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# Effects of Different Nitrogen Fertilizer Forms and Seed Treatments on Seed Yield and Quality in Sunflower

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**ABSTRACT**

Seed treatments or coatings with micronutrients, beneficial microorganisms, or pesticides, along with the use of slow-release nitrogen fertilizers, have gained prominence in recent years for their ability to increase crop yield per unit area and reduce nitrogen losses from the soil. In this study, we investigated the effects of different nitrogen fertilizer forms and seed treatments on sunflower seed yield and quality in 2022 and 2023. Field experiments were conducted in a randomized complete block design with a split-plot layout and four replications. Four nitrogen fertilizer forms ($NFF_1$: conventional form of ammonium sulfate; $NFF_2$: conventional form of urea; $NFF_3$: slow-release ammonium sulfate; and $NFF_4$: slow-release urea) were applied to the main plots, while five seed treatments ($ST_0$: no treatment (control); $ST_1$: standard seed treatment (Metalaxyl-M + Oxathiapiprolin); $ST_2$: standard seed treatment + micronutrients; $ST_3$: standard seed treatment + potassium humate; and $ST_4$: standard seed treatment + micronutrients + potassium humate) were applied to the sub-plots. Plant height, head diameter, seed yield, thousand-seed weight, crude oil content and crude oil yield were evaluated. The highest seed and crude oil yields were obtained from the $NFF_3$ and $NFF_4$ treatments in combination with the $ST_3$ treatment.

## 1. INTRODUCTION

Sunflower (*Helianthus annuus* L.) is cultivated primarily in continental climate zones and rainy regions with temperate climates. Globally, the sunflower cultivation area covers 29.3 million ha, producing 54.3 million tons with a seed yield of 2040 kg $ha^{-1}$ (FAOSTAT, 2023). Approximately 20 million tons of vegetable oil are obtained annually from sunflower seed processing worldwide. With a global share of approximately 10%, sunflower ranks fourth after palm, soybean, and rapeseed in vegetable oil production (USDA, 2024). Sunflower seeds contain 40–60% oil, which is nutritionally important for human health. Sunflower oil is one of the richest sources of alpha-tocopherol (vitamin E), a natural antioxidant. Various sunflower varieties exhibiting distinct fatty acid compositions have been developed through breeding programs for diverse industrial and nutritional applications (Hulke & Winkler-Moser, 2019). Several agronomic factors are critical to achieve optimal sunflower yield and quality, including seedbed preparation; seed quality; nutrient management; irrigation; and effective control of diseases, pests, and weeds (Bange et al., 1997; Smiderle et al., 2007; Ali et al., 2012; Parvender et al., 2014; Nasim et al., 2017).

Nitrogen is an essential plant nutrient that directly influences the development of both vegetative and reproductive components of the plant and plays a key role in crop productivity. It enhances yield, production quantity, and quality of almost all plants when applied at optimum levels (Dreccer et al., 2000; Massignam et al., 2009; Ullah et al., 2020). Nitrogen maintains leaf greenness for an extended period, thereby increasing net assimilation and photosynthetic capacity (Munir et al., 2007; Ahmad et al., 2009). It also promotes flowering and enhances seed filling. Nitrogen deficiency leads to stunted growth, leaf shrinkage, and chlorosis, resulting in pale yellow leaves. Adequate nitrogen application increases the number of seeds per head and overall productivity in sunflower. Therefore, nitrogen is one of the most critical nutrients determining the yield potential of sunflower (Oren & Celik, 2018). Nitrogen-containing fertilizers represent one of the highest input costs in agricultural production. The global expenditure on nitrogen fertilizers is estimated at 50 billion USD (Ladha & Chakraborty, 2016). However, the efficiency of nitrogen fertilizer use in agriculture remains low, with plants typically utilizing less than 50% of the applied nitrogen (Abbasi et al., 2013). Major nitrogen losses occur through leaching, soil erosion, volatilization, denitrification, and immobilization. Consequently, enhancing nitrogen use efficiency and developing effective nitrogen management strategies have become critical priorities in modern agricultural systems. An effective nitrogen management system involves applying fertilizers at rates that meet crop requirements, selecting appropriate fertilizer sources, and optimizing the timing of application (Abbasi et al., 2012; Abbasi et al., 2013). In recent years, the fertilizer industry has focused on developing specialized fertilizers to minimize nitrogen losses from soil. These fertilizers include stabilized fertilizers, foliar fertilizers, and slow-release fertilizers (Trenkel, 2010). A comprehensive meta-analysis across multiple countries and more than 8000 studies demonstrated that, compared with conventional nitrogen fertilizers, slow release fertilizers significantly increase crop yield by 5.1%, farmer profits by 8.2%, and total nitrogen uptake by 7.1%. Moreover, they considerably reduce environmental pollution, including greenhouse gas emissions, by 3.6–18.6%, and nitrogen losses by 32.6–49.1% (Zhang et al., 2024). Therefore, the development and adoption of slow-release fertilizers provide an efficient and sustainable solution for modern agriculture, enhancing crop productivity while mitigating environmental impacts (Li et al., 2020; Vejan et al., 2021; Zhang et al., 2023, Mustafa et al., 2025). Slow-release fertilizers furnish a sustained nutrient supply that improves the efficiency of N fertilizer use and reduces losses from N leaching (Bilgili & Acikgoz, 2011). It can also reduce environmental and water pollution. Since nitrogen is not lost from the soil, less fertilizer can be used (Oktem, et al. 2025).

