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Comparison of Iron and Zinc Nanoparticles with Different Sizes and Bulk Forms on Seed Yield and Its Components in Flaxseed (*Linum usitatissimum* L.) under Late-Season Water Deficit

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ABSTRACT

Flaxseed is an important crop that is used extensively for medicine, nutrition, and industry. Then, this research aims to investigate the effect of foliar spraying of bulk and nanoparticle forms of iron and zinc with different particle sizes on yield and its related traits of flaxseed under post-anthesis water deficit. To this end, a split-plot factorial experiment based on randomized complete blocks design in three replications was used at Razi University, Kermanshah, Iran, in two crop years (2019-2021). The experiment comprised two moisture regimes - optimal irrigation and post-anthesis water deficit, applied in the main plots. Different fertilizers (bulk and nanoparticles with varying particle sizes) and fertilizer concentrations (0, 300, and 600 mg l^{-1}) were tested in the subplot. The results showed that under optimal moisture conditions, the highest grain and biomass yield was in the foliar treatments of iron nanoparticles 20-30 nm and 600 mg l^{-1} and zinc nanoparticles 10-30 nm and 300 mg l^{-1}, with 2448 and 8432 kg ha^{-1}, respectively and the lowest amount was obtained in the control treatment with 2028 and 7599 kg ha^{-1}. Under post-anthesis water deficit environment, zinc nanoparticles 10-30 nm and 300 mg l^{-1} caused a 35% increase in grain yield compared to the control treatment (997 kg ha^{-1}). Also, the highest oil percentage and yield were obtained in iron nanoparticles 20-30 nm and 600 mg l^{-1} with 35.25% and 866 kg ha^{-1}, respectively. In general, the efficiency of iron and zinc nanoparticle fertilizers with different particle sizes was significantly higher than that of iron and zinc bulk forms and control treatment (without fertilization). Nanoparticle fertilizers significantly reduced the adverse effects of late-season water deficit on grain, oil, and biomass yield.

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1. Introduction

Flaxseed is a valuable oil-medicinal product. Its seeds contain between 30 and 40% oil. Flaxseed oil is one of the world's richest edible sources of omega-3, with more than twice the amount found in fish oil (Mirzaie *et al.*, 2020; Zhang *et al.*, 2016; Zare *et al.*, 2023). In addition to being an industrial plant, flaxseed is also considered an important medicinal plant, and its constituent compounds guarantee human health. The oil of this plant or the products obtained from extracting its fatty acids have a significant role in developing children's vision, skin care, reducing blood cholesterol, preventing inflammation, preventing breast and colon cancer, and strengthening the stomach (Goyal *et al.*, 2014; Zhang *et al.*, 2016). Drought stress in crops is one of the main reasons for yield reduction, especially in tropical, TEi-arid, and arid regions worldwide. The lack of water available to the plant is caused by low and irregular rainfall, lack of water storage in the soil, and the transpiration rate exceeding the water absorption rate (Seleiman *et al.*, 2021). Drought stress has a significant impact on the growth and productivity of crops. One of its effects is the loss of turgor pressure, which slows down cell growth and ultimately reduces the size of the cell. As a result, the rate of stem growth and leaf development decreases, reducing crop yield (Verbraeken *et al.*, 2021). Drought stress also limits the gas exchange in crops, affecting leaf expansion and

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development. This disruption of the photosynthetic system and its components causes leaf aging, reduces the duration of the leaf area, oxidizes chloroplast lipids, and alters the structure of proteins and pigments (Singh *et al.*, 2017).

It is essential to understand that soil contains many nutrients, but only a tiny portion is available to plants yearly. As a result, plants cannot get all the nutrients they need from the soil alone. This often leads to nutrient deficiency, which can be addressed using fertilizers (Vasu *et al.*, 2020). Today, the excessive use of chemical fertilizers such as nitrogen and phosphorus, the presence of high bicarbonate in irrigation water, the lack of use of microelement fertilizers, the presence of calcareous soils with low organic matter, and intermittent cultivation of land cause the intensification of the lack of low consumption elements in the soil for plant growth (Firoozi *et al.*, 2018).

For optimal plant growth, nutrients should be balanced and sufficient in the soil and available to the plant; therefore, in addition to the macroelements, the microelements should also be optimally available to the plants (Schjoerring *et al.*, 2019). During drought stress, the nutritional balance in plants is disrupted so that access to nutrients through the roots becomes more limited (Cakmak, 2008). Low moisture in the soil is an influential factor in the deficiency of low-use elements, especially iron and zinc, in plants. The soil application of nutrients under conditions that lack moisture is not always effective in increasing the absorption and transfer of nutrients to the plant. In such conditions, the soil application of fertilizers can cause salinity and harm the soil solution. In this situation, using the foliar spraying method is more beneficial. Therefore, to overcome this problem, it is possible to improve plant growth in drought-stress conditions by using micronutrients through spraying (Kouchak Dezfouli *et al.*, 2023). Like other new technologies, nanotechnology has received attention in the agricultural industry. Fertilizers are one of the uses of nanotechnology in modern agriculture. The use of high amounts of different fertilizers to increase yield has polluted various ecosystems. By formulating fertilizers, nanotechnology has easily controlled nutrients according to the consumption patterns of plants and prevented the application of extra fertilizers (Yadav *et al.*, 2023). Using nano fertilizers to control the release of nutrients precisely is a practical step towards achieving sustainable and environmentally friendly agriculture. With the use of nanostructure compounds, a more optimal and efficient release of the elements in fertilizers is achieved (DeRosa *et al.*, 2010; Babu *et al.*, 2022). These compounds reduce nutrient wastage and increase crop production sustainably (Dimkpa *et al.*, 2017). The small size (1-100 nm) and, as a result, the high surface-to-volume ratio of nanoparticles give them important properties compared to bulk fertilizers to effectively increase the efficiency of the use of nutrients by the plant and less fertilizer consumption (Faizan *et al.*, 2021; Li *et al.*, 2016).

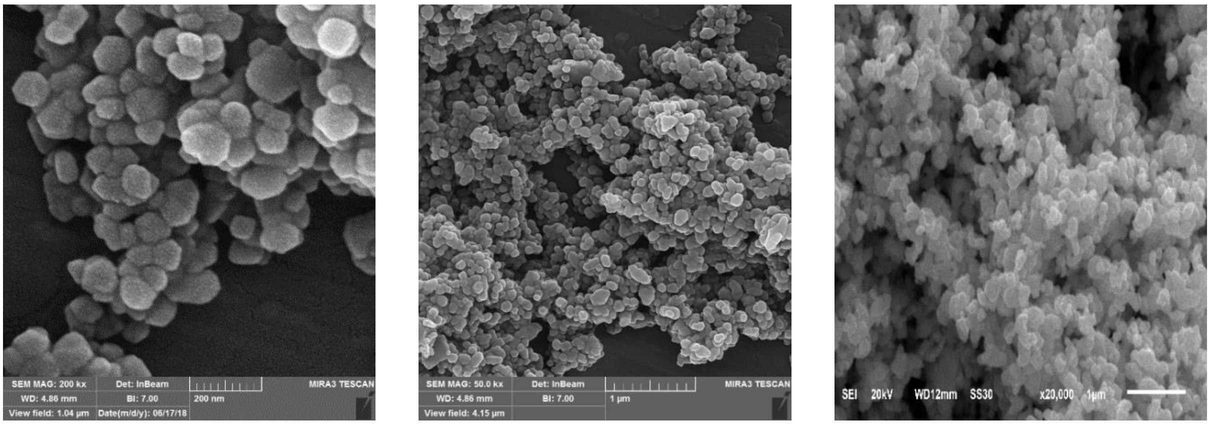
It has been determined that micronutrient elements, including iron and zinc in nanoparticles, are significantly effective in producing and increasing crop yield (Malloy, 2011). High absorption and transmission of iron and zink nanoparticle forms are more effective than bulk forms in drought-stress conditions and reduce the adverse effects of drought stress (Seyed Sharifi *et al.*, 2020; Dimkpa *et al.*, 2019). For example, Dimpka et al. (2019) observed that nanoparticle spraying treatment significantly reduced the harmful effects of drought stress on sorghum grain yield. Also, Seyed Sharifi et al. (2020) also observed that iron and zinc nanoparticles were able to reduce the adverse effects of drought stress on wheat.

