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EFFECTS OF SILICON AND ZINC SOURCES ON QUANTITATIVE AND QUALITATIVE CHARACTERISTICS OF CANOLA AT NORMAL AND LATE PLANTING DATES

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ABSTRACT

In order to study the effects of silicon (Si) and zinc (Zn) sources on yield components, seed yield, seed oil content and nutrient concentrations in canola grain at normal and late planting dates, a field experiment was conducted as a split plot-factorial in a randomized complete block design with three replications at Ghaemshahr Agricultural Research Station during the 2017-2018 and 2018-2019 growing seasons. Planting dates as the main plot at two levels (normal planting date, late planting date), silicon fertilizer sources at three levels (control, calcium silicate, nano-Si) and zinc fertilizer sources at three levels (control, zinc sulfate, nano-Zn) were considered as sub-plots. The results showed that all the agronomical and physiological traits studied improved in the normal planting date, while delay in planting date led to a significant reduction in the traits. Application of Si and Zn by both nanoparticles (NPs) and conventional forms significantly increased the yield components, seed yield, seed oil content and nutrient uptake in grain compared to the control plants. There was no significant difference between application of nano-Si and calcium silicate in terms of rapeseed yield and quality. The nano-Zn treated plants showed both higher seed yield and higher nutrient uptake, when compared to zinc sulfate treated plants. The combined application of Si with Zn, especially in the form of nanoparticles resulted in higher seed oil content than the application of Si or Zn alone. In general, the application of Si and Zn in the form of nanoparticles at normal planting date is a promising option to increasing seed yield and improving nutrient uptake in rapeseed.

Keywords: nanoparticles, nutrient concentration, oil content, planting date, canola seed yield.

INTRODUCTION

Canola or oilseed rape (*Brassica napus* L.) is one of the most important oil crops in the world, which was cultivated in more than 34.7 million hectares worldwide in 2017 (FAO, 2017). Planting date is one of the environmental factors that affect the growth and development as well as the productive performance of canola (Confortin et al., 2019). The determination of the suitable planting date in each region is essential to achieve maximum grain and biological yields of crops. Selecting the appropriate planting date to reduce the negative impacts of environmental factors on different stages of vegetative and reproductive growth of plants is very effective (Shafighi et al., 2021). Delay in planting date reduces the crop quality and yield (Sheikh Big Goharrizi et al., 2016). Delay in rapeseed planting causes the ripening period of the plant to be exposed to high ambient temperatures, which increases the respiration rate of the photosynthetic organs of the plant, resulting in reduced photosynthetic material storage and grain weight, and ultimately reduced crop yield (Coffelt and Adamsen, 2005). The results of other studies also indicate that delay in sowing date reduces characteristics such as days to flowering, flowering period and seed yield in canola (Faraji, 2010).

Silicon and zinc are known to be beneficial elements for increasing plant growth (Kheyri et al., 2019a). Silicon is the second most abundant element in soil, which is considered as a useful element for higher plants (Nakata et al., 2008). Silicon in oilseeds stimulates antioxidant defense and reduces lipid peroxidation (Liang, 2008). Hashemi et al. (2010) reported that the silicon nutrition in canola, increased plant

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growth parameters and decreased lipid peroxidation. Sharifi (2017) stated that the application of silicon (1.5 mM), significantly increased the various agronomic and physiological traits of canola including plant height, number of seeds per silique, 1000-seed weight, chlorophyll a and b content, and seed and biological yields. Bybordi (2016) found that by increasing the amount of silicon consumption from 0 to 4 $g.L^{-1}$, many quantitative and qualitative characteristics of canola such as number of siliques per plant, number of seeds per silique, biological yield, harvest index and seed oil content increased.

Zinc deficiency is one of the most important problems for plants worldwide, especially in countries where the soil has less available to zinc (Alloway, 2008). Zinc is an essential micronutrient that plays an important role in the physiological processes of plants (Qiao et al., 2014). Zinc as a cofactor of antioxidant enzymes such as catalase and peroxidase is very important in plant protection and yield improvement (Samart et al., 2017). Yang et al. (2009) indicated that zinc fertilizer application increased the number of siliques per plant, number of seeds per silique, seed yield and seed oil content in canola. Previous studies have shown that the simultaneous use of zinc and iron by both foliar application and soil application increased seed yield and seed oil content of canola (Bybordi and Memedov, 2010).

Application of nutrients by foliar application method increases yield and reduces the use of chemical fertilizers by soil application method (Bhuyan et al., 2012). Kheyri et al. (2018) reported that the foliar application of nanoparticles is superior to the soil application of elements due to the small diameter of nanoparticles and better uptake of elements by the plant. Silicon nonafertilizers are easily permeable to the leaves and form a thick silicate layer on the leaf surface (Meena et al., 2014). Zinc nanofertilizers also have the potential to increase crop yield and growth (Sabir et al., 2014). Foliar application of nano-Zn significantly improves the seed weight and oil content of rapeseed (Akhavan Hezaveh et al., 2020).

