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Performance of Oat under Different Sowing Densities and Nitrogen Levels

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ABSTRACT

Oats have historically been utilized as both animal feed and human food and continue to play a significant role in these capacities today. Understanding the extent to which agricultural practices influence the yield and quality of oat cultivars is of great importance to breeders. The aim of this study is to determine the effects of different sowing densities and nitrogen applications on the grain yield, yield components, and some quality traits of oats. In the study, various traits of oats were examined, including plant height, panicle length, number of spikelets per panicle, number of grains per panicle, grain yield, thousand-grain weight, groat percentage, ash content, protein content, starch content, β-glucan content, fat content, acid detergent fiber, and neutral detergent fiber. This study was conducted over two years during the 2019-2020 and 2020-2021 growing seasons in Bilecik, Türkiye. The experiments were established using a split-plot design, where the main plots were assigned nitrogen doses (0, 40, 80, 120, and 160 kg N ha^{-1}) and the subplots were assigned sowing densities (150, 300, 450, and 600 seeds m^2), with three replications. The highest grain yield was obtained at sowing densities of 300 and 450 seeds m^2 as 4.45 t ha^{-1} and 4.56 t ha^{-1}, respectively. Since there was no statistically significant difference in yield between these densities, a sowing density of 300 seeds m^{-2} can be recommended on oat. Additionally, the highest grain yield was achieved with a nitrogen dose of 80 kg per hectare. Based on the results of this study, the combination of nitrogen dose 80 kg and sowing density 450 seeds m^2 showed the optimal performance in terms of yield and quality. In conclusion, grain yield and quality traits in oats have shown significant differences based on the years, applied nitrogen doses, and sowing density practices.

1. INTRODUCTION

Oat belongs to the *Avena* genus of the *Poaceae* family and is classified as diploid, tetraploid, or hexaploid based on its chromosome number. Cultivated oat falls into the hexaploid group with a chromosome count of 2n=42. Türkiye, situated within various global genetic centres, serves as a significant genetic centre for oat. It is reported that the country boasts a rich diversity of oat forms and varieties, with the origins of cultivated *Avena sativa* and *Avena byzantina* tracing back to Anatolia.

Oat ranks sixth in global cereal production, following wheat, corn, rice, barley, and sorghum (FAO, 2022). In recent years, oat production has declined in many countries due to the reduced use of oats as feed. Additionally, this decline in production has been related to higher monetary returns per hectare from other crops such as corn, soybeans, and wheat (Cınar, 2023). Furthermore, factors such as sensitivity to cold and drought, grain shedding, lodging, and asynchronous maturation also constrain oat cultivation (Mut et al., 2021a). Oat, with a history dating back two millennia, has primarily been used in animal feeding. However, in recent years, oats have become increasingly popular in human nutrition due to recognizing their benefits in food and health domains. Oat is nutritionally superior to other cereal grains (Rauf et al., 2019) and is rich in certain antioxidants and anti-carcinogenic compounds, making them highly beneficial for health (Michels et al., 2020). To achieve high grain yield and quality per unit area in oat, it is essential not only to select productive varieties resilient to biotic and abiotic stress factors suitable for the region's ecological conditions but also to improve cultivation techniques. Yield is influenced by the interaction of genetic factors, environmental conditions, and cultivation practices (Erbas Kose, 2022).

These cultivation techniques, which affect plant yield and quality, encompass various operations from field preparation to harvest. Among these, fertilization and sowing density, which hold significant economic importance for growers, are paramount. Nitrogen is one of the most essential nutrients for oats, directly influencing plant growth, development, and yield potential. Nitrogen fertilization increases the protein content of oat grain, contributing significantly to their nutritional value. Furthermore, nitrogen applications enhance the biological productivity of oat, leading to improvements in yield components (Leghari et al., 2016). However, excessive nitrogen use can have negative effects, such as lodging, excessive leaf development, and increased susceptibility to diseases (Mut et al., 2021a). Therefore, the proper dosage and timing of nitrogen fertilization are crucial for achieving optimal yield and quality in oats. The effectiveness of nitrogen fertilization is influenced by environmental factors, sowing density, and genetic traits, highlighting the need for application strategies tailored to specific ecosystems (Ju et al., 2022). Providing the necessary nutrients in appropriate amounts and timing throughout the plant's growth period is crucial for achieving high yields. Among these nutrients, nitrogen stands out as the most essential substance in cultivation, serving as a building block for proteins, enzymes, vitamins, and hormones in plants (Leghari et al., 2016). In our country, due to insufficiently informed fertilizer use practices, there is a prevalent misconception that excessive nitrogen application can lead to higher yields. However, improper and excessive use of nitrogen by growers can be economically detrimental and unsuitable for plants. In cereals, nitrogen excess can promote lodging, while nitrogen deficiency can result in weak stem and leaf development, slowed growth, early flowering, and reduced yield and product quality (Farhan et al., 2024).

Sowing density is another factor that affects plant growth and development as well as fertilization. It holds significant economic importance for growers, as optimal plant density is vital for achieving higher grain yield per unit area than varieties under specific ecological conditions. In oats, traits such as panicle number per unit area, panicle length, grain count per panicle, and grain yield per panicle impact grain yield per unit area (Mut et al., 2018a) and these traits vary depending on sowing density (Altuner and Ulker, 2019). Sowing density is influenced by genotype, sowing time, seed size, and ecological conditions. Excessive seed use increases costs and can lead to yield losses.

To achieve high yield and good quality, it is essential to implement the most suitable cultivation techniques specific to the region where the crop is grown. Among these agricultural practices, sowing density and nitrogen fertilization are critical in oat cultivation.

The aim of this study is to assess the effects of different sowing densities and nitrogen fertilizer doses on grain yield, yield components, and some quality traits of oat.