Using nano-fertilizers with varying dimensions and sizes to enhance growth and crop yield production is a new research area. However, the benefits and limitations of using these nanoparticles, especially in different sizes, have not been thoroughly evaluated in crops. So, this study aims to compare the effectiveness of iron and zinc nano fertilizers with different dimensions (Fig. 1) compared to bulk fertilizers in improving the yield of flaxseed in two crop years in two different environments (one with a well-watered and the other with a late-season water deficit).

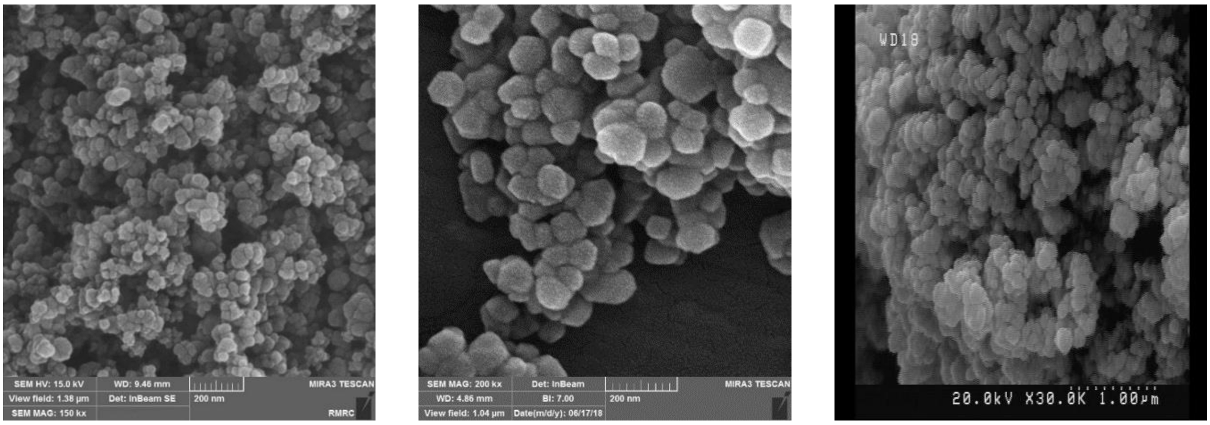
2. Materials and methods

2.1. Site description

The field experiments were carried out as a split-plot factorial design based on a randomized complete block design with three replications at Razi University's research farm in Kermanshah, Iran. The farm is located at 34°21′N, 47°19′E, at an altitude of 1319 m above sea level. The average annual temperature is 13.3 degrees Celsius, and the average annual rainfall ranges from 450-480 mm. The experiments were conducted over two growing seasons, in 2019-2020 and 2020-2021. Fig. 2 presents the average rainfall and temperature changes during both seasons, while Table 1 shows the soil analysis results done in the same period.



Iron oxide 20 to 30 nm | Iron oxide 50 to 60 nm | Iron oxide 80 to 100 nm



Zinc oxide 10 to 30 nm | Zinc oxide 40 to 60 nm | Zink oxide 80 to 100 nm

Figure 1. Scanning electron microscopy (SEM) of zinc and iron oxide nanoparticles with different particle sizes. The particle size index is available below each image.

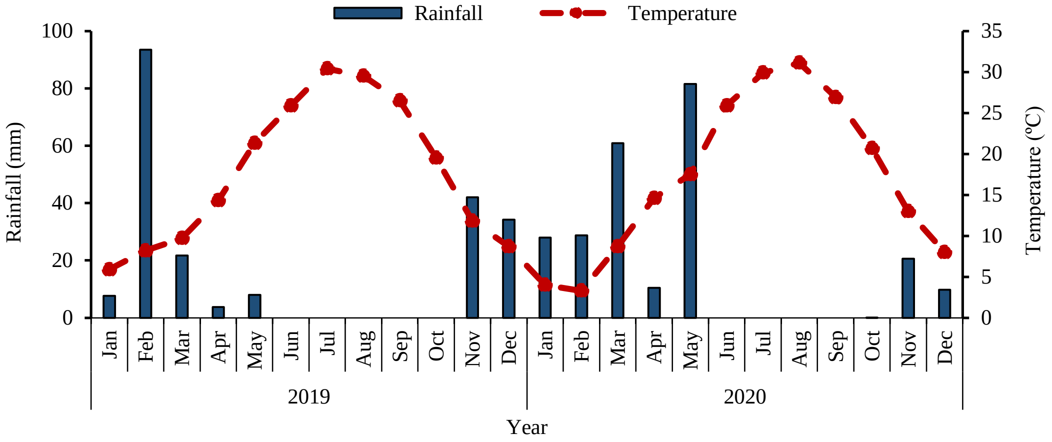


Figure 2. Distribution of mean monthly rainfall and temperature in two years of the experiment (2019 and 2020).

2.2. Experimental design and agronomic management

The investigated treatments included the environment, which was the main factor, and in two levels, including 1) water deficit environment where irrigation was stopped from flowering to maturity, and 2) well-watered environment or normal irrigation. Fertilizer concentration and type treatments were factorially placed in sub-plots as follows: 1) Fertilizer concentration in three levels (0, 300, and 600 mg l^{-1}) and 2) fertilizer type in 11 levels including T_1: bulk form of iron, T_2: iron normal nanoparticle 1-100 nm, T_3: iron nanoparticle 20 to 30 nm, T_4: iron nanoparticle

50 to 60 nm, T_5: iron nanoparticle 80 to 100 nm, T_6: bulk zinc, T_7: zinc normal nanoparticle 1-100 nm, T_8: zinc nanoparticle 10 to 30 nm, T_9: zinc nanoparticle 40 to 60 nm, T_{10}: zinc nanoparticle 80 to 100 nm and T_{11}: control (without fertilization or water spraying).

Each experimental plot included five planting lines with a length of four meters and a width of 1.5 meters. Each replication or block had 44 plots. Flaxseed were planted with a density of 400 plants m^{-2} and with a distance between rows of 25 cm and on rows of 1 cm from each other. Grains were disinfected with an appropriate fungicide to prevent fungal diseases, and after that, cultivation was done in the middle of March with the mentioned density. Foliar treatment was applied in two stages of development (the beginning of growth and the beginning of flowering). The results of the soil test are reported in Table 1. The requirement of nitrogen, phosphorus, and potash fertilizers was provided based on the soil test results.

Table 1. Physicochemical parameters of the soil of the research area

Parameters		Parameters	
Sand (%)	10.7	N (%)	0.135
Silt (%)	43.9	P (mg kg^{-1})	5.80
Clay (%)	45.4	K^+ (mg kg^{-1})	520
Texture	Silty clay	Cu^{2+} (mg kg^{-1})	1.34
pH (1:2)	7.9	Fe^{2+} (mg kg^{-1})	3.90
EC (ds m^{-1})	0.62	Zn^{2+} (mg kg^{-1})	0.48
OC (%)	1.35	Mn^{2+} (mg kg^{-1})	4.60

2.3. Measurements

2.3.1. Grain yield and its related traits

When flaxseed was technologically mature, harvesting was conducted manually at one square meter per plot. The following agronomic traits were subsequently measured.

The biological yield was determined by randomly harvesting one square meter in each plot from the collar area, weighing it, and calculating the yield in kilograms per hectare. The grain yield was obtained by harvesting plants in one square meter, threshing the grains, separating them from straw stubble and other impurities, and calculating the seed yield in kilograms per hectare.

In 10 randomly selected plants, the number of capsules was counted. Their average was considered the number of capsule per plant. The number of grains per plant was also counted, and their average was considered as the number of grains per plant. The number of grains in each capsule was calculated by dividing the number of grains in each plant by the number of capsules in that plant. In 10 randomly selected plants, the number of empty capsules was counted. Their average was considered as the number of empty capsules per plant. To calculate the weight of 1000 grains in each plot, five random 1000 samples were chosen and measured with a digital scale accurate to 0.01 grams.

Ten random plants were chosen at the time of maturity, and their heights were measured from the collar area to the end of the stem using a ruler. Additionally, the number of primary and secondary branches was measured in each plant. Then, their average was considered as the plant height and the number of primary and secondary branches. The Harvest index was calculated by dividing the seed yield by the biological yield and multiplying by 100.