Since silicon and zinc nutrition is very important in plant growth and yield, so the present study aimed to investigate the effects of different sources of silicon and zinc fertilizers on yield components, seed yield, seed oil content and nutrient concentration in rapeseed at normal and late planting dates.

MATERIAL AND METHODS

The field experiment was performed at Ghaemshahr Agricultural Research Station during the 2017-2018 and 2018-2019 growing seasons. The study site was located at 36°28′ N, 56°18′ E, which is 14.7 m above sea level. The soil was classified as a Clay-Loam-textured. The soil physical and chemical analysis was done in a soil science laboratory and is presented in Table 1. The most important characteristics of climate such as temperature, rainfall and relative humidity during 2017-2018 and 2018-2019 growing seasons were presented in Table 2.

Table 1. Physical and chemical properties of the soil (0-30 cm)

Soil texture	EC ($ds.m^{-1}$)	pH	Organic matter (%)	Total soil N (%)	Available P (ppm)	Available K (ppm)
Clay-Loam	0.56	7.5	3.2	0.16	15.7	101

Table 2. Historical monthly in 2017-2018 and 2018-2019 growing seasons climatic data of the experimental area

Month	T mean (°C)		Rainfall (mm)		Humidity (%)	
	2017-2018	2018-2019	2017-2018	2018-2019	2017-2018	2018-2019
23 September - 22 October	19.7	20.5	135.9	129.2	77	76
23 October - 21 November	17.8	15.4	18.1	59.8	78	79
22 November - 21 December	9.7	12.0	82.5	66.3	77	83
22 December - 20 January	9.2	9.3	75.4	112.2	82	78
21 January - 19 February	8.6	9.3	77.4	116.9	83	81
20 February - 20 March	12.9	10.9	18.5	95.7	81	90
21 March - 20 April	14.7	14.1	38.3	82.5	78	83

The experiment was conducted as a split plot-factorial in a randomized complete block design with three replications, each replication consisting of 18 experimental plots. The Hyola 401 cultivar was used in this experiment. Planting dates as the main plot at two levels (normal planting date, late planting date), silicon fertilizer sources at three levels (control or non-use of silicon, calcium silicate, nano-Si) and zinc fertilizer sources at three levels (control or non-use of zinc, zinc sulfate, nano-Zn) were considered as sub-plots.

Each experimental plot consisted of 4 planting rows with a distance of 25 cm between rows and a length of 4 m. The distance between the plants on the rows was 4 cm and the distance between the repetitions was 2 m. According to soil analysis, N, P and K fertilizers rates recommended. Nitrogen fertilizer (urea 150 kg.ha^{-1}; one-third at sowing time, one-third at stem elongation stage and one-third at the beginning of flowering stage) and all required phosphorus (50 kg.ha^{-1} triple superphosphate at sowing time) and potassium fertilizer (100 kg.ha^{-1} potassium sulfate at sowing time) were applied in the two years. For soil application, the calcium silicate and zinc sulfate fertilizers were applied as basal at 200 kg ha^{-1}. For foliar application, the nano-SiO_2 and nano-ZnO at a concentration of 4 per thousand was applied at two plant growth stages (flowering and podding stages) in plots. The characteristics of the nanoparticles used in this research are presented in Table 3.

Table 3. The properties of the nanoparticles used in this study

Nanoparticles	Purity percentage (%)	Particles size (nm)	True density (g cm^{-3})	SSA (g m^{-2})	Color
SiO_2	>99%	20 - 30	2.4	180 - 600	White
ZnO	>99%	10 - 30	5.606	20 - 60	Milky white

To control weeds, Trifluralin (Treflan EC 48%) herbicide was applied at 2.5 L ha^{-1} before canola cultivation in the plot, and the manual weeding was performed as needed during the experiment. At harvest time, after eliminating the marginal effect, 12 plants were randomly selected from middle of each experimental plot and plant height and yield components such as number of siliques per plant, number of seeds per silique and 1000-seed weight were determined. To measuring seed yield, two middle rows from each plot were harvested, then the grains were separated from the siliques and grain weight were calculated with an accurate scale and finally, the seed yield was determined in kg.ha^{-1}. Seed oil content determined using the Soxhlet apparatus. The determination of concentrations of Si and Zn in seed was performed according to the methods described by Fallah et al. (2004) and Emami (1996), respectively. Statistical analysis of data was performed using SAS software. Combined analysis of variance was performed for two years of experiment. Mean values were compared using least significant difference (LSD) test at 5% probability level.