2. MATERIALS AND METHODS

Plant materials and field experiments

The field experiment was conducted during the 2019-2020 and 2020-2021 growing seasons at the Agricultural Application and Research Center of Bilecik Seyh Edebali University of Bilecik. The study area is located between 30° 10' North latitude and 40° 11' East longitude, with an elevation of 500 meters above sea level. Kahraman oat cultivar, which was developed by the Thrace Agricultural Research Institute, was used as material in the experiment. This cultivar was chosen because it is one of the widely cultivated oat cultivars in Türkiye and has shown good adaptability to diverse agro-ecological conditions. Its widespread use and stable performance across regions make it a suitable candidate for evaluating agronomic responses to nitrogen application and sowing density.

Sowing dates were 2 November 2019 and 12 November 2020, respectively. The experiments were established using a Split-Plot Design with three replications. This study implemented four sowing densities (150, 300, 450, 600 seeds m^{-2}) and five nitrogen doses (0, 40, 80, 120, 160 kg ha^{-1} N). The experiments were designed with nitrogen doses assigned to the main plots and sowing densities to the subplots. Each plot was 4 meters long, with a row spacing of 20 cm and consisted of 6 rows. Sowing was carried out by hand. Along with the sowing, all plots were fertilized with 160 kg of Triple Super Phosphate fertilizer (43-44% P_2O_5) per hectare. Potassium fertilization was not applied based on the results of soil analysis. The experimental fields were previously cultivated with wheat in the preceding season. The soil analysis indicated that the potassium levels were sufficient. The adequate presence of potassium in the soil ensures that plants can naturally obtain this nutrient from the soil. Half of the nitrogen fertilizer was applied at sowing using Ammonium Sulfate (21% N), while the other half was applied during the tillering stage using Urea (46% N). Weed control was managed during the tillering stage. Harvesting was done with a sickle on July 15, 2020, for the first year, and on July 21, 2021, for the second year. All the plots were hand harvested. One row on each side of the plots and a 50 cm section from the plot ends were excluded. The harvested material was left to dry in the plots. In order to facilitate threshing with the plot threshing machine, the plants were left to dry under sunlight for one to two weeks. Then threshed using a threshing machine.

Climate and soil characteristics of the experimental area

Figure 1 presents the climate data for the 2019-2020 and 2020-2021 growing seasons in Bilecik province, obtained from the Turkish State Meteorological Service (Bilecik Meteorological Directorate). The average temperature during both the 2019-2020 and 2020-2021 growing seasons was recorded at 11.6 °C. While the total rainfall was 482.6 mm during the 2019-2020 growing season, it decreased to 436.1 mm in the 2020-2021 seasons. Relative humidity levels were recorded as 63.0% and 60.3% for the 2019-2020 and 2020-2021 growing seasons, respectively (Figure 1). Based on the soil analysis results, the soil at the experimental site was classified as clayey-loamy (40%), with a slightly alkaline pH of 7.78, moderately calcareous (6.84%), mildly saline (0.45%), rich in phosphorus (22.16 kg ha^{-1}), high in potassium (66.90 kg ha^{-1}), and having a moderate organic matter content of 2.26%.

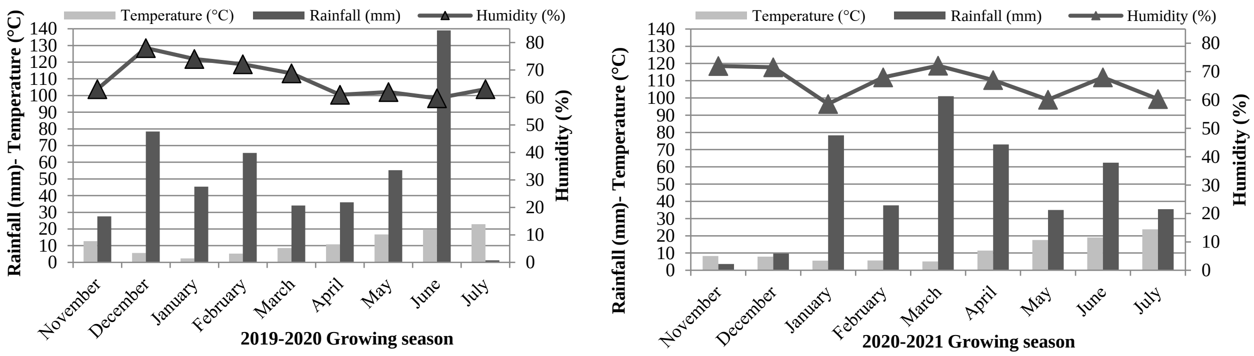

Figure 1. Meteorological conditions in the experimental areas during the 2019-2020 and 2020-2021. (In the 2019-2020 growing season, the total rainfall, average temperature, and humidity were 482.6 mm, 11.6°C, and 67.9%, respectively. In the 2020-2021 season, these values were 436.1 mm, 11.6°C, and 66.4%, respectively) (The data was obtained from Bilecik Regional Directorate of Meteorology)

Grain yield and some yield components, along with physical and chemical analyses

In this study, plant height (cm), panicle length (cm), the number of spikelet per panicle, and the number of grains per panicle were measured in 10 plants. Grain yield (GY) was calculated by converting the plot yield, determined by weighing the grains after harvest and threshing, into hectares and expressed in tons. Plant height (PH) was measured from the soil surface to the tip of the panicle. Panicle length (PL) was determined by measuring the distance in cm from the first node on the main stem to the tip of the uppermost spikelet. The number of spikelet per panicle (SPP) was recorded by counting all spikelet on each panicle. Similarly, the number of grains per panicle (KPP) was determined by counting all grains on each panicle. The thousand-grain weight (TGW) was determined by counting four sets of 100 seeds each using a seed counting device (Chopin Technologies-Numigral, France), averaging the results, and then multiplying by 10. Groat percentage (GP) was calculated by manually removing the hulls from a 20-gram sample of grains, weighing the dehulled grains, and then expressing this weight as a percentage of the total sample weight.