2.4. Oil percentage and oil yield

The oil content of the grains was obtained using the standard AOAC (1990) method and with the use of diethyl ether solvent. To measure the oil percentage, the seeds were first ground completely. Then, 2 g of each sample was weighed and placed inside the pre-weighed filter paper and inside the Soxhlet apparatus. In the next step, 100 ml of solvent was poured into the cylinder of the apparatus. Due to the heat, the solvent is vaporized and poured onto the sample. After 12 hours, the samples were exposed to the airflow so that the solvent was separated from the oil. After adding oil, the samples were re-weighed by deducting the weight of the pre-weighed cylinder, and the percentage of oil was determined. Oil yield was obtained from the Equation 1.

$$\text{Oil yield (kg ha}^{-1}\text{)} = \text{Oil content (\%)} \times \text{Grain yield (kg ha}^{-1}\text{)} \tag{1}$$

2.5. Statistical analysis

The collected data were checked for normality before analysis of variance and other statistical calculations. Then, data analysis of variance and the correlation between traits were performed with the help of SAS software (Version 16, IBM Institute, USA). Mean comparisons were made using MSTAT-C and SAS software. The least significant difference (LSD) test was used at the five percent probability level to compare the means.

3. Results and discussion

The analysis of variances showed that the treatments of year, water deficit, fertilizer type, and interaction of fertilizer type×fertilizer concentration significantly impacted grain yield, biomass, and other investigated traits. The concentration of applied fertilizers significantly affected all investigated traits except the harvest index, the oil percentage, the number of capsules, and the number of primary branches plant^{-1} (Table 2). The interaction effect of water regime×fertilizer concentration significantly affected all investigated traits except the grain yield, the number of grain capsule^{-1}, the oil percentage, and the oil yield. The interaction effect of water regime×fertilizer was also significant on all studied traits except for the grain yield, the number of capsules plant^{-1}, and the oil percentage. The interaction effect of water regime×fertilizer concentration×fertilizer type also significantly affected all traits except for the harvest index, the number of grain plant^{-1}, the number of capsules plant^{-1}, and the number of primary branches plant^{-1} (Table 2).

Table 2. Combined analysis of variance of yield and its related agronomic traits in flaxseed under moisture regimes and foliar application of bulk and nanoparticle iron and zinc with different particle sizes in two crop years, 2019-2020 and 2020-2021.

Sources of variation	d.f.	Grain yield	Biomass yield	Harvest index	Oil percentage	Oil yield	1000 seed weight	No of grain plant^{-1}
Year (Y)	1	500511**	531275**	74.1**	48.2**	102917**	0.286**	1115**
Replication / Y	4	597185	8596870	10.13	185	215071	0.289	2003
Moisture regime (W)	1	75755051**	523187472**	2084**	1124**	9882167**	11.9**	222935**
Y × W	1	11720^{ns}	77627^{ns}	5.72**	0.147^{ns}	166^{ns}	0.017*	4.77^{ns}
Ea	4	30087	62440	2.19	7.25	32897	0.065	218
Manures (M)	10	98716**	501572**	5.01**	18.4**	31589**	0.042**	241**
Concentration (C)	1	83923**	879648**	1.61^{ns}	3.69^{ns}	12072*	0.133**	92.1*
W × M	10	19444**	31405^{ns}	3.33*	8.31^{ns}	13315**	0.011*	68.9**
W × C	1	56642**	98638^{ns}	9.37**	0.939^{ns}	6101^{ns}	0.014*	279**
M × C	10	107431**	814105**	4.47*	20.4**	31143**	70.7**	4.43*
W × M × C	10	15730**	100125**	2.73^{ns}	13.8*	14923**	3.33*	1.16^{ns}
Y × M	10	2168^{ns}	41335^{ns}	0.267^{ns}	0.723^{ns}	302^{ns}	0.001^{ns}	9.28^{ns}
Y × C	1	13459^{ns}	36425^{ns}	1.88^{ns}	1.87^{ns}	1892^{ns}	0.008^{ns}	21.7^{ns}
Y × W × C	1	34022*	23315^{ns}	5.04**	2.32^{ns}	5324^{ns}	0.005^{ns}	4.30^{ns}
Y × W × M	10	1623^{ns}	17385^{ns}	0.343^{ns}	0.748^{ns}	538^{ns}	0.0006^{ns}	4.01^{ns}
Y × M × C	10	3493^{ns}	19915^{ns}	0.521^{ns}	0.149^{ns}	700^{ns}	0.0007^{ns}	5.51^{ns}
Y × W × M × C	10	1457^{ns}	18050^{ns}	0.844^{ns}	0.107^{ns}	512^{ns}	0.001^{ns}	2.08^{ns}
Eb	172	4677	46132	0.646	6.04	2817	0.002	9.14
Coefficient of variation (%)		8.34	6.19	3.88	8.34	10.24	3.71	8.20

Sources of variation	d.f.	No of capsule plant^{-1}	No of grain capsule^{-1}	No of empty capsule	Plant height	No of main branch	No of sub branch
Year (Y)	1	26.4**	0.476**	0.218**	0.656^{ns}	0.049**	0.807**
Replication / Y	4	26.6	1.04	0.002	900	0.165	0.725
Moisture regime (W)	1	2386**	154**	59.5**	2389**	34.4**	36.5**
Y × W	1	1.61**	0.127*	0.041**	12.2**	0.175**	0.018^{ns}
Ea	4	0.144	0.227	0.009	1.65	0.013	0.033
Manures (M)	10	0.465**	0.488**	0.111**	32.7**	0.013**	0.186**
Concentration (C)	1	0.012^{ns}	1.22**	1.28**	349**	0.005^{ns}	0.118**
W × M	10	0.123^{ns}	0.175**	0.013*	3.75*	0.003^{ns}	0.053**
W × C	1	8.58**	0.01^{ns}	0.785**	101**	0.087**	0.073**
M × C	10	11.4**	26.1**	14.3**	61.9**	25.1**	18.2**
W × M × C	10	0.268^{ns}	11.6**	5.13**	5.14**	0.007^{ns}	7.39**
Y × M	10	0.300^{ns}	0.015^{ns}	0.007^{ns}	1.62^{ns}	0.002^{ns}	0.004^{ns}
Y × C	1	3.45**	0.0007^{ns}	0.127**	7.1*	0.0001^{ns}	0.002^{ns}
Y × W × C	1	0.320^{ns}	0.0008^{ns}	0.185**	13.5**	0.007^{ns}	0.009^{ns}
Y × W × M	10	0.091^{ns}	0.012^{ns}	0.003^{ns}	1.26^{ns}	0.002^{ns}	0.002^{ns}
Y × M × C	10	0.695^{ns}	0.021^{ns}	0.007^{ns}	0.762^{ns}	0.001^{ns}	0.009^{ns}
Y × W × M × C	10	0.518^{ns}	0.071^{ns}	0.007^{ns}	0.682^{ns}	0.002^{ns}	0.003^{ns}
Eb	172	0.117	0.254	0.008	1.54	0.001	0.008
Coefficient of variation (%)		5.01	4.18	7.80	2.20	3.74	3.80

^{ns}, *, and ** are non-significant and significant at the probability levels 0.05 and 0.01, respectively.

3.1. Grain and biomass yield

The results showed that grain and biomass yield in the first year (with 1740 and 6660 kg ha^{-1}, respectively) was significantly higher compared to the second year (Fig. 3). The grain and biomass yield in well-watered environment was 2232 and 8023 kg ha^{-1}, respectively. Water deficit caused a significant decrease in these traits by 48% and 35%, respectively (Fig. 3).