Meeting the growing global demand for food will be possible only through improvements in the yield and quality of agricultural products. To increase yield per unit area, the use of high-quality seeds along with improved agronomic practices and advanced techniques is essential. High-quality seeds are characterized by rapid germination and emergence, a well-developed root system, and uniform growth and development. In recent years, seed treatment technologies have been widely adopted, involving the coating of seeds with macro- and micro-nutrients, beneficial microorganisms, and protective pesticides (Hill, 1999; Rufino et al., 2013; Corlett et al., 2014; Pedrini et al., 2017). Inoculant substances, hydrophilic materials, herbicides, and decomposed nutrients that protect plants by coating the seeds are applied near the seedlings during the germination phase, promoting stronger and more vigorous growth (John et al., 2005). Micronutrients, in addition to playing crucial roles in the key physiological processes such as photosynthesis and respiration, serve as cofactors in enzyme systems and participate in redox reactions (Marschner, 1995; Mengel et al., 2001). Deficiency of these elements disrupts processes, ultimately reducing yield potential. The deficiency of micronutrients has been very pronounced under multiple cropping systems due to excess removal of the nutrients by high yielding varieties and hence their exogenous application is urgently required. Micronutrient application through seed treatment improves the stand establishment, advances phenological events, increases yield and micronutrient contents in seed in most of the crops. In many cases, micronutrient application through seed treatment performed better or similar to other application methods (Singh et al., 2005).

Although several studies have examined the effects of different nitrogen fertilizer forms on sunflower growth, research on the combined effects of nitrogen fertilizer forms and seed treatments remains limited. Therefore, this study aimed to evaluate the impact of different nitrogen fertilizer forms and seed treatments on sunflower seed yield and quality.

## 2. MATERIALS AND METHODS

*Experimental site*

This study was conducted at the Agricultural Application and Research Center, Faculty of Agriculture, Bursa Uludag University (Bursa, Türkiye) during 2022 and 2023. The sunflower variety M96CL02 (May Seed Inc., Bursa, Türkiye), which is resistant to imidazolinone herbicides, a medium-sized plant with a robust stem and root system, highly resistant to drought, has a high yield potential and a high oil content, was used as the experimental material. Bursa is located in the Southern Marmara region of Türkiye and has a Mediterranean climate. According to meteorological data recorded between May and October of 2022 and 2023, the average temperatures were 20.9°C in 2022 and 22.7°C in 2023, compared to the long-term average of 21.3°C. During the same period, the mean relative humidity values were 67.3% in 2022, 63.3% in 2023, and 68.2% for the long-term period. Total precipitation between May and October was 238.9 mm in 2022, 53.0 mm in 2023, and 225.3 mm for the long-term period (Table 1).

**Table 1.** Temperature, relative humidity and precipitation data for monthly, and long-term periods in Bursa for 2022 and 2023.

| Months | Temperature (˚C) | | | Relative humidity (%) | | | Precipitation (mm) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2022 | 2023 | Long-term* | 2022 | 2023 | Long-term | 2022 | 2023 | Long-term |
| May | 17.8 | 18.2 | 18.1 | 65.1 | 64.7 | 70.5 | 16.4 | 37.2 | 51.7 |
| June | 22.3 | 24.3 | 22.2 | 71.3 | 63.0 | 70.1 | 129.2 | 0.0 | 56.7 |
| July | 24.0 | 26.1 | 24.7 | 61.5 | 58.8 | 63.5 | 2.1 | 0.0 | 12.6 |
| August | 25.3 | 27.1 | 25.2 | 69.6 | 60.4 | 64.5 | 40.3 | 0.0 | 15.4 |
| September | 20.7 | 22.6 | 21.5 | 65.2 | 62.9 | 66.5 | 39.2 | 0.0 | 36.7 |
| October | 15.8 | 18.2 | 16.1 | 71.3 | 70.5 | 74.4 | 11.7 | 7.3 | 52.2 |
| Total | - | - | - | - | - | - | 238.9 | 53.0 | 225.3 |
| Mean | 20.9 | 22.7 | 21.3 | 67.3 | 63.3 | 68.2 | - | - | - |

*A 70-year average (1950-2020).