Oat samples designated for chemical analysis were cleaned of foreign materials and ground using a hammer mill to pass through a 0.5 mm sieve. Samples were stored in a refrigerator at +4 °C and analyzed within three months after each harvest. Ash content (AC) was determined according to AACC 08-01.01, crude protein content (PC) according to AACC 46-30.01, β-glucan content (βC) according to AACC Method 32-23.0,1 and starch content (SC) according to AACC 76-33.01 methods (AACC, 2020). Fat content (FC) was determined using the Soxhlet method (Welch, 1977), while acid detergent fiber (ADF) and neutral detergent fiber contents (NDF) were determined using the method described by Van Soest et al. (1991) with an ANKOM 220 Fiber Analyzer (ANKOM, model A2001, Macedon, NY, USA).

Statistical analysis

A normality test was applied to the data of the traits, and traits that did not exhibit a normal distribution were transformed before being subjected to variance analysis. Variance analysis for all studied characteristics was conducted using the Split-Plot Design with the MSTAT-C statistical package, based on combined data across years. Differences among the means were assessed using the Duncan's multiple comparison test.

3. RESULTS AND DISCUSSION

The total rainfall at the research site was higher in the first year (482.6 mm) compared to the second year (436.1 mm). While there were no significant differences in average temperature and humidity between the years, these values varied significantly across months (Figure 1). The combined variance analysis results of the study with four sowing densities and five different nitrogen doses are presented in Table 1.

Table 1. The mean of squares and their significance found as a result of variance analysis of the data belonging to the examined features for the combined years

Source of variation	SD	PH	PL	SPP	KPP	GY	TGW	GP
Year (Y)	1	4871.3**	43.0**	1118.7	3641.9**	16.89**	61.6**	1232.8**
Replication (R)	4	9.2	5.8	14.7	17.5	4.77	15.3	64.0
Nitrogen doses (ND)	4	188.9**	5.7	435.3**	1872.2**	25.34**	6.1	16.5
Y × ND	4	59.7	1.9	126.4**	670.2*	1.69*	14.6*	15.9
$Error_1$	16	31.3	2.6	13.0	14.4	0.68	3.8	7.4
Sowing density	3	80.3**	5.1**	134.4**	583.3**	7.06**	98.3**	39.2**
Y × SD	3	8.2	2.9*	8.1	62.5*	4.72**	11.0*	7.6
ND × SD	12	20.2	2.8**	30.0**	51.8**	3.64**	9.7**	12.3
Y × ND × SD	12	20.4	1.2	28.0**	44.3*	3.14**	2.8	15.1
$Error_2$	60	12.8	1.1	6.7	20.2	0.95	3.4	12.0
Coefficient of Variation (%)		3.4	5.1	6.6	8.6	7.0	4.2	4.3

Source of variation	SD	AC	PC	SC	βG	FC	ADF	NDF
Year (Y)	1	15.130**	41.37**	5307.0**	66.77**	0.18	354.1**	1104.0**
Replication (R)	4	0.007	0.26	4.9	0.02	0.04	2.4	15.6
Nitrogen doses (ND)	4	0.008	3.93**	18.6*	0.36**	0.13	2.6	4.0
Y × ND	4	0.059**	1.37**	25.8**	0.21*	0.34	2.7	6.3
$Error_1$	16	0.004	0.23	5.1	0.05	0.20	0.9	3.6
Sowing density	3	0.202**	0.05*	138.7**	0.89**	0.49**	23.5	8.4
Y × SD	3	0.001	2.93**	9.0	0.01	0.76**	0.8	4.0
ND × SD	12	0.008	0.28	3.1	0.04	0.15	1.0	4.7
Y × ND × SD	12	0.011	0.45*	4.8	0.03	0.19	0.7	6.8
$Error_2$	60	0.006	0.22	7.9	0.08	0.12	0.6	3.3
Coefficient of Variation (%)		3.65	3.16	5.7	6.11	6.86	6.1	5.6

**Significant at P<0.01, *Significant at P<0.05, ND: Nitrogen doses, SD: Sowing density, PH: Plant height (cm), PL: Panicle length (cm), SPP: Number of spikelet per panicle, KPP: Number of kernel per panicle, GY: Grain yield (t ha^{-1}), TGW: Thousand-grain weight (g), GP: Groat percentage (%), AC: Ash content (%), PC: Protein content (%), SC: Starch content (%), βC: β-glucan content (%), ADF: Acid detergent fiber (%), NDF: Neutral detergent fiber (%)

Statistically significant differences were found between the years in terms of traits studied, excluding SSP and FC. Significant differences were identified among nitrogen doses for the traits plant height, number of spikelet per panicle, number of grains per panicle, grain yield, protein content, starch content, and βeta-glucan. Regarding sowing densities, significant differences were observed for all traits studied except NDF and NDF value (Table 2 and Table 3). The nitrogen dose (ND) × sowing density (SD) interactions are presented in Table 4 and Table 5. It was determined that the ND × SD interaction was not significant for quality traits (Table 5).

