, a high plant density of 2000 seeds/m^2 produced the highest technical length, fiber percentage, fiber length and yield/ha for seeds, oil, straw, and fiber. Our results suggest that the best preferable practice is plant density at 2000 seeds/m^2 with 112.5 kg N/ha to maximize both flax seeds and fibers yield together. However, density at 2000 seeds/m^2 with 67.5 kg N/ha strongly suggested for a high yield of fiber production, regardless of the seed yield in alluvial soil conditions. Furthermore, improving both fertilizer rates and plant densities is very crucial for maximizing flax seed and fiber production. As a result, a balanced approach that considers the specific flax variety, soil types and local growing conditions are necessary to achieve optimum levels of yields and its quality for the maximum level of revenue benefits.

SIGNIFICANCE STATEMENT

This study proves the influence of nitrogen fertilizer rates and plant density on the growth, yield, and fiber quality of flax cultivars in alluvial soils. The findings provide practical guidance for improving agronomic practices to enhance both seed and fiber productivity. This contributes to improving flax cultivation efficiency, farmer profitability, and sustainable agricultural production systems under varying environmental conditions.

REFERENCES

1. Saleem, M.H., S. Fahad, S.U. Khan, M. Din and Abid Ullah *et al*., 2020. Copper-induced oxidative stress, initiation of antioxidants and phytoremediation potential of flax (*Linum usitatissimum* L.) seedlings grown under the mixing of two different soils of China. Environ. Sci. Pollut. Res., 27: 5211-5221.
2. Arslanoglu, Ş.F., S. Sert, H.A. Şahin, S. Aytaç and A. El Sabagh, 2022. Yield and yield criteria of flax fiber (*Linum usititassimum* L.) as influenced by different plant densities. Sustainability, Vol. 14. 10.3390/su14084710.
3. Baley, C., M. Gomina, J. Breard, A. Bourmaud and P. Davies, 2020. Variability of mechanical properties of flax fibres for composite reinforcement. A review. Ind. Crops Prod., Vol. 145. 10.1016/j.indcrop.2019.111984.
4. Beyene, A., Y. Alemayehu, A. Wakijira and H. Legesse, 2022. Influence of seeding rates on seed yield, oil content, oil yield and other yield attributes of four linseed (*Linum usitatissimum* L), varieties in Horo Guduru District, Western Ethiopia. Cogent Food Agric., Vol. 8. 10.1080/23311932.2022.2124720.
5. Omar, T.A., 2020. Effect of nitrogen application methods and harvesting dates on yield and yield components of some flax cultivars. Moroccan J. Agric. Sci., Vol. 1.
6. Sanmartin, C., I. Taglieri, F. Venturi, M. Macaluso and A. Zinnai *et al*., 2020. Flaxseed cake as a tool for the improvement of nutraceutical and sensorial features of sourdough bread. Foods, Vol. 9. 10.3390/foods9020204.
7. Zhai, S.S., T. Zhou, M.M. Li, Y.W. Zhu and M.C. Li *et al*., 2019. Fermentation of flaxseed cake increases its nutritional value and utilization in ducklings. Poult. Sci., 98: 5636-5647.
8. Kozłowski, R.M., A. Kręgielczak, D.G. Radu, A.I. Pag and C. Sîrghie, 2014. Flax seeds-source of biomedical and food products. Mol. Cryst. Liq. Cryst., 603: 122-135.
9. Bakry, B.A., O.M. Ibrahim, T.A.E.F. Elewa and M.F. El-Karamany, 2014. Performance assessment of some flax (*Linum usitatissimum* L.) varieties using cluster analysis under sandy soil conditions. Agric. Sci., 5: 677-686.
10. Brunšek, R., J. Butorac, Z. Augustinović an M. Pospišil, 2022. Effect of nitrogen on the properties of flax (*Linum usitatissimum* L.) plants and fibres. Polymers, Vol. 14. 10.3390/polym14030558.
11. Fila, G., M. Montanari, C. Maestrini and M. Bagatta, 2024. Bayesian analysis of cultivar and climate effects on seed and oil production in linseed. Ind. Crops Prod., Vol. 218. 10.1016/j.indcrop.2024.118883.
12. Stavropoulos, P., A. Mavroeidis, S. Karydogianni, A. Folina and I. Roussis *et al*., 2025. Effects of plant density and type of fertilizer on nutritional quality of flaxseed (*Linum usitatissimum* L.). Agronomy, Vol. 15. 10.3390/agronomy15122738.
13. Hossain, M.F., S.F. Elahi, S.K. White, Q.K. Alam, J.A. Rother and J.L. Gaunt, 2012. Nitrogen budgets for Boro rice (*Oryza sativa* L.) fields in Bangladesh. Field Crops Res., 131: 97-109.