Some of the physical and chemical properties of the soil from the experimental area are presented in Table 2. The soil is alkaline-clay soil, rich in phosphorus and potassium, low in organic matter, and moderately calcareous, with no salinity problems.

**Table 2.** Soil analysis data of the experimental area

| Property | Data | Unit | Evaluation |
|---|---|---|---|
| Texture | 80.3 | % | Clay |
| pH | 7.73 | - | Slight alkaline |
| Salt | 0.0335 | % | Salt-free |
| Lime | 12.38 | % | Medium |
| Organic Matter | 2.0101 | % | Low |
| Total N | 0.1005 | % | Medium |
| Available $P_2O_5$ | 102.6 | mg $kg^{-1}$ | High |
| Extractable $K_2O$ | 2210.8 | mg $kg^{-1}$ | High |
| Available Fe | 13.34 | mg $kg^{-1}$ | Very high |
| Available Zn | 1.14 | mg $kg^{-1}$ | Sufficient |
| Available Cu | 1.48 | mg $kg^{-1}$ | Sufficient |
| Available Mn | 7.73 | mg $kg^{-1}$ | Sufficient |
| Extractable Ca | 7883.0 | mg $kg^{-1}$ | High |
| Extractable Mg | 545.9 | mg $kg^{-1}$ | High |
| Extractable Na | 19.9 | mg $kg^{-1}$ | Low |

*Experimental design and agronomic practices*

The experiment was conducted using a randomized complete block design in a split-plot arrangement with four replications. Four different forms of nitrogen fertilizer were applied to the main plots: $NFF_1$: conventional form of urea form of ammonium sulfate; $NFF_2$: conventional form of urea; $NFF_3$: slow-release form of ammonium sulfate; and $NFF_4$: slow-release form of urea. Five seed treatments were assigned to the sub-plots: $ST_0$: untreated control; $ST_1$: standard seed treatment (Metalaxyl-M + Oxathiapiprolin); $ST_2$: standard seed treatment + micronutrients; $ST_3$: standard seed treatment + potassium humate; and $ST_4$: standard seed treatment + micronutrients + potassium humate. The composition of the micronutrient and potassium humate are presented in Tables 3 and 4, respectively.

**Table 3.** Micronutrient composition

| Guaranteed content | w/w |
|---|---|
| Water soluble copper (Cu) and EDTA-Cu | 0.5% |
| Soluble manganese (Mn) and EDTA-Mn | 4.1% |
| Soluble zinc (Zn) and EDTA-Zn | 1.4% |
| pH range at which EDTA is stable | pH 3–7 |
| Macro elements | w/w |
| Ammonium nitrogen ($NH_4$-N) | 2.5% |

The experimental design included a row spacing of 70 cm and an intra-row plant spacing of 30 cm. Each subplot comprised four rows, each 5 m in length, resulting in a total plot area of 2.8 m × 5 m (14 $m^2$). Sowing was performed manually on May 13, 2022 and May 16, 2023 for the first and second years, respectively. Prior to planting, a 15:15:15 (NPK) compound fertilizer was applied to all plots at a rate of 60 kg $ha^{-1}$ for each nutrient. Additional nitrogen was applied at a rate of 60 kg $ha^{-1}$ using different nitrogen fertilizer formulations when the plants had 4 true leaves ($V_4$): conventional form of urea form of ammonium sulfate and its 3,4-dimethylpyrazole phosphate-coated (slow-release) form, as well as the conventional form of urea form of urea and its urease N-(n-butyl) thiophosphoric triamide inhibitor form. Harvesting was conducted manually for both years.

**Table 4.** Potassium humate composition

| Guaranteed content | By mass (w/w)% |
|---|---|
| Water soluble potassium oxide ($K_2O$) | 6 |
| pH (10% solution) | 9–11 |
| Total organic matter | 25 |
| Total humic fulvic acid | 75 |
| Maximum moisture | 20 |

*Measurements, observations, and statistical analysis*

Plant height, head diameter, seed yield, thousand-seed weight, crude oil content, and crude oil yield were measured and analyzed. Plant height and head diameter were measured in the field using 10 randomly selected plants from each plot. Seed yield was determined by harvesting the entire plot, weighing the seeds, reporting per hectare, and adjusting the values to 10% moisture. Thousand-seed weight was obtained by counting and weighing one thousand seeds from each plot. Crude oil content was determined using the Soxhlet extraction according to The American Oil Chemists Society official method (AOCS, 1993). Crude oil yield was calculated by multiplying seed yield by crude oil content for each plot. Data were analyzed using variance analysis with JMP-7 statistical software (SAS Institute, Cary, NC, USA), and differences among groups were determined using LSD (Least Significant Difference) tests at the 1% and 5% significance levels.