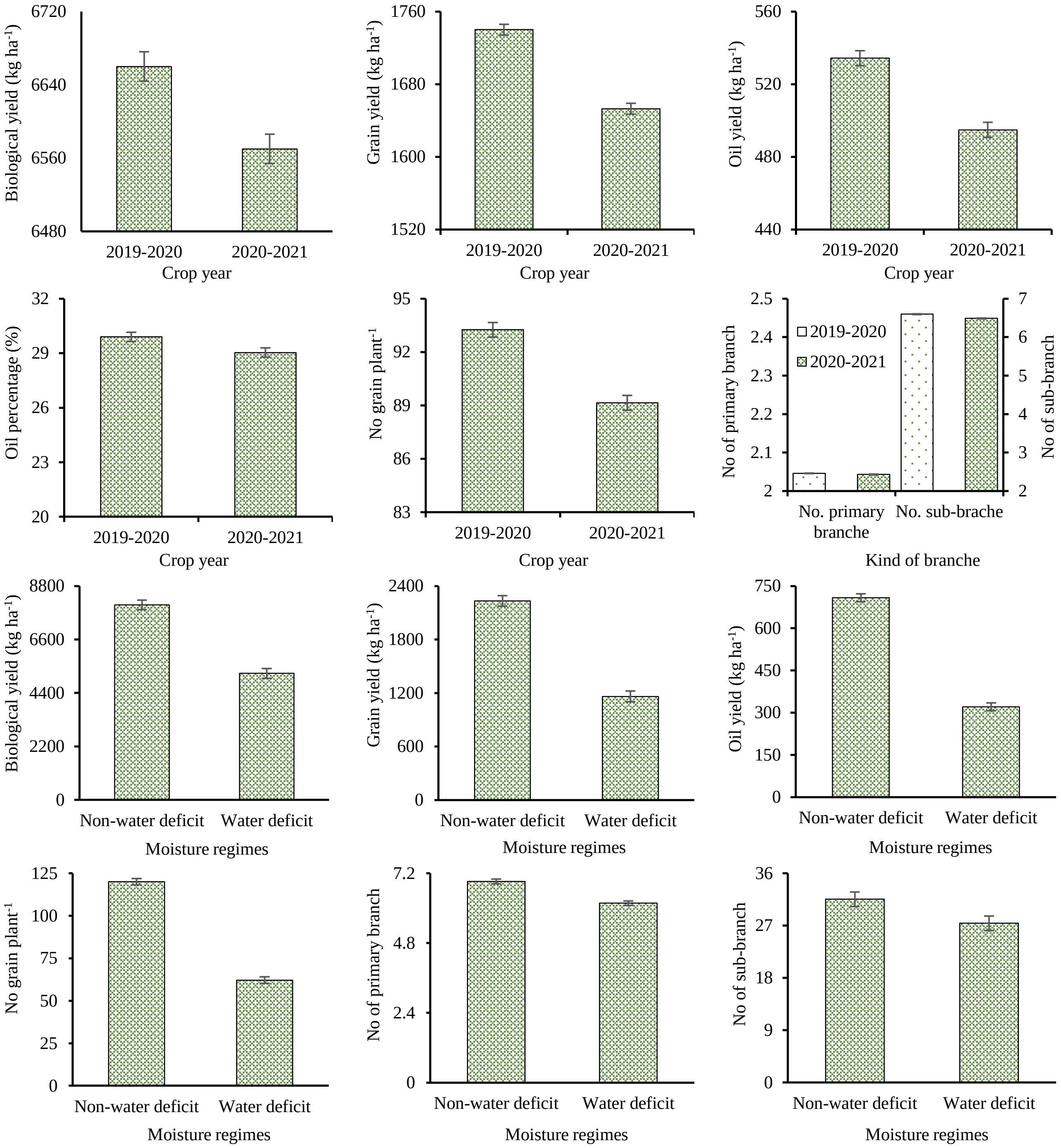


Figure 3. Means comparison of the effect of year and moisture regimes on the grain, biomass and oil yield and some related agronomic traits in flaxseed. The bars indicate the LSD number at a five percent probability level.

In well-watered environment, the highest grain and biomass yield was obtained in foliar application of iron nanoparticle fertilizer 20-30 nm 600 mg l^{-1} and zinc nanoparticle fertilizer 10-30 nm 300 mg l^{-1} with 2448 and 8432 kg ha^{-1}, and the lowest grain and biomass yield were obtained in the control treatment (no fertilizer use) with 2028 and 7599 kg ha^{-1}, respectively. In water-deficit environment, the highest grain and biomass yield was seen in the foliar application of nanoparticle fertilizers of zinc 10-30nm and 300 mg l^{-1}

concentration with 1345 and 5789 kg ha^{-1}, respectively. Also, the lowest grain and biomass yield were obtained in the control treatment (no fertilizer use) with 997 kg ha^{-1} and the foliar spraying nanoparticle fertilizer of 10-30 nm and 600 mg l^{-1} in the amount of 4748 kg ha^{-1} respectively (Table 3). In the well-watered, iron nanoparticles of 20-30 and 50-60 nm 600 mg l^{-1} and zinc nanoparticles of 10-30 nm and 40-60 nm with 300 mg l^{-1} caused a significant increase in grain yield and biomass in comparison with other fertilizer treatments and control treatment (Table 3). Iron and zinc nanoparticle fertilizers of 80-100 nm are more efficient than nanoparticle fertilizers of 1-100 nm of iron and zinc 300 mg l^{-1} and had no significant difference in the concentration of 600 mg l^{-1}. However, they were superior to the traditional form of iron and zinc fertilizers and the control treatment (without application of fertilizers) (Table 3).

In water deficit environment, zinc nanoparticles 10-30 and 40-60 nm with the concentration of 300 mg l^{-1} and iron nanoparticles 20-30 nm 300 mg l^{-1} cause a significant increase in grain and biomass yield compared to other treatments. Zinc nanoparticles 80-100 nm and 1-100 nm with a concentration of 300 mg l^{-1} were more effective than the other fertilizer and control treatments. In general, nanoparticle fertilizers had a more positive and significant effect on grain yield than bulk iron and zinc fertilizers and the control treatment. At 600 mg l^{-1} of the fertilizers, the efficiency of bulk iron and zinc fertilizers was better than that of control and nanoparticle fertilizers of iron and zinc. In this fertilizer concentration, probably due to some adverse effects caused by the high concentration of nanoparticle fertilizers in the range of 10-60 nm in the plant, the yield did not show a significant difference compared to the control (Table 3).

3.2. Harvest index

The highest and the lowest harvest index was obtained in the first year in well-watered environment with 28.22% and in the second year in water deficit treatment with 21.54% (Fig. 3). Based on the mean comparison of the tow way interaction of water deficit×fertilizer concentration, the highest and the lowest harvest index was obtained in well-watered and concentration of 600 mg l^{-1} of fertilizer with 27.95% and water deficit and concentration of 600 mg l^{-1} with 21.95%, respectively (Table 4; Fig. 4).

The highest and the lowest harvest index were obtained in iron nanoparticles 20-30 nm in non-water deficit environment (28.98%) and control (non-application of fertilizer) in water deficit environment (21.07%) (Table 5). The foliar spraying treatments of iron nanoparticle 20-30 nm 300 mg l^{-1} and the control treatment (non-application of fertilizer) had the highest and lowest harvest index with 25.87 and 23.85%, respectively (Table 4). According to the relationship between grain yield and harvest index, the water deficit causes a sharper decrease in grain yield compared to biomass yield and, as a result, a significant decrease in harvest index (Table 6). The results also showed that iron nanoparticles 20-30, 50-60, and 80-100 nm had a more positive effect on the harvest index in well-watered environment. Under water deficit environments, all fertilizer treatments were more effective than non-fertilizer treatments. However, the difference between different fertilizer concentrations was insignificant regarding the effect on the harvest index.

3.3. Oil percentage and yield

The highest oil percentage and yield in the first year were 29.90% and 534.3 kg ha, respectively, higher than the second year (Fig. 3). The oil percentage and yield in the well-watered environment were 31.53% and 708 kg ha^{-1}, respectively, higher than the water deficit environment with 27.40% and 321 kg ha^{-1}. In the well-watered environment, the highest oil percentage and yield in the foliar application of iron nanoparticles 20-30 nm 600 mg l^{-1} with 25.35% and 866 kg ha^{-1}, respectively, and the lowest oil percentage and yield in these conditions were seen in the control treatment with 28.67% and 583.4 kg ha^{-1}, respectively (Fig. 3).

In a water deficit environment, foliar spraying of zinc nanoparticles 40-60 nm 300 mg l^{-1} and zinc nanoparticles 10-30 nm 300 mg l^{-1} showed the highest oil percentage and yield, with 29.38 % and 394.6 kg ha^{-1}, respectively. Moreover, the control treatment had the lowest oil percentage and yield under these conditions, with 25.21% and 256.4 kg ha^{-1}, respectively (Table 3). According to the results obtained in optimal irrigation environment, iron nanoparticles of 20-30 and 50-60 nm 600 mg l^{-1} and zinc nanoparticles of 10-30 and 60-40 nm of 300 mg l^{-1} compared to other fertilizer treatments and control significantly increased oil percentage and yield. After that, iron and zinc nanoparticles in all sizes had higher efficiency. In the water deficit environment, zinc nanoparticles of 10-30, 40-60, and 80-100 fertilizers with a concentration of 300 mg l^{-1} and iron nanoparticles 20-30 nm 300 mg l^{-1} performed better than other fertilizers and control treatments. However, there was no significant difference between them. They were only significantly better than the control treatment (Table 3).