RESULTS AND DISCUSSION

Yield components, seed yield and seed oil content

Based on the results of combined ANOVA for the traits, the effect of year was significant on all the yield components, seed yield and seed oil content. The main effects of PD, SS and ZS were significant on all studied traits except the SS for plant height. The interaction between PD × SS was significant on plant height, number of seeds per silique and 1000-seed weight. The number of siliques per plant and seed yield was affected by the interaction of PD × ZS. Also, the interaction between SS × ZS was significant only on seed oil content (Table 4).

Table 4. Combined analysis of variance for PD, SS and ZS as well as their interactions on yield components, seed yield and seed oil content in canola

Source of variation	df	Plant height	No. siliques per plant	No. seeds per silique	1000-seed weight	Seed yield	Seed oil content
Year (Y)	1	489.38**	60208.33**	2287.12**	11.88**	29152470.05**	22.23**
Replication (Y)	4	264.03	1887.90	18.40	0.36	680680.95	14.94
Planting date (PD)	1	16872.50**	341831.25**	3996.75**	1.57**	7993318.69**	222.45**
Y×PD	1	935.74**	6627.00**	2872.67**	0.04^{ns}	50198.58^{ns}	5.42**
Error	4	56.15	15352.62	55.12	0.27	363028.50	0.74
Silicon sources (SS)	2	23.55^{ns}	10760.14**	60.77**	0.43**	1120805.21**	48.30**
Y×SS	2	95.29*	810.77^{ns}	2.25^{ns}	0.29**	12964.48^{ns}	0.77^{ns}
PD×SS	2	147.54**	416.70^{ns}	47.44**	0.25**	61747.16^{ns}	0.25^{ns}
Y×PD×SS	2	6.06^{ns}	133.77^{ns}	18.92*	0.11*	96708.95^{ns}	0.25^{ns}
Zinc sources (ZS)	2	1646.20**	37592.67**	199.69**	1.45**	3269732.67**	14.89**
Y×ZS	2	7.26^{ns}	6282.02**	27.95**	0.20**	61955.82^{ns}	0.11^{ns}
PD×ZS	2	7.95^{ns}	1412.56*	3.58^{ns}	0.03^{ns}	302680.22**	0.01^{ns}
Y×PD×ZS	2	17.71^{ns}	487.06^{ns}	13.39^{ns}	0.04^{ns}	8730.80^{ns}	0.10^{ns}
SS×ZS	4	1.81^{ns}	245.53^{ns}	8.84^{ns}	0.07^{ns}	23352.71^{ns}	3.50**
Y×SS×ZS	4	19.78^{ns}	90.72^{ns}	9.80^{ns}	0.06^{ns}	114671.08^{ns}	0.06^{ns}
PD×SS×ZS	4	27.85^{ns}	158.09^{ns}	2.23^{ns}	0.04^{ns}	18728.73^{ns}	0.39^{ns}
Y×PD×SS×ZS	4	14.88^{ns}	114.88^{ns}	9.02^{ns}	0.02^{ns}	16300.23^{ns}	0.08^{ns}
Error	64	28.86	348.87	5.19	0.032	50226.13	0.535
CV (%)	-	4.07	8.98	7.35	9.05	7.75	1.56

^{ns}, *, and ** are non-significant and significant at the 5 and 1% probability levels, respectively.

Plant height

The results of this study showed that plant height was higher in the first year (134 cm) than second year (129.8 cm) of the experiment. It seems that better weather conditions in the first year of the experiment led to improved plant growth compared to the second year of the experiment. The highest plant height was obtained in the normal planting date (144.4 cm) and with a delay in planting date, the height decreased by about 17.3% (Table 5). The results showed that the use of both zinc sources was effective in improving plant height. According to the results in this study, application of zinc sulfate and nano-Zn increased the plant height by about 5.9 and 9.7%, respectively, compared with control or non-use of zinc (Table 5). Based on the mean comparison of interaction between PD × SS, the tallest plant height was obtained by application of nano-Si at normal planting date (145.9 cm), although was not significant difference under control or calcium silicate application at normal planting date. The shortest plant height was observed on the late planting date under the treatments of silicon sources (Table 6).

Although the short plant height in canola is considered as a desirable trait, but in a specific genotype, reduction in height due to delay in planting or any other environmental stress such as heat, cold and drought stresses reduces the seed yield (Rameeh, 2016). Tall plants have a greater number of siliques and more leaves and can produce more seeds (Manaf et al., 2019). Delayed planting date reduces the vegetative growth period of the plant and consequently reduces the plant height (Nazeri et al., 2019). Also, the reduction of plant growth directly affects the yield components of the canola, especially the number of siliques per plant (Shirani Rad et al., 2014). Studies by other researchers have also shown an improvement in plant height by the use of silicon fertilizer compared to the non-use of silicon, which is consistent with the results of this experiment (Bybordi, 2016; Sharifi, 2017). Our findings are further strengthened by the findings of Manaf et al. (2019) who reported that zinc application increases growth and yield components of canola compared with control.