## 3. RESULTS

Table 5 presents ANOVA results for the effects of different nitrogen fertilizer forms and seed treatments on sunflower characteristics. Since the differences between years were found to be statistically significant in the study, each year was evaluated separately (Table 5). In 2022, the effects of different nitrogen fertilizer forms were significant at the 1% probability level for plant height, head diameter, seed yield, crude oil content, and crude oil yield. However, in 2023, application of different nitrogen fertilizer forms showed no significant effects on any of the examined traits. Effects of different seed treatments were not significant for plant height in 2022 but were significant at the 5% probability level in 2023. For head diameter, seed treatment effects were significant at the 1% probability level in 2022, but non-significant in 2023. Conversely, seed treatments significantly affected seed yield, thousand-seed weight, crude oil content, and crude oil yield at the 1% probability level for both years. The interaction between different nitrogen fertilizer forms and seed treatments was non-significant for the thousand-seed weight in 2022, but significant at the 1% probability level in 2023, whereas significant interactions at the 1% probability level were observed for all other traits for both years (Table 5).

In 2022, the highest plant height (148.7 cm) was obtained with the $NFF_4$ application, whereas the lowest (138.5 cm) was recorded with $NFF_3$. In 2023, plant height varied non-significantly between 124.8 and 127.0 cm among different nitrogen fertilizer forms. Similarly, in 2022, various seed treatments resulted in a non-significant variation in plant height (143.0–145.4 cm). In 2023, the highest plant heights were observed with $ST_3$ (128.3 cm) and $ST_4$ (126.9 cm), whereas the lowest (124.0 cm) was observed with $ST_1$ (Table 6). In 2022, $NFF_2$ and $NFF_4$ applications resulted in the largest head diameters (14.0 and 14.3 cm, respectively). In 2023, head diameters varied non-significantly between 10.9 cm and 11.5 cm among different nitrogen fertilizer forms. Among seed treatments in 2022, the largest head diameter (14.4 cm) was recorded with $ST_0$, whereas the smallest (13.5 cm) occurred with $ST_2$. In 2023, average head diameter values showed no significant differences (10.9-11.5 cm; Table 6). In 2022, $NFF_4$ application led to the highest seed yield (2471.0 kg $ha^{-1}$). In 2023, the seed yield ranged from 1834.3 kg $ha^{-1}$ to 2044.7 kg $ha^{-1}$, with no statistically significant differences observed among the various nitrogen fertilizer forms. Among seed treatments, $ST_3$ resulted in the highest seed yields for both years (2372.0 kg $ha^{-1}$ in 2022 and 2025.1 kg $ha^{-1}$ in 2023), followed closely by $ST_2$ (2030.5 kg $ha^{-1}$) in 2023. The lowest seed yields were obtained with $ST_4$ (2086.6 kg $ha^{-1}$) in 2022 and $ST_0$ (1811.3 kg $ha^{-1}$) in 2023 (Table 6). The average values of thousand-seed weight were statistically insignificant across different nitrogen fertilizer forms for both experimental years, ranging from 64.2 to 68.1 g in 2022 and from 52.1 to 53.7 g in 2023. In 2022, $ST_0$ resulted in the highest thousand-seed weight (69.6 g), whereas in 2023, $ST_3$ led to the highest value (55.2 g; Table 6).

The $NFF_4$ nitrogen fertilizer form resulted in the highest crude oil content in 2022 (45.1%). In 2023, the crude oil content showed a statistically insignificant variation, ranging from 42.7% to 43.2%. In 2022, $ST_1$ resulted in the highest crude oil content (45.8%), whereas $ST_0$ led to the lowest (44.0%). In 2023, $ST_2$ resulted in the highest crude oil content (43.2%), whereas $ST_3$ led to the lowest (42.4%). The highest crude oil yield in 2022 was obtained using the $NFF_4$ application (1120.5 kg $ha^{-1}$). In 2023, the crude oil yield values ranged from 784.6 kg $ha^{-1}$ to 883.4 kg $ha^{-1}$ among the various nitrogen fertilizer forms. Among seed treatments, $ST_3$ resulted in the highest crude oil yield in 2022 (1066.4 kg $ha^{-1}$), whereas $ST_2$ led to the highest yield in 2023 (878.3 kg $ha^{-1}$; Table 6).