Table 3. Means comparison of three-way interaction of moisture regime×fertilization concentration×fertilization on yield and its related agronomic traits in flaxseed

Water regime	Fertilizer (mg l^{-1})	Fertilizer	Biomass yield (kg ha^{-1})	Grain yield (kg ha^{-1})	1000-grain weight (g)	No. grain capsule^{-1}	Plant height (cm)	No sub-branch	No. Empty capsule plant^{-1}	Oil percentage (%)	Oil yield (kg ha^{-1})
Well-watered	300	Control	7599	2028	5.071	6.082	59.71	6.667	1.267	28.67	583
		Fe bulk	7849	2100	5.107	6.299	61.16	6.767	1.183	29.88	629
		Fe 0-100 nm	7888	2160	5.142	6.377	62.26	6.833	1.150	30.38	658
		Fe 20-30 nm	8199	2339	5.256	6.874	64.69	7.100	1.000	33.50	786
		Fe 50-60 nm	8072	2279	5.220	6.760	63.89	7.000	1.050	32.54	744
		Fe 80-100 nm	7980	2216	5.160	6.566	61.60	6.867	1.150	31.21	695
		Zn bulk	8000	2181	5.144	6.430	64.19	6.817	1.133	30.38	662
		Zn 0-100 nm	8110	2249	5.187	6.632	64.97	6.883	1.067	31.46	711
		Zn 10-30 nm	8432	2401	5.307	6.940	67.86	7.183	0.950	33.96	817
		Zn 40-60 nm	8333	2339	5.262	6.887	66.83	7.067	1.000	32.88	771
		Zn 80-100 nm	8208	2269	5.230	6.753	65.95	6.950	1.100	32.67	753
	600	Control	7735	2105	5.079	6.141	60.14	6.750	1.267	29.99	632
		Fe bulk	7956	2198	5.151	6.427	62.60	6.850	1.150	31.42	694
		Fe 0-100 nm	8082	2254	5.192	6.552	63.67	6.917	1.117	32.25	730
		Fe 20-30 nm	8405	2448	5.325	6.984	66.67	7.250	0.917	35.25	866
		Fe 50-60 nm	8240	2377	5.281	6.876	65.74	7.167	1.000	34.04	813
		Fe 80-100 nm	8139	2305	5.210	6.648	64.97	7.017	1.067	32.42	751
		Zn bulk	7940	2213	5.120	6.380	62.42	6.867	1.200	30.63	679
		Zn 0-100 nm	7895	2181	5.102	6.342	61.82	6.833	1.167	30.38	664
		Zn 10-30 nm	7696	2136	5.087	6.224	60.22	6.767	1.183	29.92	643
		Zn 40-60 nm	7729	2140	5.088	6.275	60.49	6.783	1.150	29.83	640
		Zn 80-100 nm	8012	2161	5.115	6.389	62.71	6.833	1.167	30.17	655
Water deficit	300	Control	4751	997	4.673	4.788	55.46	6.000	2.233	25.21	256
		Fe bulk	4893	1082	4.719	4.916	56.96	6.000	2.067	26.67	291
		Fe 0-100 nm	5093	1121	5.701	4.996	57.93	6.100	1.983	26.67	301
		Fe 20-30 nm	5480	1272	4.838	5.258	60.74	6.167	1.800	28.29	361
		Fe 50-60 nm	5335	1218	4.787	5.110	59.01	6.333	1.883	27.79	341
		Fe 80-100 nm	5207	1177	4.778	5.080	58.57	6.233	1.967	26.75	317
		Zn bulk	5182	1150	4.758	5.011	58.26	6.133	2.033	26.92	306
		Zn 0-100 nm	5344	1219	4.768	5.069	60.21	6.117	1.917	28.75	354
		Zn 10-30 nm	5789	1345	4.871	5.356	62.73	6.200	1.717	29.17	395
		Zn 40-60 nm	5541	1302	4.848	5.251	61.22	6.400	1.800	29.38	385
		Zn 80-100 nm	5511	1236	4.827	5.084	59.49	6.333	1.900	28.46	354
	600	Control	4899	1036	4.682	4.808	55.06	6.300	2.217	26.96	381
		Fe bulk	5422	1244	4.786	5.285	56.95	6.033	2.033	28.08	351
		Fe 0-100 nm	5214	1149	4.715	4.969	56.68	6.233	2.117	27.83	323
		Fe 20-30 nm	5191	1119	4.720	4.921	57.09	6.133	2.200	26.92	303
		Fe 50-60 nm	5179	1165	4.755	4.983	56.09	6.117	2.200	27.58	324
		Fe 80-100 nm	5327	1199	4.767	5.132	56.63	6.183	2.117	27.50	331
		Zn bulk	5362	1191	4.764	4.955	56.89	6.217	2.183	27.33	326
		Zn 0-100 nm	5110	1128	4.698	4.860	54.67	6.117	2.217	27.29	309
		Zn 10-30 nm	4748	1004	4.638	4.696	52.35	6.000	2.283	26.00	260
		Zn 40-60 nm	4882	1061	4.678	4.786	53.37	6.083	2.283	26.75	286
		Zn 80-100 nm	5099	1122	4.708	4.885	55.82	6.150	2.183	27.25	310
LSD 0.05			245	77.94	0.058	0.574	1.416	0.104	0.103	2.80	60.49

In each column, significant differences exist between averages with a difference greater than the LSD number at a five percent probability level.

3.4. 1000-grain weight

The highest 1000-grain weight was observed in the well-watered environment in the first year (5.199 g), and the lowest 1000-grain weight was observed in the treatment of water deficit in the second year (4.708 g) (Table 6). In well-watered environment, the highest and lowest 1000-grain weights were seen in the foliar application of iron nanoparticle 20-30 nm with 600 mg l^{-1} and the control treatment (non-application of fertilizer) with 5.325 and 5.071 g, respectively. In water deficit environment, the highest and the lowest 1000-grain weight were obtained in foliar spraying treatment of nanoparticle 30-10 nm with 300 mg l^{-1} and nanoparticle 30-10 nm with 600 mg l^{-1}, respectively, with 4.871 and 4.638 g (Table 3). In well-watered environment, zinc nanoparticles 30-30 and 40-60 nm 300 mg l^{-1} and iron nanoparticles 20-30 and 50-60 nm 600 mg l^{-1} caused a significant increase in the 1000-grain weight compared to other fertilizers and the control treatments. In water deficit environment, zinc nanoparticle fertilizers with different particle sizes at a concentration of 300 mg l^{-1} and then iron nanoparticle fertilizers with different particle sizes at a concentration of 300 mg l^{-1} caused a more significant increase in the weight of 1000-grain weight, but at a concentration of 600 mg l^{-1} did not have a significant effect on 1000-grain weight compared to the control treatment. 1000-grain weight is a trait related to the cultivar and is strongly influenced by genetic factors. However, its amount is also affected by the conditions of the grain growth period. These conditions may cause changes between 20 and 30% in 1000-grain weight (Table 3).

3.5. Number of capsule plant^{-1}

The highest number of capsules plant^{-1} was obtained in the first year in the water deficit environment (18.69 numbers), and the lowest number of capsules plant^{-1} was obtained in the second year under post-anthesis water deficit (12.04 numbers) (Table 6). Also, the highest and the lowest number of capsules plant^{-1} in the treatment of nanoparticle fertilizers 30-10 nm with 300 mg l^{-1} and in the control treatment (no fertilizer application) were 15.84 and 14.94, respectively (Table 4). The obtained results showed that in the well-watered environment, iron and zinc nanoparticle fertilizers with different particle sizes in both concentrations of 300 and 600 mg l^{-1} caused the production and maintenance of capsules plant^{-1} compared to the other fertilizer treatments and the control treatment. Under water water-deficit environment, iron and zinc nanoparticle fertilizers with different particle sizes at a concentration of 300 mg l^{-1} caused more capsule plant^{-1} (Table 3; Fig. 4).

Table 4. Means comparison of two-way interaction of fertilization concentration × fertilizers on the harvest index, the no. capsule plant^{-1}, the no. grain plant^{-1} and the no. primary branches in flax.