Table 5. Mean comparison of main effects of Y, PD, SS and ZS on yield components, seed yield and seed oil content in canola

Experimental treatments	Plant height (cm)	No. siliques per plant	No. seeds per silique	1000-seed weight (g)	Seed yield (kg.ha^{-1})	Seed oil content (%)
Year						
First	134.0a	231a	26b	2.31a	3411a	47.2a
Second	129.8b	184b	35a	1.65b	2372b	46.3b
Planting date						
Normal	144.4a	264a	37a	2.10a	3163a	48.2a
Late	119.4b	151b	25b	1.86b	2619b	45.3b
Silicon sources						
Control	Ns	188b	29b	1.91b	2692b	45.4b
Calcium silicate	Ns	215a	32a	1.92b	2954a	47.4a
Nano-Si	Ns	220a	32a	2.11a	3027a	47.5a
Zinc sources						
Control	124.8c	172c	28c	1.76c	2574c	46.0b
Zinc sulfate	132.7b	214b	33a	2.04b	2925b	47.0a
Nano-Zn	138.2a	236a	31b	2.14a	3174a	47.3a

Means in columns followed by the same letter(s) are not significantly different at $P \leq 0.05$.

Table 6. Mean comparison of interaction between PD × SS on plant height, number of seeds per silique and 1000-seed weight in canola

Planting date	Silicon sources	Plant height (cm)	No. seeds per silique	1000-seed weight (g)
Normal	Control	142.9a	34b	2.00b
	Calcium silicate	144.5a	39a	1.98b
	Nano-Si	145.9a	38a	2.32a
Late	Control	122.5b	24c	1.82b
	Calcium silicate	117.7b	24c	1.87b
	Nano-Si	118.0b	26c	1.89b

Means in columns followed by the same letter(s) are not significantly different at $P \leq 0.05$.

Number of siliques per plant

The number of siliques per plant was higher in the first year than second year by about 20.3%. The number of siliques per plant is one of the main components of yield, which was significantly reduced in delayed planting conditions due to weakening the plant vigor, so that the percentage of reduction in delayed planting was about 42.8% compared with normal planting date (Table 5). Based on the mean comparison of silicon sources, Si application by both nano-Si and calcium silicate increased the number of siliques per plant compared with control by 14.5 and 12.5%, respectively. However, there was no significant difference between the application of calcium silicate and nano-Si in terms of number of siliques per plant (Table 5). The application of both zinc sources was effective in increasing number of siliques per plant. According to the results in this research, application of zinc sulfate and nano-Zn increased the number of siliques per plant compared with control or non-use of zinc by about 19.6 and 27.1%, respectively. However, the Zn application in the form of nanoparticles had better impact than zinc sulfate in terms of number of siliques per plant (Table 5). Based on the mean comparison of interaction between PD × ZS, the highest number of siliques per plant was recorded by application of zinc sulfate (270 siliques) and nano-Zn (299 siliques) at normal planting date, while the lowest number of siliques per plant (123 siliques) was observed under control plant at late planting date. In this study, the application of both Zn sources, especially nano-Zn increased the number of siliques per plant compared to control treatment. Although the use of zinc sources improved the number of siliques per plant in delayed planting compared to control plant at late planting date, the number of siliques per plant was significantly lower when compared with the application of zinc sources in normal planting date (Table 7).

Late planting weakens the plants at the time of flowering and ultimately reduces the number of siliques per plant (Nazeri et al., 2019). Zareei Siahbidi et al. (2020) reported that a delay in planting date reduced the number of siliques per plant during the first and second years of the experiment by 22.7 and 30.2%, respectively, which is consistent with the results of this study. Similar to the results of the present research, Fani et al. (2019) reported that silicon foliar application had a significant impact on the number of siliques per plant. Bybordi (2016) found that the application of silicon at the rate of 4 g.L^{-1}, increased the number of siliques per plant compared with non-use of silicon. One reason for the decrease in the number of siliques per plant in control treatment may be poor pollination due to zinc deficiency. The zinc application is very effective in preventing the losses of canola siliques (Shoja et al., 2018). Zinc is effective in increasing branching and number of siliques per plant due to its important role in the production of the hormone auxin (Tandon, 2005).

Table 7. Mean comparison of interaction between PD × ZS on number of siliques per plant and seed yield of canola

Planting date	Zinc sources	No. siliques per plant	Seed yield (kg.ha^{-1})
Normal	Control	223b	2951bc
	Zinc sulfate	270a	3160ab
	Nano-Zn	299a	3379a
Late	Control	123d	2198d
	Zinc sulfate	158c	2691c
	Nano-Zn	174c	2969bc

Means in columns followed by the same letter(s) are not significantly different at $P \leq 0.05$.