14. Hossain, M.F., S.K. White, S.F. Elahi, N. Sultana and M.H.K. Choudhury *et al*., 2005. The efficiency of nitrogen fertiliser for rice in Bangladeshi farmers' fields. Field Crops Res., 93: 94-107.
15. Hossain, M.F., 2006. Nutrients removed in harvested portion of crop by continuous corn receiving organic and inorganic fertilizers. J. Plant Sci., 1: 264-272.
16. Goudenhooft, C., A. Bourmaud and C. Baley, 2019. Flax (*Linum usitatissimum* L.) fibers for composite reinforcement: Exploring the link between plant growth, cell walls development, and fiber properties. Front. Plant Sci., Vol. 10. 10.3389/fpls.2019.00411.
17. FAO, 2025. Tracking Progress on Food and Agriculture-Related SDG Indicators 2025. FAO, Rome, Italy, ISBN: 978-92-5-139913-2, Pages: 108.
18. Rashwan, E., A. Mousa, A. El Sabagh and C. Barutcular, 2016. Yield and quality traits of some flax cultivars as influenced by different irrigation intervals. J. Agric. Sci., 8: 226-240.
19. Abo El-Komsan, S.M., E.T. Abdou, G.S.A. El-Yamanee and R.H.H. Ahmed, 2024. Effect of plant density and retting method on flax yield and its components undersandy soil conditions. Moroccan J. Agric. Sci., 5: 187-194.
20. Arslanoğlu, F. and S. Aytaç, 2020. The important in terms of health of flax (*Linum usitatissimum* L.). Int. J. Life Sci. Biotechnol., 3: 95-107.
21. Yasemin, E., Y. Seviye and O. Fadil, 2018. The effect of different seeding rates on grain yield and yield components in someflax (*Linum usitatissimum L.*) varieties. Int. J. Environ. Agric. Res., Vol. 4.
22. Xie, Y., Y. Li, Y. Qi, L. Wang and W. Zhao *et al*., 2022. Effects of phosphorus supply on seed yield and quality in flax. Agronomy, Vol. 12. 10.3390/agronomy12123225.
23. Malimbayeva, A., B. Amangaliev, E. Zhusupbekov, A. Soltanayeva and A. Sagimbayeva *et al*., 2026. Effects of different mineral, foliar macro- and micronutrient, and biofertilizer fertilization strategies on oil flax (*Linum usitatissimum* L.) yield and seed quality under semi-arid rainfed conditions. Int. J. Plant Biol., Vol. 17. 10.3390/ijpb17030019.
24. Niu, J., C. Liu, M. Huang, K. Liu and D. Yan, 2021. Effects of foliar fertilization: A review of current status and future perspectives. J. Soil Sci. Plant Nutr., 21: 104-118.
25. Cochran, W.G. and G.W. Snedecor, 1980. Statistical Methods. 7th Edn., Iowa State University Press, Ames, Iowa, USA, ISBN-10: 0813815606, Pages: 507.
26. Mańkowska, G. and J. Mańkowski, 2022. The influence of selected habitat and agronomic factors on the yield of flax (*Linum usitatissimum* L.). J. Nat. Fibers, 19: 2327-2337.
27. Wu, B., Z. Cui, L. Ma, X. Li and H. Wang *et al*., 2023. Effects of planting density—potassium interaction on the coordination among the lignin synthesis, stem lodging resistance, and grain yield in oil flax. Agronomy, Vol. 13. 10.3390/agronomy13102556.
28. Hocking, P.J. and A. Pinkerton, 1991. Response of growth and yield components of linseed to the onset or relief of nitrogen stress at several stages of crop development. Field Crops Res., 27: 83-102.
29. Dudarev, I., 2022. A review of fibre flax harvesting: Conditions, technologies, processes and machines. J. Nat. Fibers, 19: 4496-4508.
30. Lemessa, G.B. and J. Zerihun, 2022. Yield and oil response of linseed (*Linum usitatissimum* L.) to nitrogen application. Int. J. Agric. Technol., 18: 1651-1670.
31. Hocking, P.J., 1995. Effects of nitrogen supply on the growth, yield components, and distribution of nitrogen in Linola. J. Plant Nutr., 18: 257-275.
32. Casa, R., G. Russell, B.L. Cascio and F. Rossini, 1999. Environmental effects on linseed (*Linum usitatissimum* L.) yield and growth of flax at different stand densities. Eur. J. Agron., 11: 267-278.
33. Berti, M., S. Fischer, R. Wilckens and F. Hevia, 2009. Flaxseed response to N, P, and K fertilization in South Central Chile. Chil. J. Agric. Res., 69: 145-153.
34. Liu, F., F. Li, G. Du and F. Xiao, 2013. Balanced fertilization improves fiber yield and quality of winter flax (*Linum usitatissimum* L.). Am. J. Plant Sci., 4: 291-296.
35. Taddese, G. and S. Tenaye, 2018. Effect of nitrogen on flax (*Linumusitatissimum* L.) fiber yield at Debre Berhan area, Ethiopia. For. Res. Eng. Int. J., 2: 284-286.
36. Andruszczak, S., U. Gawlik-Dziki, P. Kraska, E. Kwiecińska-Poppe, K. Różyło and E. Pałys, 2015. Yield and quality traits of two linseed (*Linum usitatissimum* L.) cultivars as affected by some agronomic factors. Plant Soil Environ., 61: 247-252.