Table 2. The mean values of grain yield and yield components for sowing density and nitrogen doses in the combined years

	PH	PL	SPP	KPP	GY	TGW	GP
Sowing density							
150	104.26 c	21.09 a	33.95 a	54.94 a	4.20 c	42.11 b	78.49 b
300	106.01 bc	20.59 ab	33.03 a	54.45 a	4.45ab	44.47 a	78.84 ab
450	106.66 ab	20.46 b	33.13 a	54.42 a	4.56 a	41.46 b	79.57 ab
600	108.21 a	20.09 b	29.22 b	45.80 b	4.36 b	40.14 c	81.07 a
Nitrogen dose							
N_0	102.16 c	19.74	27.73 c	41.24 d	4.16 c	41.82	79.72
N_{40}	105.58 b	20.86	28.48 c	45.06 c	4.64 b	42.94	79.83
N_{80}	106.57 ab	20.65	36.32 a	60.33 a	4.83 a	41.87	79.50
N_{120}	109.89 a	20.55	36.88 a	60.42 a	4.25 c	41.80	80.69
N_{160}	107.22 ab	20.98	32.27 b	54.94 b	4.08 c	41.78	78.71
Year							
2019-2020	112.66 a	21.16 a	35.39	57.91 a	4.51 a	42.76 a	82.70 a
2020-2021	99.91 b	19.96 b	29.28	46.89 b	4.27 b	41.33 b	76.29 b

The values followed by common letters at each column are not significant at P>0.05 level of probability using the Duncan test.

Plant height

Plant height was higher in the first year (112.66 cm) than in the second year (99.91 cm). This discrepancy is attributed to the higher rainfall in the first year (482.6 mm) than in the second year (436.1 mm) (Figure 1). The tallest plant height was determined at a seeding density of 600 seed m^2 (108.21 cm), while the shortest plant height was recorded at a seeding density of 150 seed m^2 (104.26 cm). In terms of nitrogen doses, the tallest plant height was achieved with the N_{120} treatment (109.89 cm), whereas the shortest height was observed in the N_0 treatment (102.16 cm) (Table 2). Plant height is influenced by various environmental factors including water availability, temperature, nutrient levels, soil properties, sunlight, and genetic factors (Buerstmayr et al., 2007). Furthermore, our findings indicate that plant height increased with higher nitrogen doses and sowing densities. This relationship may be explained by increased plant competition at higher sowing densities and enhanced vegetative growth due to nitrogen fertilization. Altuner and Ulker (2019) reported in their study on oat varieties that agricultural practices, such as fertilization and sowing density, influence plant height.

Table 3. The mean values of quality traits for sowing density and nitrogen doses in the combined years

	AC	PC	SC	βG	FC	ADF	NDF
Sowing density							
150	2.05 d	15.26 a	49.04 a	4.32 c	4.97 ab	14.19	32.74
300	2.10 c	15.02 ab	47.66 a	4.44 bc	4.78 b	13.65	32.68
450	2.16 b	14.79 b	46.16 b	4.51 b	4.95 ab	12.64	32.11
600	2.24 a	14.54b	44.02 c	4.73 a	5.10 a	12.28	31.61
nitrogen dose							
N_0	2.15	14.45 c	47.08 a	4.32 c	4.99	13.46	32.89
N_{40}	2.11	14.76 b	47.88 a	4.48 b	5.02	13.18	31.99
N_{80}	2.15	14.95 b	46.59 ab	4.53 ab	4.83	13.45	32.27
N_{120}	2.14	15.55 a	46.62 ab	4.66 a	4.97	12.65	31.85
N_{160}	2.14	14.81 b	45.45 b	4.50 b	4.94	13.23	32.43
Year							
2019-2020	1.78 b	14.32 b	50.87 a	3.75 b	4.91	14.91 a	35.32 a
2020-2021	2.49 a	15.49 a	42.57 b	5.24 a	4.99	11.47 b	29.25 b

The values followed by common letters at each column are not significant at P>0.05 level of probability using the Duncan test.

Panicle length

The panicle length was 21.16 cm in the first year, while it decreased to 19.96 cm in the second year. No statistically significant differences were observed in panicle length among the nitrogen doses. Jaipal and Shekhawat (2016) demonstrated that genetic factors play an important role in determining panicle length. This finding suggests that while environmental factors, such as nitrogen fertilization, can influence plant growth, genetic variation is a key determinant of this trait. The study highlights the importance of genetic diversity in shaping panicle length, emphasizing that it is a primary factor in its expression, independent of external inputs such as fertilizers. The longest panicle length of 21.09 cm was obtained at a sowing density of 150 seed m^2, while the shortest of 20.09 cm was at 600 seed m^2. Regarding panicle length, sowing densities of 150 and 300 seed m^2 were statistically classified in the same group. In the ND × SD interaction, the longest panicle length of 22.02 cm was achieved with a sowing density of 150 seed m^2 and an application of 80 kg of nitrogen per hectare. The shortest panicle length of 19.03 cm was observed at the same sowing density with no nitrogen applied (N_0). Although panicle length does not directly affect yield, it is an indirect factor (Table 4). Kaziu et al. (2019) reported that cultivars with longer panicles tend to have higher grain yields, with panicle lengths ranging from 26.0 to 37.0 cm. Mut et al. (2021b) conducted a study on 255 oat genotypes, revealing that panicle length (ranging from 21.27 to 37.70 cm) is influenced by both genotype and year.

Table 4. The mean data for the sowing density and nitrogen dose interactions of grain yield and yield components over the combined years