Number of seeds per silique

According to the results of this study, the number of seeds per silique was higher in the second year than first year of the experiment by about 25.7%. The number of seeds per silique significantly decreased under delayed planting conditions, so that this reduction was about 32.4% compared to the normal planting date (Table 5). According to the results in Table 5, application of silicon by both sources, including calcium silicate and nano-Si, increased the average number of seeds per silique from 29 to 32. Among different zinc sources, the application of zinc sulfate led to the production of the highest number of seeds per silique, which was about 6.1 and 15.1% more than nano-Zn and control, respectively (Table 5). According to the results in Table 6, the highest seeds number per silique was recorded by application of calcium silicate (39 seed) and nano-Si (38 seed) at normal planting date. Foliar application of nano-Si increased the number of seeds per silique in delayed planting date compared to treatments of control and calcium silicate at late planting date, but did not cause a significant difference.

According to Zareei Siahbidi et al. (2020), delay in sowing date led to decreased the number of seeds per silique during the first and second years of the experiment by 7.35 and 13.8%, respectively. Zinc plays a key role in protein synthesis, carbohydrate metabolism, controlling different growth hormones, increasing enzymes activity, and seed production and ripening (Laware and Raskar, 2014). In similar results, Sharifi (2017) reported that application of 1.5 mM silicon increased the number of seeds per silique by 22.3% compared with non-application of silicon.

1000-seed weight

According to the results in Table 5, the maximum 1000-seed weight (2.31 g) was recorded in the first year of the experiment. The highest 1000-seed weight was obtained in the normal planting date (2.10 g), and the delay in planting date caused a reduction of 1000-seed weight by about 11.4%. Based on the mean comparison of silicon sources, the foliar application of nano-Si improved the 1000-seed weight compared with calcium silicate application and control plant, by about 9 and 9.5%, respectively (Table 5). The results of mean comparison indicated that the Zn application significantly increased the 1000-seed weight. The minimum 1000-seed weight (1.76 g) was observed under control condition or non-use of zinc, while the use of zinc sulfate and nano-Zn increased the 1000-seed weight by 13.7 and 17.7%, respectively. However, the application of nano-Zn had better effect than zinc sulfate in terms of 1000-seed weight (Table 5). Based on the mean comparison of interaction between PD × SS, the maximum 1000-seed weight (2.32 g) was recorded by foliar application of nano-Si at normal planting date, while the minimum 1000-seed weight (1.82 g) was observed under control plant at late planting date. Application of Si sources, especially nano-Si, somewhat increased the 1000-seed weight in delayed planting date compared with control plant at late planting date, but did not cause a significant difference (Table 6).

Delay in planting date shortens the time required for plant vegetative and reproductive growth (Coffelt and Adamsen, 2005). Shortening the grain filling period and reducing the assimilate transport to the seeds reduces the seed weight (Bybordi et al., 2010). Overall, our findings showed that the application of Si and Zn in the form of nanoparticles was more effective than soil application of Si and Zn in increasing the 1000-seed weight. These results showed that the nutrients availability for the plant increases the 1000-seed weight by affecting cell division and growth and assimilate transport to the seeds. Similar findings were confirmed by Sharifi (2017), who reported that the silicon treated plants showed significantly higher values for 1000-seed weight over control plants. Zinc due to the supply of macro and micro nutrients for the plant improves the assimilate accumulation in seeds and ultimately increases the seed weight (Shoja et al., 2018). Previous studies demonstrated that the ZnO nanoparticles had positive impacts on seed weight of canola (Akhavan Hezaveh et al., 2020) and soybean (Seyed Sharifi, 2016).

Seed yield

According to the results in Table 5, the highest seed yield (3411 kg.ha^{-1}) was obtained in the first year of the experiment, which was about 30.5% higher than the second year. The comparison of data means revealed that the seed yield in the normal planting date was about 17.2% higher than the delayed planting date (Table 5). In this research, seed yield was increased in response to Si fertilizers application. Based on the mean comparison of silicon sources, the highest seed yields were obtained by application of calcium silicate (2954 kg.ha^{-1}) and nano-Si (3027 kg.ha^{-1}), while the lowest seed yield (2692 kg.ha^{-1}) was observed when no silicon fertilizer was applied. However, there was no significant difference between the application of calcium silicate and nano-Si in terms seed yield (Table 5). Based on the mean comparison of zinc sources, application of both nano-Zn and zinc sulfate improved seed yield compared with control plants by 18.9 and 12%, respectively, although the ZnO NPs-treated plants produced higher seed yield than zinc sulfate treated plants (Table 5). According to the results in Table 7, the application of zinc sulfate and nano-Zn at normal planting date resulted in higher seed yield than the control plant at normal planting date by 6.6 and 12.7%, respectively, while the lowest seed yield (2198 kg.ha^{-1}) was observed under control plant at late planting date. Also, seed yield was significantly improved by using zinc sulfate and nano-Zn in delayed planting conditions compared to the control plant at late planting date. However, nano-Zn treated plants showed an increase in seed yield both normal and late planting date, when compared to zinc sulfate treated plants, which was most likely due to their increased ability to be absorbed by the plant.

