



Titanium Dioxide Impact on Growth and Yield Parameters of Sunflower

Sibel Day^{1,*}, Nilüfer Koçak-Şahin¹

¹Ankara University, Faculty of Agriculture, Department of Field Crops, Ankara, Türkiye

HIGHLIGHTS

- Oil ratio of sunflower did not improved.
- Titanium dioxide application had benefit on seed yield.
- Seed application with titanium dioxide had superiority over application to leaves in different growth stages.

Abstract

Nanoparticles have unique properties and are used in fertilizers. Seed priming can improve seed germination and seedling growth. Various nanoparticles are used in seed germination and the growth of various plant species and varieties. This experiment was conducted to investigate the effect of TiO₂ nanoparticles on plant morphology when applied to leaves at different growth stages of sunflower and used as seed priming material. Before the field experiment, the seeds were soaked in 20 mg/L TiO₂ for 8 hours at 21±1 °C. The experiment was laid out in a randomized complete block design using three times replicated doses of 0 (control) and 20 mg L⁻¹ TiO₂ treatments to seeds, and at different growth stages. Plant height reached its highest level with TiO₂ treatments to seeds in both years. The maximum seed yield was observed in TiO₂ treatments for seeds in the first year of the experiment. Results revealed that seed priming with TiO₂ and 20 mg L⁻¹ TiO₂ at the V-4 stage is the most effective stage on sunflower growth.

Keywords: oil crop; nanoparticle; seed priming; growth stages

1. Introduction

Nanoparticles have unique physico-chemical properties, high stability, anticorrosion, and photocatalyst activity, which suggests their application in many areas like cosmetics, cleaning products, transportation, energy, and agriculture (Haghighi and Teixeira da Silva 2014).

In agriculture, nanoparticles are active components in nano-fertilizers (Estrada et al. 2018; Liu and Lal 2015; Prasad et al. 2012; Kolenčík et al. 2022). Liu and Lal (2015) categorised nano-fertilizers as macro-nutrient nano-fertilizers, micro-nutrient nano-fertilizers such as (ZnO, CuO, Fe₂O₃, etc.), nutrient-augmented nanomaterials, and plant growth enhancing materials such as TiO₂ and carbon nanotubes. Nano-fertilizers have a high capability of penetration into plants, and their foliar application to sunflowers, due to their broad leaves and stomata morphology, is a highly efficient way for growth support (Liu and Lal 2015).

Citation: Day S, Koçak-Şahin N (2025). Titanium dioxide impact on growth and yield parameters of sunflower. *Selcuk Journal of Agriculture and Food Sciences*, 39(2), 427-433. <https://doi.org/10.15316/selcukjafsci.1643850>

*Correspondence: day@ankara.edu.tr

Received date: 20/02/2025

Accepted date: 19/06/2025

Author(s) publishing with the journal retain(s) the copyright to their work licensed under the CC BY-NC 4.0.

<https://creativecommons.org/licenses/by-nc/4.0/>

Seed priming under optimum and unfavorable conditions could be used to increase seed germination efficiency and seedling fidelity (Day 2022). With the growing industry, new concepts are being developed (Acharya et al. 2017). Various nanoparticles (NPs) such as silver, aluminum oxide, cerium oxide, titanium dioxide, silicon, iron oxide, zinc oxide, and carbon nanotubes are used in plants. Nanoparticles affect plant growth; toxic or supportive, depending on species, form, and concentration (Haghighi et al. 2014; Prasad et al. 2017)

Plants' hormone levels can be altered by TiO₂ NPs. Tobacco showed increased zeatin riboside and brassinolide after being treated with TiO₂ nanoparticles (Hao et al. 2018). The supportive effect of TiO₂ NPs on plant growth and nutrient uptake has been observed in barley (Marchiol et al. 2016), and wheat (Faraji and Sepehri 2019; Zahra et al. 2019).

Mainly, oilseed-type sunflower cultivation is common in Türkiye, with 899.254 ha (TUIK 2024). Sunflower seeds, a snack type, cover 80.435 ha (TUIK 2024) and are used in several food sectors, where they are consumed as a snack (Day et al. 2008). Snack-type sunflower yield (2490 kg ha⁻¹) is less than that of oilseed sunflower (2610 kg ha⁻¹). Germination is vital for sunflower cultivation. It ensures fast germination and healthy seedlings, which are key to high sunflower yields. Pre-sowing seed treatments speed up field emergence in many oilseed crops (Day 2022; Bourioung et al. 2020; Shrestha et al. 2019).