Fertilizer concentration (mg l^{-1})	Fertilizers	Harvest index (%)	No. capsule plant^{-1}	No. grain plant^{-1}	No. primary branch
300	Control	23.85	14.94	81.82	2.392
	Fe bulk	24.51	15.22	86.55	2.383
	Fe 0-100 nm	24.78	15.35	88.87	2.425
	Fe 20-30 nm	25.87	15.52	95.81	2.475
	Fe 50-60 nm	25.55	15.52	93.51	2.475
	Fe 80-100 nm	25.19	15.44	90.98	2.425
	Zn bulk	24.70	15.28	88.94	2.417
	Zn 0-100 nm	25.25	15.53	92.81	2.442
	Zn 10-30 nm	25.85	15.84	99.29	2.542
	Zn 40-60 nm	25.43	15.72	97.05	2.508
	Zn 80-100 nm	25.18	15.60	94.07	2.458
600	Control	24.14	15.17	85.24	2.400
	Fe bulk	25.22	15.57	92.86	2.457
	Fe 0-100 nm	24.92	15.51	91.95	2.483
	Fe 20-30 nm	25.50	15.57	96.24	2.475
	Fe 50-60 nm	25.65	15.56	95.47	2.458
	Fe 80-100 nm	25.60	15.51	93.83	2.483
	Zn bulk	24.97	15.69	91.18	2.433
	Zn 0-100 nm	24.85	15.38	88.63	2.408
	Zn 10-30 nm	24.34	15.14	85.28	2.383
	Zn 40-60 nm	24.71	15.20	86.55	2.408
	Zn 80-100 nm	24.57	15.52	89.48	2.433
LSD 0.05		0.648	0.275	2.437	0.031

In each column, significant differences exist between averages with a difference greater than the LSD number at a five percent probability level.

Table 5. Mean comparison of two-way interaction of moisture regimes × fertilizers on the harvest index and the no. grain plant^{-1} in flaxseed.

Moisture regimes	Fertilizer treatment	Harvest index (%)	No. grain plant^{-1}
Well-watered	Control	26.92	111
	Fe bulk	27.28	117
	Fe 0-100 nm	27.61	119
	Fe 20-30 nm	28.98	129
	Fe 50-60 nm	28.54	126
	Fe 80-100 nm	28.24	121
	Zn bulk	27.46	118
	Zn 0-100 nm	27.65	120
	Zn 10-30 nm	28.11	122
	Zn 40-60 nm	27.88	121
	Zn 80-100 nm	27.57	121
Water deficit	Control	21.07	56.53
	Fe bulk	22.45	62.76
	Fe 0-100 nm	22.09	61.42
	Fe 20-30 nm	22.40	63.44
	Fe 50-60 nm	22.66	62.99
	Fe 80-100 nm	22.55	63.51
	Zn bulk	22.21	62.17
	Zn 0-100 nm	22.45	61.78
	Zn 10-30 nm	22.08	62.99
	Zn 40-60 nm	22.27	62.97
	Zn 80-100 nm	22.18	63.02
LSD 0.05		0.648	2.437

In each column, significant differences exist between averages with a difference greater than the LSD number at a five percent probability level.

Table 6. Means comparison of two-way interaction of year×moisture regimes on the harvest index and some other agronomic traits related to yield in flaxseed.

Year	Moisture regimes	Harvest index (%)	1000-grain weight (g)	No of Capsule plant^{-1}	No of grain capsule^{-1}	Plant height	No of primary branch	No of empty capsule plant^{-1}
2019-2020	Well watered	28.22	5.199	18.69	6.603	63.33	2.794	1.095
	Water deficit	22.90	4.790	12.83	5.030	57.75	2.123	2.018
2020-2021	Well watered	27.46	5.150	18.21	6.474	63.45	2.818	1.121
	Water deficit	21.54	4.708	12.04	4.988	57.00	2.044	2.103
LSD 0.05		0.276	0.017	0.117	0.173	0.427	0.0133	0.031

In each column, significant differences exist between averages with a difference greater than the LSD number at a five percent probability level.

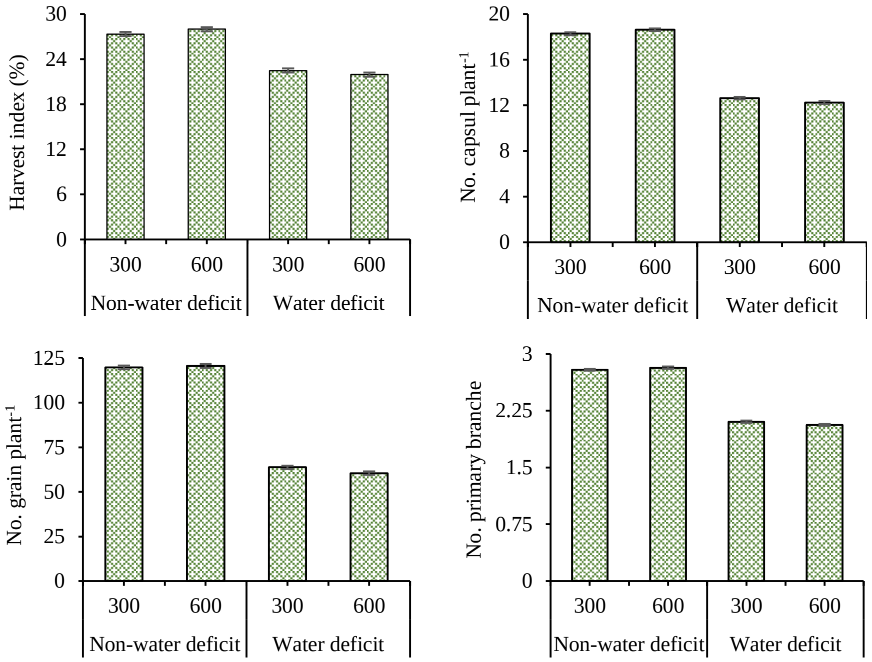


Figure 4. Means comparison of two-way interaction of moisture regimes×fertilizer concentration on the harvest index, the no. capsule plant^{-1}, the no. grain plant^{-1} and the no. primary branches in flaxseed. The bars indicate the LSD number at a five percent probability level.

3.6. Number of grains plant^{-1}

The highest and lowest numbers of grain plant^{-1} were obtained in well-watered environment and fertilizers with 600 mg l^{-1} (120.7) and water deficit environment and fertilizers with 600 mg l^{-1} (60.52), respectively (Table 5; Fig. 4). Also, the highest and lowest number of grains plant^{-1} were observed in iron nanoparticles 20-30 nm and the well-watered environment (128.6) and no fertilizer application in the water-deficit environment (56.53), respectively (Table 4). The results of mean comparisons showed that the foliar application of fertilizer on nanoparticles of 30-10 nm and 300 mg l^{-1} and the control treatment had the highest and lowest number of grain plant^{-1} with 99.29 and 82.81, respectively (Table 3). Also, the results showed that in the environment of well-watered, iron nanoparticles of 20-30, 50-60, and 80-100 nm and after them, zinc nanoparticles of 10-30, 60-40, and 80-100 nm had more positive effect on the number of grain plant^{-1} than non-fertilizer application treatment. Under water deficit environment, different concentrations of fertilizer were better than the control treatment. However, the difference between different fertilizer concentrations was insignificant in increasing the number of grains plant^{-1}.

3.7. Number of grain capsule^{-1}

The highest and lowest number of grains in the capsule were obtained in the first year and the treatment of well-watered (6.603) and the second year and the water deficit treatment (4.988), respectively (Table 6). In the well-watered environment, the highest and lowest number of grains in the capsule was in the treatment of iron nanoparticles 20-30 nm and 600 mg l^{-1} and the control treatment (6.984 and 6.082, respectively) and in the water deficit environment, the highest and lowest number of grain in the capsule was in the treatment of zinc nanoparticles 10-30 nm and 300 mg l^{-1} and zinc nanoparticle 10-30 nm and 600 mg l^{-1} (5.356 and 4.696, respectively) respectively (Table 3). Based on the results, in water deficit environment, iron nanoparticle fertilizers of 20-30, 50-60, and 80-100 nm in both concentrations of 300 and 600 mg l^{-1} and zinc nanoparticle fertilizers of 10-30, 40-60 and 80-100 nm and 300 mg l^{-1} had a higher positive effect on the number of grain in the capsule (Table 3).