Among the interaction effects of nitrogen fertilizer forms with seed treatments (Table 7), the highest plant heights were recorded for the $NFF_4 \times ST_3$ interaction (151.7 cm) in 2022 and for the $NFF_3 \times ST_3$ interaction (133.6 cm) in 2023. For head diameter, the $NFF_1 \times ST_0$ interaction yielded the highest value (15.1 cm) in 2022, whereas the $NFF_1 \times ST_3$ and $NFF_3 \times ST_3$ interactions resulted in the highest values (12.3 and 12.0 cm, respectively) in 2023. For seed yield, the maximum values were obtained from the $NFF_4 \times ST_3$ interaction (2721.5 kg $ha^{-1}$) in 2022 and the $NFF_3 \times ST_3$ interaction (2360.4 kg $ha^{-1}$) in 2023. The nitrogen fertilizer form × seed treatment interaction for thousand-seed weight was statistically insignificant in 2022; however, in 2023, the highest value (56.4 g) was observed for the $NFF_3 \times ST_3$ interaction. The highest crude oil content was obtained with the $NFF_4 \times ST_1$ interaction (46.5%) in 2022 and the $NFF_3 \times ST_2$ interaction (44.1%) in 2023. For crude oil yield, the highest values were achieved with the $NFF_4 \times ST_3$ interaction (1242.2 kg $ha^{-1}$) in 2022 and the $NFF_3 \times ST_3$ interaction (1011.7 kg $ha^{-1}$) in 2023 (Table 7).

**Table 5**. Analysis of variance (ANOVA) for the characteristics in the experiment.

| Source | Plant height | | | Head diameter | | | Seed yield | | | Thousand seed weight | | | Crude oil content | | | Crude oil yield | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Means of squares | | | | | | | | | | | | | | | | | |
| | 2022 | 2023 | Combined | 2022 | 2023 | Combined | 2022 | 2023 | Combined | 2022 | 2023 | Combined | 2022 | 2023 | Combined | 2022 | 2023 | Combined |
| Year | - | - | 12464.4 | - | - | 276.4 | - | - | 251057.0 | - | - | 6589.3 | - | - | 165.8 | - | - | 93988.2 |
| Block (Y) | 62.4 | 14.1 | 38.3 | 0.4 | 1.1 | 0.7 | 5208.1 | 220.1 | 2714.2 | 61.1 | 21.2 | 41.1 | 0.3 | 0.1 | 0.2 | 914.6 | 38.6 | 476.6 |
| NFF | 381.9 | 17.3 | 165.2 | 2.9 | 1.4 | 0.5 | 70195.3 | 18352.4 | 16830.6 | 80.9 | 9.2 | 63.5 | 3.1 | 1.0 | 2.8 | 16473.1 | 3829.6 | 4271.3 |
| YxNFF | - | - | 234.0 | - | - | 3.8 | - | - | 71717.2 | - | - | 26.5 | - | - | 1.3 | - | - | 16031.7 |
| MPE | 17.3 | 29.5 | 23.4 | 0.2 | 0.7 | 0.5 | 3893.6 | 5611.2 | 4752.5 | 75.9 | 5.4 | 40.7 | 0.1 | 0.3 | 0.2 | 851.4 | 1169.5 | 1010.5 |
| ST | 13.9 | 42.6 | 42.6 | 2.1 | 0.5 | 1.5 | 21295.0 | 13557.6 | 26629.1 | 101.3 | 53.3 | 110.9 | 6.5 | 1.4 | 3.6 | 5296.4 | 2391.3 | 5707.6 |
| NFFxST | 38.2 | 60.1 | 53.5 | 2.4 | 1.2 | 1.6 | 15078.2 | 17473.5 | 19602.3 | 30.8 | 14.7 | 26.7 | 3.9 | 1.1 | 2.4 | 3333.7 | 2654.1 | 3195.2 |
| YxST | - | - | 13.8 | - | - | 1.1 | - | - | 8223.0 | - | - | 43.7 | - | - | 4.4 | - | - | 1980.2 |
| YxNFFxST | - | - | 44.8 | - | - | 2.0 | - | - | 12949.1 | - | - | 18.8 | - | - | 2.7 | - | - | 2792.6 |
| SPE | 8.5 | 13.6 | 11.1 | 0.2 | 0.2 | 0.2 | 2551.4 | 2860.4 | 2705.2 | 27.2 | 3.9 | 15.6 | 0.2 | 0.3 | 0.3 | 523.2 | 518.7 | 520.9 |
| CV(%) | 2.0 | 2.9 | 2.5 | 3.5 | 4.3 | 3.9 | 7.3 | 8.7 | 8.0 | 7.92 | 3.7 | 6.6 | 1.0 | 1.3 | 1.1 | 7.3 | 8.6 | 7.9 |
| | LSD values | | | | | | | | | | | | | | | | | |
| $LSD_{Y}$ | - | - | 1.6** | - | - | 0.2** | - | - | 72.4** | - | - | 2.1** | - | - | 0.2** | - | - | 33.4** |
| $LSD_{NFF}$ | 3.1** | ns | 2.3** | 0.3** | ns | ns | 139.8** | ns | 102.4* | ns | ns | ns | 0.3** | ns | 0.2** | 66.0** | ns | 47.2* |
| $LSD_{YxNFF}$ | - | - | 3.2** | - | - | 0.5** | - | - | 144.8** | - | - | ns | - | - | 0.3** | - | - | 66.7** |
| $LSD_{ST}$ | ns | 2.6* | 1.6** | 0.3** | ns | 0.2** | 98.6** | 104.4** | 81.6** | 5.3* | 1.8** | 1.9** | 0.6** | 0.3** | 0.3** | 51.4** | 51.1** | 35.7** |
| $LSD_{NFFxST}$ | 2.3** | 2.4** | 3.3** | 0.6** | 0.7** | 0.5** | 71.2** | 82.2** | 163.2** | ns | 1.4** | ns | 0.4** | 0.3** | 0.5** | 102.8** | 102.3** | 71.5** |
| $LSD_{YxST}$ | - | - | ns | - | - | 0.3** | - | - | 115.4* | - | - | 2.7* | - | - | 0.4** | - | - | 50.6** |
| $LSD_{YxNFFxST}$ | - | - | 4.7** | - | - | 0.7** | - | - | 230.8** | - | - | ns | - | - | 0.7** | - | - | 101.2** |