The research about nano-fertilizers is mainly conducted in laboratories or in greenhouses (Rizwan et al. 2019), and field experiments are not common about nano-fertilizers (Ernst et al. 2023). This experiment was conducted to investigate the impact of TiO₂ nanoparticles on plant morphology when applied to leaves in different growth stages of sunflower and used as seed priming material.

Treatment of seeds with different agents and comparing their efficiency with treatments done at different growth stages is important. Therefore, the study aimed to investigate the impacts of TiO₂ NPs as a pre-sowing agent and as a nano-fertilizer on sunflower.

2. Materials and Methods

The seeds of the sunflower (*Helianthus annuus* L.) cultivar Ahmet Bey were obtained from the Turkish Republic Ministry of Agriculture and Forestry, Variety Registration and Seed Certification Centre. TiO₂ nanoparticles were purchased from a producer (NG Materials) of nanoparticles with a size of 50 nm. The experiment was conducted during the 2022 and 2023 seasons at the experimental fields of the Department of Field Crops, Faculty of Agriculture, Ankara University.

2.1. Soil analysis

To measure the qualitative and quantitative properties of soil, samples from the field were taken before sowing and analyses of soil samples (taken from depths of 0-20 and 20-40 cm) were performed at "the Soil Quality and Fertility Analysis Laboratory" of the Central Forestry Soil, Fertilizer and Water Resources Research Institute, Ankara, Türkiye.

2.2. Experimental design and field management

The experiment was designed as a one-factor randomized complete block design with three replications. Doses of 0 (control) and 20 mg L⁻¹ TiO₂ were applied to seeds and leaves. Prior to the start of the field experiment the seeds were soaked in 20 mg L⁻¹ for 8 hours at 21±1 °C. Leaves were sprayed with TiO₂ at different growth stages of V4, R1, and R4 as determined by Schneiter and Miller (1981). Seeds of sunflower were sown by hand on March 12 and 20, 2022, and 2023, respectively. Mechanical weed control and hand weeding were performed. The plot size was 11.2 m² (4 m × 2.8 m). Every individual plot had 70 cm row space and 30 cm intra-row spacing. Fertilizer (DAP and ammonium sulphate) treatment to the soil was made soon after sowing. The ammonium sulphate was applied twice, and the second application was before the R3 stage. Irrigation was carried out soon after sowing, before and after flowering. The plants were harvested on the 9th of September in 2022 and the 12th of September in 2023. Morphological characteristics like plant height, head

diameter, seed yield per head, 1000 seed weight, hull ratio, seed yield and oil ratio were investigated after the harvest.

Chlorophyll measurements were done with SPAD-502 Plus (Konica Minolta) using five leaves per plant. Ten plants from each replicate were used for sampling.

Oil content was determined using hexane-based extraction. The oil was extracted from 2 g sunflower seed samples using a homogenized 3 hexane: 2 isopropanol (v/v) solution. The extraction was replicated three times (Akyıldız 1968).

2.3. Statistical analysis

The experimental data were subjected to analysis of variance using randomized complete block design with three times replicated, and the post hoc tests were performed with Duncan's Multiple Range Test (MSTAT-C Software, Michigan State University, 1991). Measurements of parameters were observed 10 plants obtained from each replicate. The field experiment was one factorial, completely randomized design. The differences between means were determined using Duncan test at 0.05 and 0.01 depending on the results of variance analysis. Principal component analysis (PCA): correlations were used to evaluate the pattern of similarities using JMP statistical software. The relationship among parameters were indicated with Pearson's correlation coefficient.

3. Results

3.1. Soil and climate properties

The texture of the soil in the research area was clay-loam, alkaline. The soil was containing low organic matter and nitrogen (Table 1). Lime (CaCO_3) was determined between 73.0-82.0 g kg^{-1} . The phosphorus content of soil samples was in the range of 1.2-7.9 mg kg^{-1} . The potassium content of soil samples was 130.0-155.0 mg kg^{-1} (Table 1).