Delay in sowing date reduces plant vegetative growth and consequently reduces photosynthetic material that can be transferred to seeds during plant developmental stage and ultimately reduces seed yield (Tobe et al., 2013). Shafighi et al. (2021) reported that delay in planting date reduced the grain yield by 39% and 45.4% in the first and second years, respectively. The findings of other researchers also confirm the reduction in canola seed yield with a delay in planting date (Coffelt and Adamsen, 2005; Faraji, 2010). The reason for increasing seed yield by silicon fertilizers application, especially in the form of nanoparticles can be related to increasing yield attributes and improving nutrients uptake in rapeseed. Kheyri et al. (2019b) attributed the increase in rice grain yield by Si application to the nutrients availability and the improvement of their absorption and transport to the grains. Silicon affects crop yield through sedimentation in leaves, increasing leaf resistance, increasing chlorophyll content on leaf surface and subsequently improving light absorption by plants (Saadatmand and Enteshari, 2013). Similar to the results of this research, Sharifi (2017) reported that the Si application at the rates of 1 and 1.5 mM increased the seed yield compared with control by about 9.1 and 12.7%, respectively. Sabaghnia et al. (2018) noted that the use of nanofertilizers such as nano-Si can be useful to improve fertilizer efficiency and increase crop yield. Foliar application of Zinc oxide nanoparticles increase photosynthesis and improve the yield and nutritional quality of oil crops by increasing the activity of antioxidant enzymes such as catalase, superoxide dismutase and peroxidase (Sohail et al., 2020). Prasad et al. (2012) stated that higher bioavailability of the zinc oxide nanoparticles in peanut is the reason for higher yields compared to zinc sulfate. Similar results were found in chickpea and coffee plants treated with zinc nanoparticles and zinc sulfate. Previous research on chickpea (Pavani et al., 2014) and coffee (Rossi et al., 2019) plants showed an increase in fresh and dry weight of plants treated with zinc nanoparticles, while plants treated with zinc sulfate showed lower growth.

Seed oil content

The results of the experiment indicated that seed oil content was higher in the first year (47.2%) than the second year (46.3%). The highest seed oil content was obtained in the normal planting date (48.2%) and with a delay in planting date, the seed oil content decreased by about 6% (Table 5). In this study, application of both types of silicon fertilizer used in the experiment improved seed oil content compared with control. Application of calcium silicate and nano-Si increased the seed oil content compared with control or non-use of silicon by about 4.2 and 4.4%, respectively. However, there was no significant difference between the application of calcium silicate and nano-Si in terms of seed oil content (Table 5). Based on the mean comparison of zinc sources, the application of both nano-Zn and zinc sulfate improved the seed oil content compared to control plants (Table 5). Based on the mean comparison of interaction between SS × ZS, plants treated with co-application of Si and Zn, especially in the form of nanoparticles (47.75%) contained higher amounts of seed oil, when compared to separate application of Si or Zn treated plants, while control plants (43.98%) had the lowest seed oil content. When the nano-Zn was added to calcium silicate or nano-Si, the highest seed oil content was observed. Among the elements used in this experiment, the Si fertilizers had better effects on the improvement of seed oil content compared to Zn fertilizers. Overall, the application of zinc fertilizers, especially nano-Zn in combination with silicon fertilizers can improve the seed oil content (Figure 1).

According to Safdari-Monfared et al. (2019), the averages values of traits such as seed yield and seed oil content significantly decreased in late planting date. Confortin et al. (2019) reported that the highest seed yields for all hybrids used in the experiment were obtained when canola was sown in early or mid-autumn and with a delay in planting date (late season), the samples contained small amounts of oil. The addition of silicon to the plant improves the rapeseed oil content (Bybordi, 2016; Lalne et al., 2019). Fani et al. (2019) demonstrated that foliar application of silicon had a positive and significant impact on rapeseed oil yield. Application of nano-fertilizers due to the gradual release of nutrients improves the physiological characteristics of the plant and various seed nutritional status (Kolenclk et al., 2019). Akhavan Hezaveh et al. (2020) reported that foliar application of ZnO nanoparticles caused a 20.82% increase in rapeseed oil content compared to the non-application of nanoparticles.