Y: Year, NFF: Nitrogen Fertilizer Forms, MPE: Main Plot Error, ST: Seed Treatment, SPE: Sub Plot Error, *, Significant at $p < 0.05$, ** Significant at $p < 0.01$, ns: not significant

**Table 6.** Main effects of nitrogen fertilizer forms (NFF) and seed treatments (ST) on the investigated traits of sunflower in 2022 and 2023

| Treatments | Plant height (cm) | | Head diameter (cm) | | Seed yield (kg ha$^{-1}$) | | Thousand-seed weight (g) | | Crude oil content (%) | | Crude oil yield (kg ha$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2022 | 2023 | 2022 | 2023 | 2022 | 2023 | 2022 | 2023 | 2022 | 2023 | 2022 | 2023 |
| *Nitrogen Fertilizer Forms (NFF)* | | | | | | | | | | | | |
| $NFF_1$ | 142.3 c[x] | 126.2 | 13.5 b | 11.5 | 2078.3 b | 1995.1 | 64.2 | 52.1 | 44.4 b | 42.7 | 921.7 b | 852.1 |
| $NFF_2$ | 145.5 b | 124.8 | 14.0 a | 10.9 | 2113.2 b | 1890.4 | 67.1 | 53.1 | 44.9 ab | 42.9 | 952.1 b | 810.7 |
| $NFF_3$ | 138.5 d | 127.0 | 13.6 b | 11.4 | 2102.5 b | 2044.7 | 64.2 | 53.3 | 45.1 ab | 43.2 | 949.5 b | 883.4 |
| $NFF_4$ | 148.7 a | 126.5 | 14.3 a | 11.0 | 2471.0 a | 1834.3 | 68.1 | 53.7 | 45.2 a | 42.8 | 1120.5 a | 784.6 |
| *Seed Treatments (ST)* | | | | | | | | | | | | |
| $ST_0$ | 143.0 | 125.9 b | 14.4 a | 11.1 | 2128.1 c | 1811.3 c | 69.6 a | 53.1 b | 44.0 c | 43.1 ab | 938.3 b | 780.4 c |
| $ST_1$ | 143.8 | 124.0 bc | 13.6 c | 11.0 | 2237.3 b | 1943.6 ab | 66.2 ab | 54.1 ab | 45.8 a | 42.9 ab | 1025.4 ab | 833.5 ab |
| $ST_2$ | 143.2 | 125.5 b | 13.5 c | 11.2 | 2132.5 c | 2030.5 a | 64.2 b | 50.4 c | 45.1 b | 43.2 a | 962.7 b | 878.3 a |
| $ST_3$ | 145.4 | 128.3 a | 14.0 b | 11.5 | 2372.0 a | 2025.1 a | 66.5 ab | 55.2 a | 44.9 b | 42.4 c | 1066.4 a | 859.5 ab |
| $ST_4$ | 143.2 | 126.9 ab | 13.6 c | 11.2 | 2086.6 c | 1894.0 bc | 63.0 b | 52.4 bc | 44.9 b | 42.8 b | 937.0 b | 811.6 bc |

[x] Means followed by the same letter(s) in each column are not significantly different at $p < 0.05$.