Table 1. Physical and chemical properties of the experimental fields.

Years	Depth (cm)	Soil Texture	Saturation (%)	pH	CaCO_3 (g kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	Total N (g kg^{-1})	Organic matter (g kg^{-1})
2022	0-20	Clay-loam	78	7.9	73.0	1.2	153.0	0.90	1.52
	20-40	Clay-loam	62	7.6	74.1	4.2	140.0	0.18	1.55
2023	0-20	Clay-loam	70	7.8	82.0	7.9	155.0	0.60	1.25
	20-40	Clay-loam	60	8.0	79.0	6.5	130.0	0.17	1.14

* Soil analysis laboratory of the Ministry of Agriculture and Forestry

The experiment was carried out in the area of Ankara University, Faculty of Agriculture and Department of Field Crops. Long-term average humidity, average temperature and total precipitation were determined to be 60.41%, 11.94 °C and 395.1 mm per year, respectively (Directorate General of Meteorology, 2024). The average temperature, relative humidity and precipitation of the vegetation period and the long-term average of the meteorological data are shown in Table 2.

3.2. Growth and yield contributing characters

Plant height only showed differences in between years ($p < 0.01$). The highest plant height was observed in 2022 with 175.43 cm (Table 3). The year \times TiO₂ interaction did not affect plant height statistically and the plant height values were observed between 169.13 and 178.63 cm. Head diameter showed statistically significant differences ($p < 0.01$) between 2022 (16.04 cm) and 2023 (20.46 cm). TiO₂ treatments at different growth stages affected head diameter and statistically important differences ($p < 0.01$) were observed. The maximum and minimum head diameters were noted in treatment at V-4 stage with 19.33 cm and treatment at R-2 stage with 17.78 cm (Table 3).

Table 2. Meteorological data of the experimental site.

Months	Temperature (°C)			Precipitation (mm)			Relative Humidity (%)		
	1929- 2022	2022	2023	1929-2022	2022	2023	1929-2022	2022	2023
January	0.2	0.9	3.9	40.6	36.2	4.3	77.4	72.6	66.9
February	1.7	4.0	2.7	35.2	29.6	21.0	72.9	72.6	62.4
May	5.7	2.3	8.2	39.7	42.6	67.2	64.5	59.5	68.2
April	11.2	14.1	11.0	42.9	2.6	38.1	58.6	43.2	62.5
March	16.0	16.6	15.8	52.1	13.4	101.1	57.2	49.6	62.4
June	20.0	20.9	19.9	34.9	97.6	94.8	52.0	58.7	64.7
July	23.4	23.1	25.0	14.3	22.9	1.3	44.5	47.5	40.4
August	23.4	26.2	28.3	12.7	25.7	0.0	43.5	46.0	32.9
September	18.8	20.5	21.0	18.4	3.4	27.0	48.0	42.8	45.7
October	13.2	13.7	15.9	28.0	14.3	2.5	58.8	60.7	51.4
November	7.2	10.0	10.7	31.5	9.5	81.7	69.9	61.7	73.1
December	2.5	6.3	6.9	44.8	22.3	29.1	77.6	78.9	80.3
Total /Average	11.94	13.21	14.1	395.1	320.1	468.1	60.4	57.8	59.2

*Directorate General of Meteorology, Ankara, Türkiye 2023.

Table 3. Impact of TiO₂ treatments on plant height and head diameter.

TiO ₂ treatment	Plant height			Head diameter		
	2022	2023	Mean	2022	2023	Mean
Control	174.73	169.20	171.97	16.03	20.37	18.20 b*
Seed treatment	178.63	170.10	174.37	16.17	19.61	17.89 b
Treatment at V-4 stage	176.57	169.77	173.17	16.60	22.06	19.33 a
Treatment at R-2 stage	172.37	169.27	170.82	15.80	19.76	17.78 b
Treatment at R-4 stage	174.87	169.13	172.00	15.60	20.53	18.06 b
Mean	175.43 A	169.43 B**		16.04 B	20.46 A**	

*, **: Figures having a similar letter(s) are not statistically and significantly different using Duncan's test at $p < 0.05$, $p < 0.01$.