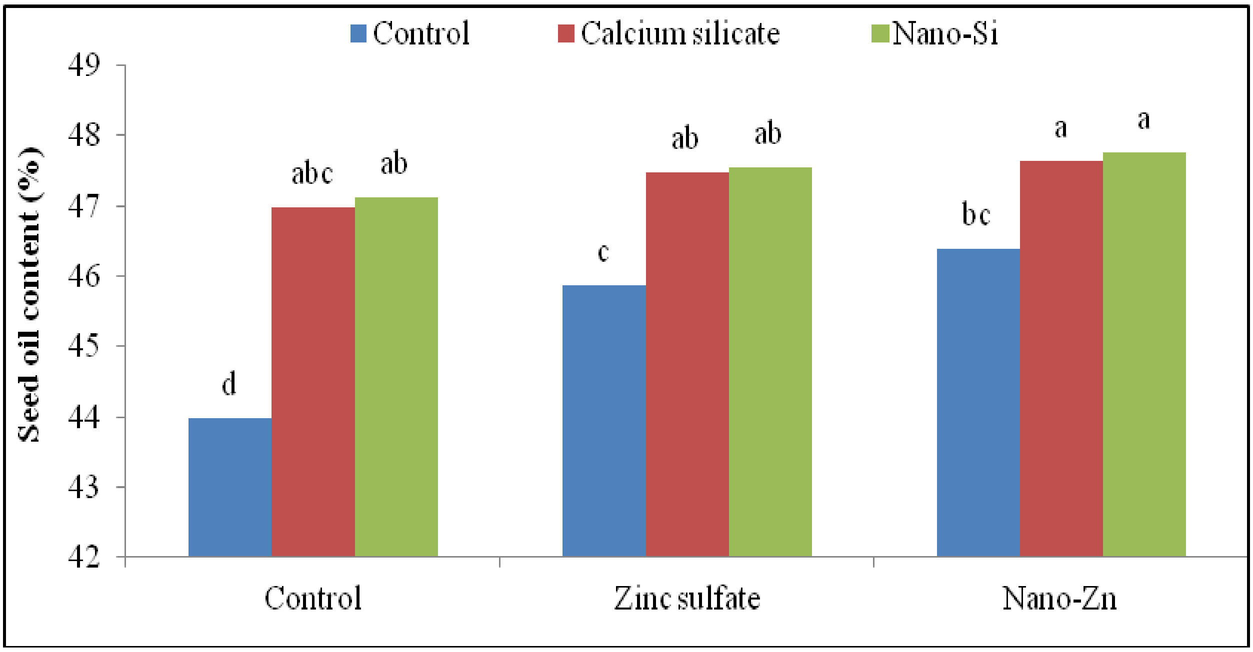

Figure 1. Mean comparison of interaction between SS × ZS on rapeseed oil content

Si and Zn concentrations in grain

Based on the results of combined ANOVA for the nutrients concentration, the impact of year was significant only on Zn concentration in rapeseed. The main effects of PD, SS and ZS were significant on both Si and Zn concentrations in rapeseed. The dual and triple interactions of the experimental treatments were not significant on Si and Zn concentrations in rapeseed (Table 8).

Table 8. Combined analysis of variance for PD, SS and ZS as well as their interactions on Si and Zn concentration in rapeseed

Source of variation	df	Si concentration	Zn concentration
Year (Y)	1	1125.57^{ns}	347.78^{**}
Replication	4	693700.77	7.97
Planting date (PD)	1	220154.78^{*}	1354.68^{**}
Y×PD	1	922.26^{ns}	14.13^{ns}
Error	4	95457.92	46.71
Silicon sources (SS)	2	878918.25^{**}	150.83^{*}
Y×SS	2	9626.46^{ns}	2.81^{ns}
PD×SS	2	2580.31^{ns}	29.50^{ns}
Y×PD×SS	2	6307.89^{ns}	33.10^{ns}
Zinc sources (ZS)	2	307760.17^{**}	1672.28^{**}
Y×ZS	2	5310.28^{ns}	2.41^{ns}
PD×ZS	2	5389.27^{ns}	12.16^{ns}
Y×PD×ZS	2	1192.01^{ns}	5.75^{ns}
SS×ZS	4	21956.27^{ns}	9.75^{ns}
Y×SS×ZS	4	8171.57^{ns}	2.65^{ns}
PD×SS×ZS	4	8771.95^{ns}	4.17^{ns}
Y×PD×SS×ZS	4	1617.74^{ns}	1.19^{ns}
Error	64	44494.80	40.30
CV (%)	-	9.69	13.50

^{ns}, *, and ** are non-significant and significant at the 5 and 1% probability levels, respectively.

