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Effects of Nanofertilizer Applications at Different Growth Stages of Sweet Corn (*Zea mays* var. *saccharata*) on Biochemical Stress Factors

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ABSTRACT

Background: Nanofertilizers are known to be more effective than other types of fertilizers. The present study aims to determine the biochemical stress parameters and yield values obtained when different nanofertilizer applications and doses were applied at different times in sweet corn.

Methods: This study was carried out in Antalya, Turkey during the 2020-2021 corn production season. The effects of different nanofertilizer applications on the yield and quality of the Rain Hazar F1 corn variety were investigated. The present study employed 3 different fertilizer application times (3-leaf stage, 12-leaf stage and corn tasseling season), 4 different nanofertilizers (nano-zinc, nano-molybdenum, nano-boron and nano-iron) and 2 different fertilizer doses (125 ppm and 200 ppm). The study was set up using the split-plot design in randomized blocks with 3 replications.

Result: The total phenolic content ranged between 271.90±1.51 and 118.80±12.47 mg GAE/g. The total antioxidant content ranged between 87.22±4.58 and 60.39±2.54%. The ascorbic acid peroxidase activity ranged between 4.54±1.46 and 0.17±0.01 EU/mg protein. The total chlorophyll content ranged between 7.43±1.96 and 1.97±0.09 mg/g. It was found in the present study that nanofertilizers can have a significant effect on the growth and development of corn plants.

Key words: APX, CAT, MDA, Nanofertilizer, Sweet corn.

INTRODUCTION

Sweet corn (*Zea mays* var. *saccharate*) is an important food crop worldwide (Davidson, 2002). It has a higher sugar content than other corn varieties and is used in many food products, such as cornflakes, popcorn, jam, marmalade, syrup and ice cream (Liu and Russell, 2008). Sweet corn is also a good source of vitamins A, C and E (Kim and Kim, 2010). In addition, it is rich in antioxidants, which help protect cells from damage caused by free radicals (Simić *et al.,* 2023; Öğüt and Atay, 2012).

The world's leading corn producers are the United States (with the largest share, 39.1%), Brazil, Mexico, China and India (Tacon *et al.,* 2011). In 2022, the total corn production in the world was 1.092 billion metric tons, with the United States, Brazil, China, India and Mexico producing 339.449, 171.380, 106.965, 95.159 and 39.182 million metric tons, respectively. Corn production in Turkey has increased significantly in recent years. In 2022, Turkey produced 1.5 million metric tons of corn, ranking 15th in the global corn production. The provinces with the highest corn production in Turkey are Adana, Mersin, Hatay, Antalya and Osmaniye (Yılmaz *et al.,* 2019).

Nanofertilizer technology is a technology that breaks down fertilizer into nano-sized particles in order to deliver it to plants more effectively (Kozanoğlu, 2006). Nanofertilizers can bring higher yields with less application when compared to conventional fertilizers (Çerifoğlu *et al.,* 2021; Satar *et al.,* 2022). Nanofertilizers are also less harmful to the environment when compared to conventional fertilizers since they can bring higher yields with lower application rates (Gökdemir *et al.,* 2023). Given this information, the present study aims to evaluate the changes in biochemical and yield values of corn under different growth stages with different nanofertilizers and doses.

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MATERIALS AND METHODS

Plant material and trial design

This study was carried out in Antalya - Turkey during the 2020-2021 corn production season. The Rain Hazar F1 variety was used in the trial. The study used 3 different fertilizer application times (3-leaf stage, 12-leaf stage and corn tasseling season), 4 different nanofertilizers (nano-zinc, nano-molybdenum, nano-boron and nano-iron) and 2 different fertilizer doses (125 ppm and 200 ppm). According to soil analysis results in 2020 and 2021, the pH was found to be 7.4 and 7.9, EC to be 568 ms/cm and 687 ms/cm and organic matter content to be 4.5% and 5.7%, respectively. In addition to nanofertilizer applications, standard fertilizer applications were made and these were applied at the concentration of 25 kg/da for nitrogen, 5 kg/da for phosphorus and 20 kg/da for potassium (NPK and urea) per decare. The trial was set up as a split-plot design with three replications in randomized blocks.

Nanofertilizer preparation for application

Nano-zinc fertilizer was prepared by using commercially available nanoparticles having the following properties: CAS No. 1314-13-2; EC No. 215-222-5; concentration (% w/w) >= 90 - <= 100 (commercial company Merck). Nano-molybdenum fertilizer was prepared by using a commercially available fertilizer that contains 3.5% water-soluble boron and 5.5% water-soluble molybdenum. Nano-borate fertilizer was prepared according to the methods of Bekişli *et al.* (2016) and Erfani *et al.* (2012). Fertilizer applications were performed by spraying leaves after doses were prepared. Samples were collected for analysis 10 days after the last application.

Biochemical analysis

Total phenolic content: Determined by Folin-Ciocalteu reagent by using the gallic acid standard (Slinkard and Singleton, 1977).

Total flavonoid content: Determined by using quercetin standard calibration curve (Zhishen *et al.* 1999; Ay *et al.* 2023).