**Table 7.** Interaction effects of various nitrogen fertilizer forms (NFF) and seed treatments (ST) on yield and yield components of sunflower in 2022 and 2023

| Treatment | 2022 | | | | | 2023 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Seed Treatments (ST) | | | | | Seed Treatments (ST) | | | | |
| | $ST_0$ | $ST_1$ | $ST_2$ | $ST_3$ | $ST_4$ | $ST_0$ | $ST_1$ | $ST_2$ | $ST_3$ | $ST_4$ |
| *Plant Height (cm)* | | | | | | | | | | |
| $NFF_1$ | 147.6 a-e[x] | 139.3 hı | 142.4 f-h | 144.1 e-g | 138.3 hı | 128.9 a-e | 120.7 h | 122.4 gh | 129.0 a-d | 129.8 a-c |
| $NFF_2$ | 144.5 d-f | 145.2 c-f | 141.8 f-h | 147.5 b-e | 149.2 a-c | 128.1 b-f | 123.6 f-h | 122.0 gh | 127.0 b-g | 123.5 f-h |
| $NFF_3$ | 136.5 ı | 139.4 hı | 140.0 g-ı | 138.2 hı | 138.3 hı | 124.6 d-h | 126.4 b-g | 126.2 b-g | 133.6 a | 124.2 d-h |
| $NFF_4$ | 144.8 d-f | 151.2 ab | 148.5 a-d | 151.7 a | 147.1 b-e | 122.1 gh | 125.2 c-h | 131.3 ab | 123.8 e-h | 130.2 a-c |
| *Head Diameter (cm)* | | | | | | | | | | |
| $NFF_1$ | 15.1 a | 12.5 i | 12.6 i | 14.6 a-c | 12.6 h-i | 11.0 d-g | 10.7 e-h | 11.6 b-d | 12.3 a | 11.7 a-c |
| $NFF_2$ | 14.3 b-d | 14.2 b-e | 14.0 b-e | 13.5 d-f | 13.6 e-g | 11.4 b-e | 10.6 f-h | 10.5 g-h | 11.5 b-d | 10.6 g-h |
| $NFF_3$ | 14.2 b-e | 12.9 g-i | 13.3 f-h | 12.9 g-i | 14.5 a-c | 11.1 c-g | 11.5 b-d | 11.0 d-g | 12.0 ab | 11.2 c-g |
| $NFF_4$ | 14.0 b-e | 14.7 ab | 14.2 b-e | 14.7 ab | 13.9 c-f | 10.9 d-g | 11.3 b-f | 11.5 b-d | 10.3 h | 11.3 c-f |
| *Seed Yield (kg ha$^{-1}$)* | | | | | | | | | | |
| $NFF_1$ | 2213.0 c-f | 2197.6 c-f | 1899.0 g-i | 2401.4 bc | 1682.0 i | 2029.0 b-e | 1693.1 h-j | 210.5 b-d | 2248.2 ab | 1902.2 d-h |
| $NFF_2$ | 1847.5 h-i | 2101.0 e-g | 2053.5 e-h | 2210.8 c-f | 2354.3 b-d | 1756.3 f-j | 1970.7 d-g | 1983.7 d-f | 1844.7 e-i | 1895.6 d-h |
| $NFF_3$ | 2177.2 c-f | 2252.7 c-e | 1999.3 f-h | 2156.2 d-f | 1925.2 g-h | 1887.2 d-i | 2238.2 a-c | 2001.9 c-e | 2360.4 a | 1735.1 g-j |
| $NFF_4$ | 2277.4 c-e | 2396.1 b-c | 2577.2 ab | 2721.5 a | 2386.4 bc | 1574.5 j | 1871.4 d-i | 2035.5 b-e | 1646.2 i-j | 2045.3 b-e |
| *Thousand-Seed Weight (g)* | | | | | | | | | | |
| $NFF_1$ | 72.0 | 59.7 | 62.2 | 67.3 | 59.5 | 52.3 c-g | 51.8 d-g | 51.9 d-g | 53.9 b-f | 50.6 e |
| $NFF_2$ | 67.9 | 71.4 | 64.6 | 66.4 | 64.9 | 54.0 b-e | 55.9 ab | 46.0 f | 54.9 b | 54.4 b-d |
| $NFF_3$ | 68.8 | 63.0 | 62.4 | 64.2 | 62.5 | 52.0 d-g | 54.4 b-d | 52.3 c-g | 56.4 a | 51.2 d-g |
| $NFF_4$ | 69.6 | 70.4 | 67.3 | 67.8 | 65.2 | 54.2 b-d | 54.5 b-d | 51.3 d-g | 55.4 ab | 53.1 c-g |
| *Crude Oil Content (%)* | | | | | | | | | | |
| $NFF_1$ | 42.5 k | 45.0 e-g | 44.5 g-i | 44.5 g-i | 45.3 d-f | 42.6 d-e | 43.5 a-c | 43.2 b-d | 41.6 f | 42.6 de |
| $NFF_2$ | 42.9 k | 46.2 a-c | 45.0 e-g | 45.6 c-e | 45.0 e-g | 43.1 b-d | 42.6 de | 43.2 b-d | 42.6 de | 42.8 de |
| $NFF_3$ | 46.3 ab | 45.5 de | 44.8 f-h | 43.8 j | 45.2 d-f | 43.0 b-d | 42.5 de | 44.1 a | 42.89 c-e | 43.7 ab |
| $NFF_4$ | 44.3 h-j | 46.5 a | 45.9 a-d | 45.6 b-e | 44.1 i-j | 43.5 a-c | 42.9 c-e | 42.57 de | 42.63 de | 42.3 ef |
| *Crude Oil Yield (kg ha$^{-1}$)* | | | | | | | | | | |
| $NFF_1$ | 941.2 e-h | 990.0 d-f | 846.7 h-j | 1069.2 cd | 761.5 j | 866.0 b-e | 738.2 g-ı | 907.7 b-d | 937.7 a-c | 810.7 d-g |
| $NFF_2$ | 793.7 ıj | 971.5 d-g | 925.5 e-h | 1008.2 de | 1061.5 cd | 757.2 f-ı | 841.7 c-f | 856.7 b-f | 787.0 e-ı | 810.7 d-g |
| $NFF_3$ | 1008.5 de | 2025.2 c-e | 896.2 f-ı | 946.0 e-h | 871.7 g-ı | 812.5 d-g | 951.2 ab | 882.2 b-e | 1011.7 a | 759.2 f-ı |
| $NFF_4$ | 1009.7 d-e | 1115.0 bc | 1182.5 ab | 1242.2 a | 1053.2 cd | 686.0 ı | 803.0 e-h | 866.5 b-e | 701.7 hı | 865.7 b-e |