Years \times TiO₂ treatment showed statistically significant interaction ($p < 0.05$) on 1000 seed weight (Table 4). The seed treatment in the first year of the experiment resulted in a maximum seed weight of 1000 seeds of 177.01 mg. The minimum 1000 seed weight was observed with 152.91 mg at R-4 stage treatment in the second year. The hull ratio of the seeds statistically differed between years ($p < 0.01$). The hull ratio in the second year (54.45%) of the experiment is higher than in the first year (46.19%). The hull ratio values were observed between 45.13% and 56.35% (Table 4).

Table 4. Impact of TiO₂ treatments on 1000 seed weight and hull ratio.

TiO ₂ treatment	1000 seed weight (g)			Hull Ratio (%)		
	2022	2023	Mean	2022	2023	Mean
Control	158.81 ab	156.37 b*	157.59	46.96	53.28	50.12
Seed treatment	177.01 a	154.70 b	165.85	46.98	54.61	50.79
Treatment at V-4 Stage	168.64 ab	176.10 a	172.37	46.33	55.67	51.00
Treatment at R-2 stage	154.91 b	169.85 ab	162.38	45.54	56.35	50.95
Treatment at R-4 stage	161.51 ab	152.91 b	157.21	45.13	52.32	48.73
Mean	164.17	161.98		46.19 B	54.45A**	

*, **: Figures having a similar letter(s) are not statistically and significantly different using Duncan's test at $p < 0.05$, $p < 0.01$.

Analysis of variance showed significant differences ($p < 0.01$) among the mean of TiO₂ treatments over years and in between years ($p < 0.05$). The maximum chlorophyll index value were observed in TiO₂ treated seeds with 41.68 SPAD units. TiO₂ treatment at R-2 stage with value of 36.74 SPAD units reflected the minimum chlorophyll index value (Table 5).

The analysis of variance on oil ratio reflected no statistical significant differences in terms of parameters observed in this research. The oil ratio of the cultivar ranged in between 47.97% and 52.83% (Table 5).

Table 5. Impact of TiO₂ treatments on SPAD value and oil ratio.

TiO ₂ treatment	Chlorophyll index (SPAD)			Oil content (%)		
	2022	2023	Mean	2022	2023	Mean
Control	42.93	36.78	39.86 ab**	52.83	49.10	50.97
Seed treatment	45.08	38.27	41.68 a	50.80	47.97	49.39
Treatment at V-4 stage	41.71	37.38	39.54 ab	52.70	48.52	50.61
Treatment at R-2 stage	38.48	35.01	36.74 b	51.67	51.06	51.36
Treatment at R-4 stage	37.23	37.30	37.27 b	51.87	48.90	50.37
Mean	41.28 A	37.18 B*		51.97	49.11	

*, **: Figures having a similar letter(s) are not statistically and significantly different using Duncan's test at $p < 0.05$, $p < 0.01$.

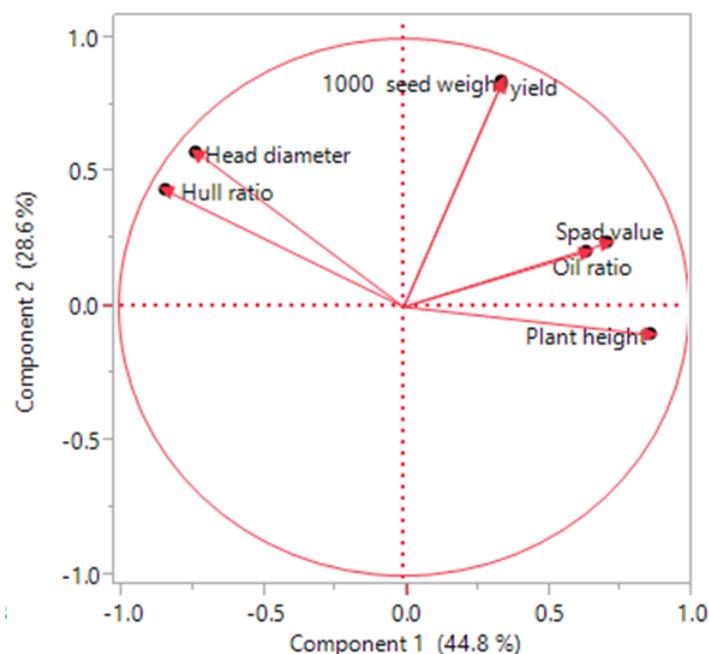
Seed yield represented a statistical difference over TiO₂ treatments at different stages ($p < 0.05$). A comparison among treatments at different stages showed that while TiO₂-treated seeds had the maximum seed yield with 260.47 kg da⁻¹, the control treatment had the minimum seed yield with 218.86 kg da⁻¹ (Table 6).