Total antioxidant content: Determined by using DPPH radical (Brand-Williams *et al.*, 1995).

Proline content: Determined by using Bates method (Bates, 1973).

Catalase activity, ascorbic acid, lipid peroxidation activity: Determined by using spectrophotometry Cho *et al.,* 2000; Nakano and Asada, 1981; Cakmak and Horst, 1991).

Pigment analysis

Total Chlorophyll and Carotenoid Determination by using the Arnon method (Arnon, 1949).

Statistical analysis

Data were analyzed using one-way analysis of variance (ANOVA) in SPSS 26.0. Differences were grouped by using Duncan's test at a statistical significance level of 99%.

RESULTS AND DISCUSSION

Total phenolic content (mg GAE/g)

Total phenolic content was significantly affected by application, dose, period and their interactions. The highest value was found in the 2nd period of nano-ZN-125 ppm application, while the lowest value was found in the 3rd period of nano-IR-200 ppm application. In terms of efficiency, nano-MO-125 ppm > nano-BO-200 ppm > nano-ZN-125 ppm > nano-IR-125 ppm (Table 1). Application of all fertilizer types at 125 ppm yielded better results than the application at 200 ppm. These findings are supported by a similar study carried out by Bleidere *et al.* (2013).

Total flavonoid content (mg QE / g)

Total flavonoid content was significantly affected by application, dose, period and their interactions. The highest value was found in the 2nd period of nano-ZN-125 ppm application, while the lowest value was found in the 3rd period of nano-IR-200 ppm application (Table 1). It is apparent that 125 ppm nanofertilizer is more effective than 200 ppm nanofertilizer. Nanofertilizers can be utilized to enhance plant growth and development and when used adequately, nanofertilizers can be useful in increasing the production of flavonoid compounds in plants, thus enhancing their immunity against diseases, pests and environmental stressors.

Total antioxidant content at (%)

The distributions of total antioxidant content were statistically different in terms of application, dose, period, dose*period, application*dose, application*period, application*dose*period, year*application and year*application*period*dose interactions ($p<0.01$). Examining the averages for two years, the highest value was obtained from 3rd period of nano-ZN-125 ppm application to be 87.22±4.58%. The lowest value was obtained from 3rd period of nano-MO-200 ppm fertilizer to be 60.39±2.54% (Table 1). Nano-BO and Nano-IR 200 ppm nanofertilizer is more effective than 125 ppm nano fertilizer. The opposite applies to others.

Proline (µg/ml)

Proline distributions were affected by application, dose, period and their interactions. The highest value was found in the 3rd period of nano-BO-125 ppm fertilizer, while the lowest value was found in the 1st period of nano-BO-125 ppm fertilizer. Nano-BO-200 ppm is more effective than 125 ppm (Table 2). Poustini *et al.* (2007) found that salt stress applications caused an increase in proline levels in leaf tissues in 30 bread wheat cultivars. Other studies have also shown that proline levels increased in tomato (Doğan and Tipirdamaz, 2010) and corn (Yakıt and Tuna, 2006) plants under salt stress.

Catalase activity (CAT) (EU/mg protein)

Catalase activity was affected by application, dose, period and their interactions. The highest value was found in the 3rd period of nano-BO-125 ppm fertilizer, while the lowest value was found in the 1st period of nano-BO-125 ppm fertilizer. Nano-O-200 ppm is more effective than 125 ppm (Table 2).

Ascorbic acid peroxidase activity (APX) (EU/mg protein)

APX distribution was affected by application, dose, period and their interactions. The highest value was found in the 3rd period of nano-BO-125 ppm fertilizer, while the lowest value was found in the 1st period of nano-BO-125 ppm fertilizer (Table 2).

Table 1: Effects of nanofertilizer doses applied at different stages on total carotenoid, total phenolic content (mg GAE/g), total flavonoid content (mg QE/g) and 25 µg/ml (total antioxidant content) (%) in sweet corn.