ND	SD	PH	PL	SPP	KPP	GY	TGW	GP
N_0	**150**	97.29	19.03e	27.57e	42.93ef	4.11fgh	42.22bcd	76.38
	300	102.56	20.11b-e	28.87de	44.35ef	4.12fgh	43.16bcd	76.78
	450	101.89	20.18b-e	28.13de	41.44fg	4.24e-h	40.84d-g	80.55
	600	106.89	19.65de	26.37e	36.26g	4.16 fgh	40.07fg	81.19
N_{40}	**150**	104.67	20.96a-d	29.30de	46.19ef	4.20fgh	41.27c-g	78.67
	300	105.72	21.03a-d	29.40de	45.36ef	4.61cde	46.45a	80.57
	450	104.72	20.23b-e	29.30de	48.13de	4.95abc	42.27c-f	77.96
	600	107.22	21.22abc	25.90e	40.58fg	4.80a-d	41.79c-g	82.16
N_{80}	**150**	105.39	22.02a	39.27a	59.35ab	4.51def	40.29rfg	78.68
	300	104.22	20.28b-e	34.97b	61.02ab	4.68bcd	44.88ab	79.26
	450	110.00	20.31b-e	34.33b	64.13a	5.09a	42.63b-e	78.23
	600	106.67	20.00cde	36.70ab	56.82bc	5.04ab	39.69g	81.84
N_{120}	**150**	108.56	21.57ab	39.33a	64.40a	4.02gh	43.41bc	81.41
	300	110.28	20.85a-d	37.23ab	62.95a	4.39d-g	42.85bcd	79.12
	450	109.89	20.20b-e	39.87a	61.66ab	4.62cde	41.42c-g	81.29
	600	110.84	19.58de	31.07cd	52.68cd	3.98gh	39.52g	80.95
N_{160}	**150**	105.39	21.87a	34.30b	61.81ab	4.15fgh	42.36cc-f	77.33
	300	107.28	20.67a-d	34.70b	58.58ab	4.45def	45.00ab	78.45
	450	106.78	21.37abc	34.00bc	56.73bc	3.91h	40.14fg	79.85
	600	109.45	20.02cde	26.07e	42.63ef	3.83h	39.64g	79.22

The values followed by common letters at each column are not significant at P>0.05 level of probability using the Duncan test.

Number of spikelet per panicle

In the first year, the number of spikelets per panicle was significantly higher at 35.39 no, compared to 29.28 no in the second year. The lowest number of spikelets per panicle was observed with the N_0 treatment (27.73 no), while the highest was with the N_{120} dose (36.88 no). Statistical analysis indicated that the N_{80} and N_{120} nitrogen doses were in the same group regarding spikelet numbers per panicle. The highest number of spikelets per panicle, 33.95 no, was obtained at a sowing density of 150 seeds m², while the lowest, 29.22 no, was at 600 seeds m². For spikelet numbers, the sowing densities of 150, 300, and 450 seed per m² were statistically grouped together (Table 2). In the ND × SD interaction, the maximum number of spikelets per panicle of 39.87 no, was achieved with N_{120} dose and a sowing density of 450 seed per m² (Table 4). In oats, the number of spikelets per panicle is one of the important selection criteria for improving grain yield. Doehlert et al. (2001) reported that the number of spikelets per panicle is influenced by both variety and environmental factors. Mut et al. (2021b) found that in their two-year study with 255 oat genotypes, the number of spikelets per panicle varied depending on the year and genotype. In our study, it is thought that the high number of spikelets per panicle in the first year was due to the greater total rainfall during the growing season of that year. However, in the experimental field, the first year experienced higher winter rainfall, while spring rainfall was lower. This could influence flowering, as winter rainfall supports early vegetative growth, whereas spring rainfall is crucial for reproductive development. Therefore, the higher spikelet number observed in the first year may be attributed to favorable winter conditions, while the limited spring rainfall could have impacted flowering and yield development (Buerstmayr et al., 2007).

Table 5. The mean data for the sowing density and nitrogen dose interactions of quality traits over the combined years

ND	SD	AC	PC	SC	βG	FC	ADF	NDF
N_0	**150**	2.04	14.31	50.08	4.24	4.93	14.96	33.48
	300	2.06	14.49	48.75	4.26	4.74	14.20	33.50
	450	2.21	14.59	46.23	4.34	5.11	12.54	31.38
	600	2.29	14.41	43.25	4.44	5.18	12.10	30.72
N_{40}	**150**	2.04	14.99	49.51	4.36	4.91	14.14	32.41
	300	2.06	14.92	49.26	4.45	4.92	13.20	32.14
	450	2.11	14.63	47.77	4.44	5.10	12.41	32.08
	600	2.23	14.51	44.98	4.68	5.15	12.96	31.34
N_{80}	**150**	2.02	15.53	49.09	4.30	4.82	14.53	34.30
	300	2.15	14.98	47.27	4.45	4.67	14.14	32.81
	450	2.19	14.85	46.15	4.56	4.73	13.00	33.45
	600	2.25	14.43	43.87	4.83	5.10	12.15	31.02
N_{120}	**150**	2.08	16.02	48.38	4.31	4.98	13.32	31.51
	300	2.15	15.90	47.28	4.63	5.04	12.84	32.06
	450	2.15	15.23	45.62	4.70	4.80	12.40	31.68
	600	2.20	15.06	45.22	5.00	5.08	12.03	32.15
N_{160}	**150**	2.08	15.47	48.16	4.38	5.21	14.01	32.03
	300	2.10	14.83	45.80	4.43	4.55	13.89	32.88
	450	2.14	14.65	45.06	4.49	5.01	12.84	31.98
	600	2.25	14.30	42.80	4.69	4.98	12.16	32.85

The values followed by common letters at each column are not significant at P>0.05 level of probability using the Duncan test.

Number of kernel per panicle

The number of kernels per panicle was 57.91 in the first year, while it decreased to 46.89 in the second year. The number of seeds per panicle ranged from a minimum of 41.24 under the N_0 treatment to a maximum of 60.42 under the N_{120} dose. In terms of the number of kernels per panicle, the 80 kg and 120 kg nitrogen doses per hectare were statistically in the same group. The number of kernels per panicle was highest at 54.94 with a sowing density of 150 seeds m², and lowest at 45.80 seeds with a sowing density of 600 seeds m². Regarding the number of kernels per panicle, the sowing densities of 150, 300, and 450 seeds m² were statistically in the same group (Table 2). In the ND × SD interaction, the number of kernels per panicle was highest at 64.40 seeds with the N_{120} dose and a sowing density of 150 seeds m², and lowest at 36.26 seeds with the N_0 treatment and a sowing density of 600 seeds m² (Table 4). Among the factors influencing yield in oats, the number of kernels per panicle is one of the most critical criteria. It is known that this trait has a key role in indirect selection in breeding programs. Kaziu et al. (2019) highlighted that the number of kernels per panicle is a vital criterion for oat production and that it is affected by different years and varieties. Our study also found significant differences between years, with these variations attributed to changes in environmental conditions. The number of kernels per panicle increased up to a nitrogen dose of 120 kg per hectare and then decreased (Table 2). Up to a certain level, nitrogen promotes vegetative growth and reproductive development, enhancing processes such as photosynthesis and nutrient allocation to seed formation. This leads to an increase in the number of kernels per panicle. Excess nitrogen often promotes vegetative growth, diverting nutrition resources away from reproductive structures, such as seeds. Altuner and Ulker (2019) reported that nitrogen doses did not affect the number of kernels per panicle in oat varieties, whereas Pecio and Bichoński (2010) observed that the number of kernels per panicle increased with higher nitrogen doses.