Table 6. Impact of TiO₂ treatments on the seed yield of sunflower in 2022 and 2023 years.

TiO ₂ treatment	Seed Yield (kg da ⁻¹)		
	2022	2023	Mean
Control	216.32	221.40	218.86 b*
Seed treatment	272.90	218.04	260.47 a
Treatment at V-4 stage	252.14	240.34	246.24 ab
Treatment at R-2 stage	214.82	252.27	233.54 ab
Treatment at R-4 stage	234.16	229.53	231.85 b
Mean	238.07	238.32	

*: Figures having a similar letter(s) are not statistically and significantly different using Duncan's test at $p < 0.05$.

Principal components 1 and 2 PCA results obtained from different parameters of sunflower subjected to TiO₂ under different periods are illustrated in Fig. 1. Component 1 and component 2 were 44.8% and 28.6% in this study, respectively, and their cumulative impact was 73.4% (Fig. 1). 1000 seed weight, yield, spad value, oil ratio and plant height made up 44.8% of the variation. However, head diameter and hull ratio accounted the 28.6% of the variation in PCA.

**Figure 1.** Principal components 1 and 2 obtained from sunflower phenologic parameters subjected to TiO₂ under different periods.

4. Discussion

TiO₂ is known as the newly developed nanoparticle fertilizer. Studies have shown that TiO₂ nanoparticles (NPs) have the ability to alter the hormonal levels of plants during growth. In fact, an increase in zeatin riboside and brassinolide was observed in tobacco plants after the application of TiO₂ NPs to their leaves (Hao et al. 2018). Additionally, the positive impact of TiO₂ NPs on plant growth, microorganism activity, and nutrient uptake has been observed in barley (Marchiol et al. 2016), as well as in wheat (Faraji and Sepehri 2019; Zahra et al. 2019). In the first year of the experiment, the sunflower plants were taller than in the second year. This difference may be due to the higher precipitation levels in March of the second year, which caused late sowing.

Head diameter had the highest level with treatment of TiO₂ at V-4 stage (19.33 cm). This application to new developed real leaves indicates the importance of early application of TiO₂ to sunflower from leaves. 1000 seed weight had the maximum levels from TiO₂ treated seeds in the first year and TiO₂ treatment from leaves at V-4 stage with 177.01 and 176.10 mg respectively.

The positive effect of TiO₂ on the oil content of sunflower was confirmed (Kolenčík et al. 2020), but the oil content in this experiment did not show any benefit from TiO₂. Chlorophyll pigments are the primary components of chloroplasts, playing a crucial role in regulating the rate and process of photosynthesis. Studies indicate that the SPAD value, which is used to measure chlorophyll levels, is closely associated with nitrogen content in plants and is sensitive to environmental stress. Improving results of TiO₂ in sunflower chlorophyll index was observed. The beneficial impact of the TiO₂ attributed to the increased light absorption by chloroplast by upregulated genes due to TiO₂ as reported by Ze et al. (2011), and improved translocation of nitrogen due to TiO₂ (Burke et al. 2014). The improving effect of TiO₂ nanoparticles on chlorophyll was observed in wheat (Satti et al. 2021) and *Dracocephalum moldavica* (Gohari et al. 2020).

Principal component analysis (PCA) is a powerful tool in analyzing relationships. Visualization of data obtained from growth parameters clearly separated hull ratio and head diameter were grouped together and separated from other parameters. One thousand seed weight, spad value and oil ratio were grouped together in the biplot which suggests that these parameters had a positive correlation among themselves. Plant height visualization reflected that it is also separated from other parameters (Fig. 1).