3.8. Number of empty capsules

In the well-watered environment, the highest and lowest number of empty capsules were observed in the control condition (non-application of fertilizers) and the foliar application of iron nanoparticles 20-30 nm iron with 600 mg l^{-1} (1.267 and 0.917, respectively), and in the water deficit environment, the highest and lowest number of empty capsules was obtained in the foliar application of zinc nanoparticles 40-60 nm with 600 mg l^{-1} and zinc nanoparticles 10-30 nm with 300 mg l^{-1} (2.283 and 1.717 respectively) (Table 3). Based on the results obtained, in the well-watered environment, iron nanoparticles of 20-30 and 50-60 nm with 600 mg l^{-1} and zinc nanoparticles of 30-10 and 60-40 nm with 300 mg l^{-1} cause a significant reduction in the number of empty capsules plant^{-1} compared to other fertilizer treatments and the control. In the water deficit environment, zinc nanoparticles 10-30 and 40-60 nm with 300 mg l^{-1} and iron nanoparticles 20-30 and 50-60 nm with 300 mg l^{-1}, the number of empty capsule plant^{-1} is less than other fertilizers and control treatment. Based on the results obtained, in the well-watered environment, iron nanoparticles of 20-30 and 50-60 nm with 600 mg l^{-1} and zinc nanoparticles of 10-30 and 40-60 nm with 300 mg l^{-1} cause a significant reduction in the number of empty capsules plant^{-1} compared to other fertilizer treatments and the control. In the water deficit environment, zinc nanoparticles 10-30 and 40-60 nm with 300 mg l^{-1} and iron nanoparticles 20-30 and 50-60 nm with 300 mg l^{-1}, the number of empty capsule plant^{-1} is less than other fertilizer and control treatment. However, at a fertilizer concentration of 600 mg l^{-1}, bulk iron fertilizer had a more significant effect on the empty capsule plant^{-1} than other fertilizer treatments and the control (Table 3).

3.9. Plant height

The highest plant height was obtained in the second year in the well-watered environment (63.45 cm), and the lowest plant height was obtained in the second year in the water-deficit environment (57 cm) (Table 6). In the post-anthesis water deficit, the maximum and minimum plant height was seen in the foliar application of iron nanoparticles 20-30 nm and 300 mg l^{-1} as 67.86 and 59.71 cm, respectively. In water deficit environment, the minimum and maximum plant height in the foliar spraying treatments of zinc nanoparticle fertilizer 40-60 nm and 300 mg l^{-1} and zinc nanoparticle fertilizer 30-30 nm and 600 mg l^{-1} were 61.22 cm (Table 3).

In the well-watered environment, zinc nanoparticles 10-30 and 40-60 nm 300 mg l^{-1} and iron nanoparticles 20-30 and 50-60 nm 600 mg l^{-1} caused a more significant increase in plant height than other fertilizer treatments and controls. Under water deficit environment, zinc nanoparticles of 10-30 and 40-60 nm 300 mg l^{-1} and iron nanoparticles of 20-30 and 50-60 nm 300 mg l^{-1} had higher plant height than other fertilizer treatments and controls. In these conditions, bulk iron and zinc fertilizers with a concentration of 600 mg l^{-1} caused a higher plant height than other fertilizer treatments and the control (Table 3).

3.10. Number of primary branches

The highest number of primary branches was obtained in the second year in the well-watered environment (2.818), and the lowest number of primary branches was obtained in the second year and the water deficit environment (2.044) (Table 6). The number of primary branches in the well-watered environment and fertilizer concentration of 600 mg l^{-1} (2.820 numbers) was the highest, and this trait in the water deficit environment with fertilizer concentration of 600 mg l^{-1} (2.061 numbers) was the lowest value (Fig. 4). The highest number of primary branches were obtained in the foliar application iron nanoparticles 20-30 nm and 300 mg l^{-1} (2.542) and the lowest number of primary branches were obtained in foliar treatment bulk iron fertilizer and 300 mg l^{-1} and zinc nanoparticle fertilizer 10-30 nm and 600 mg l^{-1} (2.383) (Table 4).

According to the obtained results, in the well-watered environment, iron nanoparticle fertilizers in both concentrations of 300 and 600 mg l^{-1} and zinc nanoparticle fertilizers in a concentration of 300 mg l^{-1} had more suitable conditions in terms of the number of primary branches, and in water deficit environment, iron and zinc nano-particle fertilizers worked better at a concentration of 3 parts per thousand. In terms of stimulating the production of the primary branch under water water-deficit environment, nanoparticles from iron and zinc fertilizers at a concentration of 300 mg l^{-1} had a more positive effect than other fertilizer treatments (Table 3).

3.11. Number of sub-branches

The number of sub-branches in the first year (6.60) was significantly higher than in the second year (Fig. 3), and in the well-watered environment (6.92 numbers) was significantly higher than the water deficit environment (6.17 numbers) (Table 6). In the environment of well-watered, the application of iron nanoparticles with a size of 20-30 nm and a concentration of 600 mg l^{-1} resulted in the highest number of sub-branches (7.250), while the control treatment had the lowest number of sub-branches (6.667). In the water deficit environment, the highest number of sub-branches in the treatment of foliar spraying of zinc nanoparticles 30-10 nm with a concentration of 300 mg l^{-1} (6.400), and the lowest number of sub-branches in this condition was in the control treatment, and the foliar spraying treatment of nanoparticles 10-30 nm belonged to a concentration of 600 mg l^{-1} (6 numbers) (Table 2). In the well-watered environment, iron nanoparticles 20-30 and 50-60 nm in both concentrations of 300 and 600 mg l^{-1} and zinc nanoparticles 10-30 and 40-60 in a concentration of 300 mg l^{-1} and then iron and zinc nanoparticles with a size particle of 80-100 nm had a higher positive effect on the number of sub-branches. In the water deficit environment, zinc nanoparticles of 10-30 and 40-60 nm with a concentration of 300 mg l^{-1} and iron nanoparticles of 20-30 and 50-60 nm with a concentration of 300 mg l^{-1} had a higher number of sub-branches than other fertilizer treatments and control treatment (Table 3).

3.12. Correlation between yield and its related traits

The study found that grain yield has a positive and significant correlation at P≤0.01 with biological yield (r^2=0.988**), harvest index (r^2=0.959**), thousand seed weight (r^2=0.955**), number of capsules plant^{-1} (r^2=0.981**), number of grain plant^{-1} (r^2=0.993**), number of grain capsule^{-1} (r^2=0.981**), number of primary branches (r^2=0.980**), number of sub-branches (r^2=0.972**), oil percentage (r^2=0.718**), and oil yield (r^2=0.973**). This result was the same for the biomass yield, and only the trait of empty capsule plant^{-1} showed a negative and significant correlation with the grain yield (r^2=-0.957**) (Table 7).

Table 7. Correlation coefficient between yield and its related traits in flaxseed under moisture regimes and foliar application of iron and zinc nanoparticles with different particle sizes in two crop years, 2019-2020 and 2020-20212.

Traits	GY	BY	PH	HI	1000 GW	CP	GP	GC	PB	SB	EP	OP	OY
GY	1												
BY	0.988**	1											
PH	0.680**	0.725**	1										
HI	0.959**	0.914**	0.550**	1									
1000 GW	0.955**	0.925**	0.726*	0.904**	1								
CP	0.981**	0.980**	0.686*	0.904**	0.942**	1							
GP	0.993**	0.987**	0.696**	0.941**	0.958**	0.948**	1						
GC	0.981**	0.968**	0.682**	0.937**	0.957**	0.948**	0.983**	1					
PB	0.980**	0.975**	0.673**	0.928**	0.952**	0.979**	0.982**	0.953**	1				
SB	0.972**	0.961**	0.736**	0.930**	0.946**	0.944**	0.967**	0.966**	0.940**	1			
EP	-0.957**	-0.931**	-0.637**	-0.937**	-0.933**	-0.933**	0.946**	-0.947**	-0.956**	-0.919**	1		
OP	0.718**	0.731**	0.681**	0.642**	0.977**	0.686**	0.742^{ns}	0.736*	0.677**	0.784**	-0.616**	1	
OY	0.973**	0.966**	0.723**	0.917**	0.958**	0.946**	0.974**	0.969**	0.944**	0.975**	-0.910**	0.862**	1

^{Ns}, *, and ** are non-significant and significant at the probability level 0.05 (P≤0.01) and 0.01, respectively. GY: the grain yield, BY: the biological yield, PH: the plant height, HI: the harvest index, 1000GW: 1000-the grain weight, CP: the number of capsules plant^{-1}, GP: the number of grain plant-1, GC: the number grain capsule-1, PB: the number of primary branches, SB: the number of sub-branche, EP: the number of empty capsules, OP: the oil percentage, OY: the oil yield

The results of this two-year study showed that the late season water deficit significantly reduced the grain yield, oil yield and percentage, biomass yield, number of grains in plant^{-1}, 1000-grain weight, number of primary branches and sub-branches in plant^{-1}, harvest index, and plant height of flax (Table 3; Fig. 3). According to this research, post-anthesis water deficit stress significantly reduced grain and biomass yield by 48% and 35%, respectively, compared to non-stress conditions. The negative effect of water deficit on grain yield can attributed to the reduction of leaf area index and its durability, the rate of photosynthesis, and, as a result, the reduction of crop growth in this condition (Tardieu, 2013; Sah *et al.*, 2020). Regarding this matter, Laei et al. (2019) research has revealed that stopping irrigation at the time of 50% flowering in sesame plants resulted in a significant reduction of some physiological traits, including photosynthetic pigments and, consequently photosynthesis, which resulted in a decrease in grain yield. Applying iron and zinc micronutrients in well-watered and late-season water deficit environments caused a significant increase in grain yield compared to non-application of iron and zinc micronutrients. So, iron and zinc fertilizer treatments reduced the harmful effects of water deficit on grain yield and biomass (Azhand *et al.*, 2023). Metal ions such as iron and zinc participate as cofactors in the structure of many antioxidant enzymes. The results of the studies indicate that under micronutrient deficiency, the activity of antioxidant enzymes decreases. Therefore, the resistance of plants to environmental stresses increases. In this condition, the plant's yield increases compared to when fertilizer treatment is not applied (Mahmood *et al.*, 2019).