Si concentration in rapeseed

According to the results in Table 9, the highest seed Si concentration (2221.9 mg Si kg^{-1}) was obtained in the normal planting date and delay in sowing date reduced the seed Si by 4.1%. The results showed that the application of both Si and Zn fertilizers improved the seed Si concentration compared to the control plants. Based on the mean comparison of silicon sources, Si application by both nano-Si and calcium silicate significantly increased the seed Si concentration compared with control plant by 12.9 and 10.4%, respectively. However, there was no significant difference between the application of calcium silicate and nano-Si in terms of seed Si concentration (Table 9). In this study, application of both zinc sources significantly improved the seed Si concentration compared with control plant, although the application of nano-Zn (2270.9 mg Si kg^{-1}) produced higher amounts of seed Si than the conventional form of Zn (2173.1 mg Si kg^{-1}) (Table 9).

Hashemi et al. (2010) reported that the silicon nutrition significantly increased the Si concentration in both roots and shoots of canola. Improvement of grain Si concentration by foliar spray of silicon nanoparticles in other crops such as rice (Kheyri et al., 2019a) has been reported. Simultaneous application of zinc and silicon via either soil application or foliar spray improves the Si concentration and uptake in the plant due to synergistic interaction between these two elements (Kheyri et al., 2019b). Sohail et al. (2020) stated that the foliar spray of ZnO nanoparticles have the potential to improve the biochemical and nutritional status in rapeseed.

Table 9. Mean comparison of main effects of Y, PD, SS and ZS on Si and Zn concentration in rapeseed

Experimental treatments	Si concentration ($mg.kg^{-1}$)	Zn concentration ($mg.kg^{-1}$)
Year		
First	Ns	48.8a
Second	Ns	45.2b
Planting date		
Normal	2221.9a	50.5a
Late	2131.6b	43.5b
Silicon sources		
Control	2000.1b	44.6b
Calcium silicate	2232.9a	48.0a
Nano-Si	2297.1a	48.3a
Zinc sources		
Control	2086.1b	39.4c
Zinc sulfate	2173.1ab	49.0b
Nano-Zn	2270.9a	52.6a

Means in columns followed by the same letter(s) are not significantly different at $P \leq 0.05$.

Zn concentration in rapeseed

The results of this experiment indicated that seed Zn concentration was higher in the first year (48.8 mg Zn kg^{-1}) than the second year (45.2 mg Zn kg^{-1}). Delay in planting date reduced the concentration of seed Zn by about 13.9% (Table 9). In this research, the application of nano-Si and calcium silicate led to improved seed Zn concentration compared with control plant by about 7.7 and 7.1%, respectively. However, there was no significant difference between the application of nano-Si and calcium silicate in terms of the rapeseed Zn content (Table 9). Based on the mean comparison of zinc sources, the application of zinc to both nanoparticles and conventional forms resulted in a significant increase in seed Zn concentration compared with control plant by 25.1 and 19.6%, respectively, although the nano-Zn treated plants produced significantly higher amounts of seed Zn (52.6 mg Zn kg^{-1}) when compared to zinc sulfate treated plants (49 mg Zn kg^{-1}) (Table 9).

Our results support the findings of Kheyri et al. (2019a) who demonstrated that addition of Si to the plant through both nano-Si and calcium silicate sources increases the Zn concentration and uptake in rice tissue compared to control plants. The results of other researchers indicated that the application of silicon (Mehrabanjoubani et al., 2015) and nano-Si (Wang et al., 2015) improved the Zn concentration in plant. Zinc application increased the Zn concentration in rapeseed compared with control or non-use of zinc by about 26.2% (Shoja et al., 2018), which is consistent with the results of this study. Improvement of Zn concentration in rapeseed by foliar application of nano-Zn has been reported by other researchers (Akhavan Hezaveh et al., 2020; Sohail et al., 2020).

The Zn application by both nanoparticles and zinc sulfate improved the Zn concentration in rice grain compared with control (Kheyri et al., 2019a). Zinc oxide nanoparticles are absorbed by plants to a greater value compared with zinc sulfate (Prasad et al., 2012). The positive effects of zinc nanoparticles on improving grain Zn uptake in other crops such as rice (Kheyri et al., 2019a), onion (Laware and Raskar, 2014), coffee (Rossi et al., 2019) and chickpea (Pavani et al., 2014) have also been reported.

CONCLUSIONS

Our findings showed that delay in planting date significantly decreased the quantitative and qualitative characteristic of canola. The application of Si and Zn by both nanoparticles and conventional forms improved all the agronomical and physiological traits of canola compared with control or non-use of fertilizer treatments. There was no significant difference between the application of nano-Si and calcium silicate in terms of yield components, seed yield, seed oil content and nutrient uptake in rapeseed. The nano-Zn treated plants showed an increase in yield attributes, seed yield and concentration of rapeseed Si and Zn, when compared to zinc sulfate treated plants. Overall, the results of the present study showed that the NPs foliar application of Si and Zn at normal planting date is a promising option to increasing yield and improve rapeseed quality, especially in areas where Si and Zn deficiency is high.

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