5. Conclusions

This study combines the seed application and foliar application of TiO₂ at different growth stages on field. The results revealed that TiO₂ seed application improved chlorophyll index value along with seed yield in field conditions compared to foliar applications. However, the results showed that oil ratio of sunflower did not improve with TiO₂ applications at any stages. Foliar application has the benefit of using lower amounts of nanoparticles that lead to lower contamination of soil and thus are more sustainable. Results revealed that TiO₂ application to seeds and at V-4 stage is the most effective stages on sunflower growth.

Author Contributions: Conceptualization, S.D.; methodology, S.D.; software, S.D.; validation, S.D. and N.K.Ş.; formal analysis, S.D. and N.K.Ş.; investigation, S.D. and N.K.Ş.; resources, S.D.; data curation, N.K.Ş.; writing—original draft preparation, S.D.; writing—review and editing, S.D.; visualization, S.D.; supervision, S.D.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to express their appreciation to Dr. Yasin Özgen for oil content analysis.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Acharya D, Mohanta B, Pandey P, Singha M, Nasiri F (2017). Optical and antibacterial properties of synthesised silver nanoparticles. *Micro & Nano Letters* 12(4), 223-226.
- Akyıldız AR (1968). Yemler bilgisi laboratuvar klavuzu. *Ziraat Fakültesi Yayınları*, 358. Uygulama Klavuzu. 122 s. Ankara.
- Bourioum M, Ezzaza K, Bouabid R, Alaoui-Mhamdi M, Bungau S, Bourgeade P, Alaoui-Sossé L, Alaoui-Sossé B, Aleya L (2020). Influence of hydro-and osmo-priming on sunflower seeds to break dormancy and improve crop performance under water stress. *Environmental Science and Pollution Research* 27, 13215-13226.
- Burke DJ, Zhu S, Pablico-Lansigan MP, Hewins CR, Samia ACS (2014) Titanium oxide nanoparticle effects on composition of soil microbial communities and plant performance. *Biology and Fertility of Soils* 50, 1169–1173. <https://doi.org/10.1007/s00374-014-0938-3>
- Day S (2008). Bazı çerezlik ayçiçeği (*Helianthus Annuus* L.) genotiplerinin çimlenmesi üzerine NaCl konsantrasyonlarının etkileri. *Journal of Agricultural Sciences* 14(03), 230-236
- Day S (2022). Impact of seed priming on germination performance of fresh and aged seeds of Canola. *International Journal of Agriculture Environment and Food Sciences* 6(1), 37-40.
- Estrada-Urbina J, Cruz-Alonso A, Santander-González M, Méndez-Albores A, Vázquez-Durán A (2018) Nanoscale zinc oxide particles for improving the physiological and sanitary quality of a Mexican landrace of red maize. *Nanomaterials* 8, 247.
- Ernst D, Kolenčík M, Šebesta M, Ďurišová L, Ďúranová H, Kšíňan S, Illa R, Safarik I, Černý I, Kratošová G, Žitniak Čurná V, Ivanič Porhajašová J, Babošová M, Feng H, Dobročka E, Bujdoš M, Pospiskova KZ, Afzal S, Singh NK, Aydın E (2023). Agronomic investigation of spray dispersion of metal-based nanoparticles on sunflowers in real-world environments. *Plants* 12(9), 1789. <https://doi.org/10.3390/plants12091789>
- Faraji J, Sepehri A (2019). Ameliorative effects of TiO₂ nanoparticles and sodium nitroprusside on seed germination and seedling growth of wheat under PEG-stimulated drought stress. *Journal of Seed Science* 41, 309-317.
- Gohari G, Mohammadi A, Akbari A, Panahirad S, Dadpour MR, Fotopoulos V, Kimura S (2020). Titanium dioxide nanoparticles (TiO₂ NPs) promote growth and ameliorate salinity stress effects on essential oil profile and biochemical attributes of *Dracocephalum moldavica*. *Scientific Reports* 10, 912. <https://doi.org/10.1038/s41598-020-57794-1>
- Hao Y, Yuan W, Ma C, White JC, Zhang Z, Adeel M, Zou T, Rui Y, Xing B (2018). Engineered nanomaterials suppress Turnip mosaic virus infection in tobacco (*Nicotiana benthamiana*). *Environmental Science: Nano* 5(7), 1685-1693.
- Haghighi, M, Teixeira da Silva, JA (2014). The effect of N-TiO₂ on tomato, onion, and radish seed germination. *Journal of Crop Science and Biotechnology* 17, 221–227. <https://doi.org/10.1007/s12892-014-0056-7>
- JMP®, Version <x>. SAS Institute Inc., Cary, NC, 1989–2023.
- Kolenčík M, Ernst D, Urík M, Ďurišová L, Bujdoš M, Šebesta M, Dobročka E, Kšíňan S, Illa R, Qian Y, Feng H, Černý I, Holišová V, Kratošová G (2020). Foliar application of low concentrations of titanium dioxide and zinc oxide nanoparticles to the common sunflower under field conditions. *Nanomaterials* 10(8), 1619. <https://doi.org/10.3390/nano10081619>
- Kolenčík M, Ernst D, Komár M, Urík M, Šebesta M, Ďurišová L, Bujdoš M, Černý I, Chlpík J, Juriga M, Illa R, Qian Y, Feng H, Kratošová G, Barabaszová KČ, Dučay L, Aydın E (2022). Effects of foliar application of ZnO nanoparticles on lentil production, stress level and nutritional seed quality under field conditions. *Nanomaterials* 12(3), 310. <https://doi.org/10.3390/nano12030310>