Grain yield

The grain yield was 4.51 t ha⁻¹ in the first year, while it decreased to 4.27 t ha⁻¹ in the second year. The lowest grain yield was obtained with the N_{160} nitrogen dose at 4.08 tons ha⁻¹, while the highest was with the N_{80} nitrogen dose at 4.83 t ha⁻¹. The highest grain yield was achieved at 4.56 t ha⁻¹ with a sowing density of 450 seeds per m², and the lowest at 4.20 t ha⁻¹ with a sowing density of 150 seeds per m². In terms of grain yield, the sowing densities of 300 and 450 seeds per m² were statistically in the same group. In the ND × SD interaction, the highest grain yield was 5.09 t ha⁻¹ with the N_{80} dose and a sowing density of 450 seeds per m², while the lowest was 3.83 t ha⁻¹ with the N_{160} nitrogen dose and a sowing density of 600 seeds per m² (Table 2). Grain yield, one of the most complex inherited agronomic trait, is influenced by numerous factors. Studies have shown that grain yield is affected by genetic differences (Kahraman et al., 2021), environmental factors (Kebede et al., 2023), both genetic differences and environmental factors (Buerstmayr et al., 2007), as well as agricultural practices (Mut et al., 2021a; Altuner and Ulker, 2019). In our study, it is believed that the variations in grain yield across years are primarily due to environmental factors, especially total rainfall during the growing season. The second year experienced a higher amount of rainfall during the spring. As a result, the higher total winter rainfall in the first year likely contributed more significantly to tillering and vegetative growth, providing a more substantial water supply. This suggests that winter precipitation plays a critical role in supporting early plant development, which is essential for optimal growth and productivity in cereals such as oats. In their study on oats, Pecio and Bichoński (2010) reported that grain yield varied based on nitrogen fertilizer doses. May et al. (2020) conducted a study to determine the effects of nitrogen dose and fungicide applications on oat yield and quality traits. They tested eight different nitrogen doses ranging from 0 to 140 kg per hectare and reported that grain yield increased up to the highest nitrogen rate. Our study found that grain yield increased by applying an 80 kg nitrogen dose per hectare, but subsequently declined with higher doses (Table 2). Moderate nitrogen levels enhance photosynthetic capacity and biomass accumulation, thereby supporting grain filling. However, higher doses may lead to excessive vegetative growth, causing nutrients to be allocated to leaves and stems rather than to grains. In other words, in this study, excessive nitrogen is thought to negatively affect flowering and grain filling. A high sowing density in oats does not always result in increased grain yield due to the potential reduction in the number of grains per panicle and individual grain weight. Excessive tillering or sowing density can lead to a decrease in yield components (Ju et al., 2020). For oats, specific environmental factors, such as the timing and amount of rainfall, play a significant role in determining how sowing density affects yield. These factors are critical for optimizing growth, as winter rainfall often enhances early vegetative growth, while spring rains are essential for reproductive development.

Thousand-grain weight and Groat percentage

It was determined that the thousand-grain weight was higher in the first year (42.76 g) compared to the second year (41.33 g). Nitrogen doses did not have an effect on the thousand-grain weight. The highest thousand-grain weight of 44.47 g was obtained at a sowing density of 300 seeds per m², whiles the lowest, 40.14 g, and was observed at 600 seeds per m². In the ND × SD interaction, the thousand-grain weight was highest at 46.45 g with the N_{40} dose at a sowing density of 300 seeds per m², and lowest at 39.52 g with the N_{120} dose at a sowing density of 600 seeds per m² (Table 4). It was observed that the groat percentage was higher in the first year (82.70%) compared to the second year (76.26%). Nitrogen doses did not affect the groat percentage. In the study by Peltonen-Sainio (1997), it was reported that while nitrogen applications improved overall yield and other yield components, no significant change was observed in the groat percentage. The highest groat percentages of 81.07% was achieved at a sowing density of 600 seeds per m², while the lowest, 78.49%, was recorded at a sowing density of 150 seeds per m² (Table 2). Thousand-grain weight and groat percentage, which define grain size and nutritional value and are critical physical quality criteria, are considered varietal traits. However, these characteristics can vary significantly depending on the year and climatic factors (Mut et al., 2018b). In our study, the total rainfall in the first year was greater than that in the second year (Figure 1). Consequently, it was determined that the grains developed better in the first year, and these characteristics were higher compared to the second year (Table 2). Kaziu et al. (2019) reported that thousand-grain weight varies based on genetic factors, agro-ecological conditions, and agricultural practices, and identified it as a key factor for in defining high production potential in varieties. Mohr et al. (2003) found that thousand-grain weight decreases with increasing nitrogen doses, whereas Maral et al. (2013) reported that it increases with higher nitrogen doses. In contrast, Altuner and Ulker (2019) observed that thousand-grain weight was unaffected by nitrogen doses. Groat percentage represents the economic yields for millers and the digestible portion of the grain for animal husbandry. Research on oats suggests that higher sowing densities can impact grain development by increasing competition among plants. This can reduce grain formation within the panicles, potentially lowering the thousand-grain weight. Feng et al. (2024) found that higher sowing densities can influence the accumulation of dry matter and grain development, leading to a decrease in the individual grain weight. Oats with a low hull ratio are preferred in both the food industry and animal feeding. Additionally, the food industry favors oat grains that offer high efficiency and are easy to dehull (Doehlert et al., 2001). Previous studies have reported that the groat percentage of oat genotypes ranges from 56.30% to 81.10% (Buerstmayr et al., 2007; Mut et al., 2018b).