In general, nanoparticle-based iron and zinc fertilizers are more effective than bulk iron and zinc fertilizers and control (non-application of fertilizer) treatments. In a well-watered environment, they increase grain and biomass yield. Moreover, in water deficit environment, they help prevent the reduction of grain and biomass yield. Most farmers use excessive amounts of bulk fertilizers to increase crop yield. This procedure leads to the pollution of agricultural soils, damage to the physical, chemical, and biological properties of the soil, contamination of agricultural products, and underground water. The efficiency of using bulk fertilizers in crops is between 30 and 35% due to the loss of these fertilizers through washing, evaporation, and stabilization (Mahmud *et al.*, 2021). Due to the characteristics of nanoparticle fertilizers, extensive research is being done on the efficiency of these fertilizers worldwide (Hu and Xianyu, 2021; Kah *et al.*, 2018; Kumar *et al.*, 2021). In this regard, Kumar et al. (2021) announced that the absorption efficiency of zinc and urea nanoparticle fertilizers is about 80% higher compared to their bulk form and, in agreement with the results of this research, reported that zinc nanoparticle fertilizer is more effective in increasing yield compared to bulk forms of these fertilizers. Also, Baghai and Maleki-Farahani (2013) conducted a study that demonstrated the effectiveness of iron nano fertilizer in increasing the yield of saffron. They found that applying iron nano fertilizer resulted in a significant increase in yield compared to bulk iron fertilizer and no fertilization. The researchers attributed this to the improved production of photosynthetic materials, which led to more leaves and the optimal transfer of these materials to the reservoirs. The study highlights the potential benefits of using nano iron fertilizer to improve crop production.

According to the relationship between grain yield and harvest index, the water deficit causes a sharper decrease in grain yield compared to biomass yield and, as a result, a significant decrease in harvest index. Providing enough nutrients along with irrigation during the grain-filling period increases the rate of photosynthesis and then increases the length of the reproductive stage and the effective period of grain-filling, ultimately increasing seed weight and yield. An increase in grain yield can also lead to an increase in the harvest index (Melki *et al.*, 2022). As mentioned, water deficit stress reduced the harvest index, while foliar application of nano fertilizers improved it. Applying nano-fertilizers affects the harvest index by influencing the grain yield and biological yield. It seems that the treatment of iron and zinc nano-particle fertilizers in this research increases the harvest index by increasing the grain yield more than the biological yield.

The reduction in the flaxseed plant height caused by the water deficit (Table 3) according to the report by Pholo et al. (2018), may be due to a significant reduction in relative turgor and dehydration of the protoplasm, which is associated with a reduction in photosynthesis and the production of photosynthetic substances, cell growth and cell division. In this relation, Guardiola-Márquez et al. (2023) reported that zinc and iron nanoparticles treatments improved plant height of corn significantly ($p<0.05$) by 28.03-44.66% and 24.15-36.06%, respectively, compared to untreated plants.

The 1000-grain weight is a varietal characteristic and is strongly influenced by genetic factors, but its amount is also affected by the conditions of the ripening period. These conditions may cause changes between 20 and 30% in the weight of one thousand seeds (Schierenbeck *et al.*, 2021). The means comparison regarding the use of nano-fertilizers showed that use of iron and zinc nanoparticles in comparison with bulk forms of fertilizers and control treatment increased the 1000-grain weight in both irrigation conditions and nano fertilizers were more effective. The effect of zinc and iron fertilizers, especially in nanoparticle form, on the 1000-grain weight can be due to the participation of these two types of fertilizers in increasing enzyme activity, improving membrane structure, chlorophyll formation, nitrogen metabolism, stomatal regulation, and ultimately increasing seed storage (Hera *et al.*, 2018).

As mentioned, iron and zinc nanoparticle fertilizers with different particle sizes caused a significant increase in the number of capsules per plant under water deficit environment and lack of stress compared to other bulk iron and zinc fertilizer treatments and the control treatment. Fertilization using iron and zinc microelements causes an increase in the number of flowers, followed by an increase in the number of fruits, and finally, an increase in crop yield (Fahad *et al.*, 2014). In agreement with the findings of this research, Waqas Mazhar et al. (2022) found that the application of iron nanoparticle fertilizer caused a significant increase in the number of capsules plant^{-1}.

In the present study, in the absence of water stress, fertilizer treatments (especially nanoparticle fertilizers) caused a significant increase in the number of seeds in the capsule. However, under water deficit stress environments, no significant difference was observed between the different fertilizer treatments and the control treatment (non-application of fertilizers) regarding the effect on the number of seeds in the capsule. Compared to other yield components, the number of grains in the capsule seems less sensitive to drought stress. In this regard, Rahimi et al. (2020) found that oilseed flaxseed plants subjected to supplementary irrigation once or twice significantly increased grain yield and oil percentage by 50 and 30% and 51 and 35%, respectively. Furthermore, the number of grains in the capsule increased to 24 and 34%.

According to available scientific reports, the flaxseed plant produces between one and five tillers (Mirshekari *et al.*, 2012; Kariuki *et al.*, 2016). Water deficit significantly decreased the number of primary branches plant^{-1}. In this research, fertilizers caused significant increase in the number of tillers plant^{-1}. Pandao et al. (2021) also reported that using foliar spraying by zinc oxide nanoparticles 1 and 2 g l^{-1} in flaxseed plants caused significant increase in the number of primary and sub-branches plant^{-1} (without fertilization).

Post-anthesis water deficit reduced oil yield more (55%) than biomass yield (35%) and seed yield (48%). Therefore, it seems that the sensitivity of oil production to water deficit stress is higher than biomass and grain yield. The application of water deficit during the grain growth stage hurts oil production due to its adverse effect on the destruction of seed metabolic processes, disturbance in the transfer of photosynthetic materials to grains, and possibly the production of undesirable secondary compounds. The oil content of soybean seeds under water deficit was significantly reduced, which can be attributed to the high sensitivity of lipid accumulation to water deficit in the grain filling stage, the reduction of current photosynthesis, and the reduction of photosynthetic materials supplied for filling. It also mentioned reducing the seed-filling period (Bellaloui *et al.*, 2013).

4. Conclusion

The findings from these studies suggest that, in well-watered, the biological, seed, and oil yields were 8023, 2232, and 708 kg ha^{-1}, respectively. Post-anthesis water deficit caused their reduction by 35, 48, and 55%, respectively. Concerning these results, the sensitivity of oil yield in flaxseed to drought stress after flowering is higher than that of biomass and seed yield. Applying foliar spraying treatments of fertilizers, especially iron and zinc nanoparticle fertilizers in different concentrations, reduced the adverse effects of water deficit and increased grain, oil, and biomass yields compared to not applying them in these conditions. In general, the nanoparticle form of fertilizers was more efficient than their bulk form in well-watered and water-deficit environments in increasing seed and oil yield. In well-watered environment, iron nanoparticles 20-30 nm 600 mg l^{-1} and post-anthesis water-deficit environment, zinc nanoparticles 10-30 nm 300 mg l^{-1} were the best treatments in increasing the grain, biomass, and oil yield.

Conflict of interests

The authors declare no conflicts of interest.

Ethics approval and consent to participate

No human or animals were used in the present research.

Consent for publications

All the authors have approved the manuscript and agree with the submission.

Availability of data and material

All the data are embedded in the manuscript.

Authors' contributions

Mohammad Naseh Hoseini: Investigation, Farm work and data collection. Mohsen Saeidi: Project administration, Methodology, Writing - review & editing, Supervision. Leila Zarei: Consultation at different stages of implementation of the project.

Informed consent

The authors declare not to use any patients in this research.

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