- Liu R, Lal R (2015). Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. *Science of the Total Environment* 514, 131–139.
- Marchiol L, Mattiello A, Pošćić F, Fellet G, Zavalloni C, Carlino E, Musetti R (2016). Changes in physiological and agronomical parameters of barley (*Hordeum vulgare*) exposed to cerium and titanium dioxide nanoparticles. *International Journal of Environmental Research and Public Health* 13(3), 332.
- MSTAT-C (1991). A software program for the design, management and analysis of agronomic research experiments. Michigan State University, East Lansing.
- Prasad, TNVKV, Sudhakar P, Sreenivasulu Y, Latha P, Munaswamy V, Reddy KR, Sreeprasad TS, Sajanlal PR, Pradeep T (2012). Effect of nanoscale zinc oxide particles on the germination, growth and yield of peanut. *Journal of Plant Nutrition* 35, 905–927.
- Prasad R, Bhattacharyya A, Nguyen QD (2017). Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. *Frontiers in microbiology* 8, 1014.
- Rizwan M, Ali S, Ali B, Adrees M, Arshad M, Hussain A, Rehman MZ, Waris, AA (2019). Zinc and iron oxide nanoparticles improved the plant growth and reduced the oxidative stress and cadmium concentration in wheat. *Chemosphere* 214, 269-277.
- Satti SH, Raja NI, Javed B, Akram A, Mashwani ZuR, et al. (2021). Titanium dioxide nanoparticles elicited agro-morphological and physicochemical modifications in wheat plants to control *Bipolaris sorokiniana* PLOS ONE 16(2), e0246880. <https://doi.org/10.1371/journal.pone.0246880>
- Schneiter AA, Miller JF (1981). Description of sunflower growth stages. *Crop Science* 21, 901-903.
- Shrestha A, Pradhan S, Shrestha J, Subedi M (2019). Role of seed priming in improving seed germination and seedling growth of maize (*Zea mays* L.) under rain fed condition. *Journal of Agriculture and Natural Resources* 2(1), 265-273.
- TUIK (2024). Agricultural statistics summary. <https://biruni.tuik.gov.tr/medas/?kn=92&locale=tr> (access date: 20.11.2024).
- Zahra Z, Maqbool T, Arshad M, Badshah MA, Choi HK, Hur J (2019). Changes in fluorescent dissolved organic matter and their association with phyto available phosphorus in soil amended with TiO₂ nanoparticles. *Chemosphere* 227, 17-25.
- Ze Y, Liu C, Wang L, Hong M, Hong F (2011). The regulation of TiO₂ nanoparticles on the expression of light-harvesting complex II and photosynthesis of chloroplasts of *Arabidopsis thaliana*. *Biological Trace Element Research* 143, 1131–1141. <https://doi.org/10.1007/s12011-0>