Ash content

The ash content was observed to be 1.78% in the first year and 2.49% in the second year. No significant differences were found among nitrogen levels regarding ash content, which varied between 2.11% and 2.15%. The highest ash content, at 2.24%, was observed at a sowing density of 600 seeds m², while the lowest, at 2.05%, was recorded at a sowing density of 150 seed m². A high mineral content in food is desirable due to its nutritional value. The ash content, which reflects the total accumulation of minerals in the grain, has been reported to be influenced by both genotype and environmental factors (Mut et al., 2018b). Ash content in seeds increases under drought conditions. In our study, since the total rainfall in the second year was lower (Table 1), it is thought that the ash content was also higher in the second year (Table 2). Furthermore, ash content is influenced not only by genetic and environmental factors but also by cultivation techniques. As the density of sowing increases, the plants enter into competition with one another, resulting in the formation of weaker grains within the panicle. Consequently, smaller grains tend to have a higher husk percentage and a lower groat percentage, which may explain the increase in ash content with rising sowing density. Previous studies have reported ash content ranging from 1.73 to 2.90% (Erbas Kose et al., 2021) and from 2.60 to 3.90% (Sandhu et al., 2017).

Protein content

The protein content was observed to be 14.32% in the first year and 15.49% in the second year. The highest protein content (15.55%) was recorded with an application of 120 kg nitrogen per hectare, while the lowest (14.45%) was observed in the untreated control group. Regarding sowing density treatments, the highest protein content (15.26%) was obtained at a density of 150 plants m², and the lowest (14.54%) at a density of 600 plants m² (Table 3). Protein content is a critical quality parameter for oat grains. Protein levels are influenced by both environmental and genotypic factors. The lower average protein content observed during the 2019-2020 growing season (Table 3) is likely due to the fact that cereals grown under high rainfall or irrigated conditions tend to have lower protein content. Rainfall in the growing regions, its monthly distribution, temperatures, and cultural practices all impact the protein content and quality of cereal grains (Buerstmayr et al., 2007). In our study, protein content in oat grains increased up to a nitrogen dose of 120 kg per hectare, after which a slight decrease was observed (Table 2). Nitrogen is a crucial element for protein synthesis, and at optimal levels, its applications can typically enhance protein content. However, the effects of excessive nitrogen are more complex. High nitrogen levels can disrupt plant metabolism, causing an imbalance in amino acid composition, which may reduce the efficiency of protein synthesis. Furthermore, excessive nitrogen can promote vegetative growth during critical phases such as flowering and grain filling, causing imbalances in growth and maturation processes. These disruptions are believed to negatively affect protein content. Consistent with our findings, Zhou et al. (1998) reported that the protein content in cereals increased with increasing sowing density.

Starch content

The starch content was observed to be 55.87% in the first year and 42.57% in the second year. Regarding nitrogen fertilization, the highest starch content (47.95%) was achieved with a nitrogen dose of 40 kg ha^{-1}, while the lowest (45.45%) was recorded with 160 kg ha^{-1}. All nitrogen treatments, except for the 160 kg ha^{-1} dose, were statistically in the same group. The highest starch content (49.04%) was observed at a sowing density of 150 seeds m², and statistically, the starch contents at 150 and 300 seeds m² were in the same group. The lowest starch content (44.02%) was recorded at a sowing density of 600 seeds m² (Table 3). Starch, composed of amylose and amylopectin, is found in the endosperm of oat grains, which is surrounded by bran layers rich in β-glucan and protein. Since starch is the primary digestible carbohydrate in plants, it serves as a major energy source in both human and animal diets. Doehlert et al. (2001) reported that environmental factors have a much greater influence on starch content. In our study, the higher starch content observed during the 2019-2020 growing season (Table 3) is likely due to the increased total rainfall during that season (Figure 1). Mut et al. (2018b) noted that starch content is affected by both environmental and genetic factors, with values ranging from 42.7% to 49.6%. Previous study has reported starch content ranging from 45.7% to 46.3% (Brunava et al., 2014). In our study, starch content decreased with increasing nitrogen levels (Table 3). Similarly, Sterna et al. (2015) found that starch content in oat genotypes decreased with increasing nitrogen fertilizer doses. Furthermore, in our study, the decrease in starch content with increasing sowing density was likely due to the corresponding reduction in thousand-grain weight (Table 2).

β-glucan content

The starch content was observed to be 3.75% in the first year and 5.24% in the second year. The highest β-glucan content (4.73%) was obtained at a sowing density of 600 seeds m², while the lowest (4.32%) was recorded at a density of 150 seeds m². Regarding nitrogen fertilization, the highest β-glucan content (4.66%) was achieved with a nitrogen dose of 120 kg ha^{-1}, while the lowest (4.32%) was observed in the untreated control group (Table 3). Beta-glucan, which is present in significant amounts in oat grains, is a type of soluble dietary fiber important for human health. β-glucans are widely utilized in the cosmetics, food, and pharmaceutical industries. Consequently, oat varieties intended for human and animal nutrition are expected to have high beta-glucan content. Previous studies have reported that β-glucan content is influenced by genotype (Doehlert et al., 2001), environmental conditions (Mut et al., 2018b), and agricultural practices. In our study, conducted during the 2020-2021 growing season with low total rainfall (Figure 1), it is thought that the high β-glucan content is associated with a decrease in thousand-grain weight and an increase in husk percentage. Soil nitrogen levels and nitrogen fertilization are also considered as key factors affecting beta-glucan content. Fan et al. (2009) demonstrated that nitrogen application significantly enhanced the β-glucan content in oats. Mantai et al. (2016) highlighted that nitrogen fertilization improves the grain quality and increases the β-glucan content, which is an essential factor for the nutritional quality of oats. In our research, β-glucan content increased up to a nitrogen dose of 120 kg ha^{-1}, after which it slightly decreased (Table 2). Other studies have reported β-glucan content ranging from 1.02 to 6.33% (Rauf et al., 2019) and 1.27 to 3.48% (Erbas Kose et al., 2021).