[x] Means followed by the same letter(s) in each column are not significantly different at $p < 0.05$.

## 4. DISCUSSION

The findings of the study revealed that nitrogen fertilizer forms had a significant effect on plant height, spike diameter, seed yield, crude oil content, and crude oil yield in 2022, but showed no significant effect on any of the examined characteristics in 2023.The amount of precipitation during the vegetation period in 2023 was

considerably lower compared to that in 2022, and it is possible that the reduced nitrogen leaching played an important role in the lack of differences among nitrogen fertilizer forms. The effectiveness of slow-release nitrogen fertilizers increases under rainy conditions (Bahar et al., 2019). Consistent with this finding, in our study, the highest seed and crude oil yields were obtained from the $NFF_3$ and $NFF_4$ in combination with $ST_3$ treatment. Numerous studies have demonstrated that slow-release nitrogen fertilizers significantly reduce nitrogen losses associated with conventional nitrogen fertilizers (Gioacchini et al., 2002; Abalos et al., 2012; Cantarella et al., 2018). These fertilizers improve nitrogen use efficiency by minimizing nitrogen losses (Watson et al., 1996; Khan et al., 2013), and thereby contribute to reducing environmental pollution (Hartman et al. 2022). Abalos et al. (2012) reported that slow-release urea reduced ammonia losses by 58% and nitrous oxide and nitric oxide losses by 86% and 88%, respectively, under dry Mediterranean conditions. Similarly, Soares et al. (2012) observed a 54–78% reduction in nitrogen loss when using slow-release urea to minimize urea volatilization to ammonia.

Seed coating with materials such as nutrients, hormones, pesticides, or mycorrhiza-based fungi is considered a reliable and efficient method to ensure the localized availability of these substances around the root zone during seedling development (Colla et al., 2015; Rodríguez-Liébana et al., 2016). Coating seeds with protective materials can improve germination percentage, emergence of uniform plants, seedling development, and yield under favorable conditions (Yang et al., 2014; Mandal, 2015). Furthermore, coating seeds with micronutrients is a simple and effective technique. Most researchers have used zinc, boron, iron, copper, manganese, molybdenum, or other micronutrients for the seed-coating process (Rehman & Farooq, 2013; Oliveira et al., 2014; Adhikari et al., 2016). Micronutrient-coated seeds promote phenological development (for example, leaf area, stem diameter, and plant height) and significantly enhance yield (Korishettar et al., 2016; Ullah et al., 2019).

## 5. CONCLUSION

In this study, the effects of different nitrogen fertilizer forms and seed treatments on sunflower seed yield and quality were examined. Although the effects of nitrogen fertilizer forms on seed yield and yield-related characteristics were significant in the first year of the study, reduced nitrogen leaching due to low rainfall in the second year limited the effect of nitrogen fertilizer forms. In contrast, seed treatment effects were statistically significant for seed yield, thousand-seed weight, crude oil content, and crude oil yield for both years. Based on the findings of this study, the application of the $NFF_3$ (Slow-release form of ammonium sulfate) and $NFF_4$ (Slow-release form of urea), in combination with the $ST_3$ (Standard seed treatment + potassium humate) treatment, is recommended for maximizing seed and crude oil yields in sunflower.

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