Fat content

The fat content was determined to be 4.91% in the first year and 4.99% in the second year. No statistically significant differences were observed in fat content across nitrogen fertilizer doses, which ranged from 4.83% to 5.02%. Some studies have shown that nitrogen application has little or no effect on the fat content of cereals. Devi et al. (2019) reported that while nitrogen doses increased protein content in oat, they generally had no significant impact on fat content. This may be because nitrogen is primarily utilized for protein synthesis, contributing less to fat synthesis. The highest fat content, 5.10%, was obtained at a sowing density of 600 seeds m², and the sowing densities of 150, 450 and 600 seeds m² were statistically grouped together in terms of fat content. The lowest fat content, 4.78%, was recorded at a sowing density of 300 seeds m² (Table 3). Fat content is largely determined by genetic factors, and cultivation practices such as nitrogen application or sowing density appear to have limited influence on this trait. Sowing density may indirectly affect fat content by influencing competition among plants for light, water, and nutrients (Zhang et al., 2023). The nutritional value of oats is primarily attributed to their high fat content. Carlson et al. (2019) reported that, in terms of fat content, oat grains are particularly rich in healthy unsaturated fatty acids compared to other cereals. However, breeders typically prefer low-fat genotypes for oats intended for human consumption (Mut et al., 2018b). The fat content of oats is influenced by both genetic and environmental factors. In a study examining the effects of different nitrogen doses on the chemical composition of oats, Pecio and Bichoński (2010) found that nitrogen doses had no statistically significant effect on fat content. Other studies have reported varying fat contents among oat genotypes: Martinez et al. (2010) recorded a range of 3.1 to 11.6%, Erbas Kose et al. (2020) reported values between 5.03 and 6.88%, and Erbas Kose et al. (2021) observed a range of 2.71 to 7.16%. Additionally, our study determined that fat content increased slightly with higher sowing densities. Similarly, Podolska et al. (2009) reported that increasing sowing densities enhanced fat content of oats.

Acid detergent fiber and Neutral detergent fiber

It was determined that both ADF and NDF values were higher in the first year than the second year. No statistically significant differences in ADF and NDF values were found among nitrogen doses and sowing densities with respect to ADF and NDF values. Based on sowing densities, ADF values ranged from 12.28% (600 seeds m²) to 14.19% (150 seeds m²), while NDF values ranged from 31.61% (600 seeds m²) to 32.74% (150 seeds m²). According to nitrogen doses, ADF and NDF values varied between 12.65% (N_{120}) and 13.46% (N_0), and 31.85% (N_{120}) and 32.89% (N_0), respectively (Table 3). In our study, neither sowing density nor nitrogen dose had a significant effect on ADF and NDF values in oats. This finding suggests that, within the range of nitrogen levels and sowing densities tested, these factors did not have a major impact on the fiber content of the oats. This could be attributed to the inherent genetic traits of oats, which may not be as sensitive to changes in these cultivation practices as other crops. Similar results were reported in previous studies, where changes in nitrogen application and plant density had minimal effects on fiber content in oats (Peltonen-Sainio et al., 2009). It is important to note that fiber content in oats may be more strongly influenced by genetic factors rather than agronomic practices such as nitrogen fertilization or sowing density. This aligns with findings from other research that suggests environmental and genetic factors play a more significant role in determining fiber composition (Mut et et al., 2022; Ju et al., 2022). Our results also highlight that factors like genotype and environmental conditions may have a greater influence on fiber content than the specific agronomic practices applied in the study. Similarly, in another study involving different oat cultivars, the average ADF and NDF values were reported as 15.25% and 32.60%, respectively (Erbas Kose et al., 2020).

4. CONCLUSION

Providing the necessary nutrients in appropriate amounts and at the correct time during the growing period, along with maintaining optimal plant density, is essential for achieving high yields. Fertilization and plant density are not only economically important for growers but are also critical for maximizing grain yield per unit area under specific ecological conditions. Based on the results of this two-year study conducted to determine the effects of different nitrogen doses and sowing densities on grain yield, yield components, and certain quality traits in oats, significant differences were found between the years, nitrogen doses, and sowing densities for many of the traits examined.

The highest grain yield was obtained at sowing densities of 300 and 450 seeds m², and since no statisticaly significant difference was observed between these densities, a sowing density of 300 seeds m² can be recommended. Additionally, a nitrogen dose of 80 kg ha^{-1} was found to be sufficient for oat cultivation under these conditions. At the same time, the study demonstrated that oat grain quality, including thousand-grain weight, groat percentage, protein, starch, β-glucan, and ash content, is influenced by environmental factors such as rainfall and agronomic practices like nitrogen fertilization and sowing density. Higher rainfall in the first year resulted in better grain development and higher quality parameters. Nitrogen fertilization positively impacted protein and β-glucan content, while higher sowing densities generally reduced thousand-grain weight. These findings highlight the importance of considering local environmental conditions and management practices to optimize oat grain quality for various uses. Both fertilization and sowing density are economically important factors. By optimizing these factors—sowing density and nitrogen application-farmers can achieve high yields without overinvesting in inputs, thereby ensuring both ecological and economic sustainability.

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