Application	Dose	Period	Total carotenoid content (mg/g)			Total phenolic content (mg GAE/g)			Total flavonoid content (mg QE/g)			25 µg/ml (Total antioxidant content) (%)		
			2020	2021	Mean	2020	2021	Mean	2020	2021	Mean	2020	2021	Mean
ZN	125	1	0.70±0.01^{b}	0.71±0.00^{b}	0.71±0.01^{b}	266.66±1.51^{a}	269.23±1.45^{a}	267.94±1.48^{a}	156.38±1.46^{ab}	159.61±0.67^{a}	158.00±0.99^{a}	79.40±0.24^{bc}	80.38±1.07^{bc}	79.89±0.64^{bc}
		2	0.74±0.02^{b}	0.72±0.01^{b}	0.72±0.02^{b}	270.96±0.48^{a}	272.84±2.54^{a}	271.90±1.51^{a}	159.80±1.11^{a}	160.53±1.50^{a}	160.16±1.30^{a}	80.62±0.48^{b}	82.28±0.44^{b}	81.45±0.46^{b}
		3	0.66±0.02^{b}	0.69±0.01^{b}	0.68±0.01^{b}	164.05±0.96^{ij}	166.95±1.24^{gh}	165.50±1.10^{ghi}	113.73±1.07^{hi}	117.73±0.78^{fg}	115.73±0.92^{hi}	86.93±4.76^{a}	87.50±4.55^{a}	87.22±4.58^{a}
	200	1	0.64±0.02^{b}	0.65±0.03^{b}	0.65±0.02^{b}	160.08±1.52^{jk}	165.15±0.32^{gh}	162.61±0.90^{hi}	113.47±1.61^{hi}	116.19±1.20^{g}	114.83±1.40^{i}	77.78±0.18^{cde}	77.94±0.29^{cde}	77.86±0.23^{cde}
		2	0.75±0.01^{b}	0.76±0.02^{b}	0.76±0.02^{b}	150.65±1.39^{m}	152.19±3.16^{fg}	151.42±2.27^{j}	110.38±1.83^{i}	106.11±5.15^{h}	108.25±3.28^{i}	68.97±0.52^{mnop}	68.80±0.37^{mno}	68.89±0.44^{nop}
		3	0.20±0.02^{b}	0.16±0.06^{b}	0.18±0.04^{b}	181.37±1.62^{f}	186.66±7.29^{e}	184.01±4.37^{e}	123.71±1.38^{f}	127.83±1.80^{e}	125.77±1.58^{f}	68.41±0.15^{nop}	67.70±0.09^{mnop}	68.06±0.12^{nopr}
MO	125	1	0.51±0.01^{b}	0.54±0.01^{b}	0.53±0.01^{b}	196.11±1.40^{e}	195.99±1.56^{d}	196.05±1.42^{d}	130.60±6.53^{e}	138.07±5.23^{d}	134.34±5.46^{e}	70.02±0.18^{kmno}	69.63±0.23^{kmn}	69.82±0.21^{mno}
		2	0.60±0.01^{b}	0.59±0.00^{b}	0.60±0.01^{b}	254.42±1.07^{b}	254.93±6.58^{b}	254.67±3.72^{b}	148.49±1.38^{cd}	151.84±0.97^{b}	150.16±1.17^{bc}	70.71±0.21^{kmn}	70.14±0.17^{km}	70.42±0.18^{kmn}
		3	0.79±0.01^{b}	0.78±0.01^{b}	0.79±0.01^{b}	256.63±2.26^{b}	260.12±1.63^{b}	258.37±1.90^{b}	151.69±1.41^{bc}	153.27±1.80^{b}	152.48±1.61^{b}	71.31±0.24^{jkm}	72.12±0.22^{jk}	71.71±0.23^{jkm}
	200	1	0.49±0.01^{b}	0.52±0.01^{b}	0.50±0.01^{b}	148.46±1.25^{mn}	151.68±0.82^{ij}	150.07±1.01^{jk}	101.75±3.33^{j}	101.31±1.24^{h}	101.53±2.29^{k}	63.32±0.70^{s}	63.36±0.89^{r}	63.34±0.77^{s}
		2	0.55±0.01^{b}	0.57±0.01^{b}	0.56±0.01^{b}	144.08±1.85^{no}	146.32±1.55^{j}	145.20±1.69^{jkm}	93.85±1.52^{k}	95.61±1.27^{i}	94.73±1.34^{m}	60.42±2.08^{t}	60.35±3.05^{s}	60.39±2.54^{t}
		3	0.83±0.02^{b}	0.80±0.01^{b}	0.82±0.02^{b}	143.18±0.84^{no}	143.27±1.49^{jk}	143.22±1.15^{km}	78.37±9.51^{m}	86.42±5.59^{j}	82.40±6.23^{n}	78.63±0.40^{bcd}	78.77±0.23^{cd}	78.70±0.31^{cd}
BO	125	1	0.32±0.05^{b}	0.34±0.06^{b}	0.33±0.06^{b}	139.11±2.53^{op}	137.20±1.81^{k}	138.15±2.17^{mn}	68.28±1.46^{n}	74.20±3.14^{k}	71.24±2.28^{o}	65.48±1.33^{rs}	65.54±0.20^{pr}	65.51±0.76^{rs}
		2	0.47±0.01^{b}	0.50±0.01^{b}	0.48±0.01^{b}	203.69±2.72^{cd}	204.92±1.12^{c}	204.31±0.90^{c}	144.86±1.30^{d}	144.96±1.35^{c}	144.91±1.33^{d}	66.94±0.17^{pr}	66.58±0.17^{op}	66.76±0.17^{pr}
		3	0.85±0.00^{b}	0.83±0.02^{b}	0.84±0.01^{b}	208.18±2.22^{c}	207.22±2.83^{c}	207.70±2.52^{c}	145.96±1.25^{cd}	147.91±2.62^{bc}	146.94±1.92^{cd}	67.75±0.40^{opr}	67.24±0.11^{nop}	67.50±0.26^{opr}
	200	1	0.40±0.02^{b}	0.40±0.02^{b}	0.40±0.02^{b}	199.17±0.97^{de}	201.90±3.53^{cd}	200.54±2.20^{cd}	144.32±2.01^{d}	145.18±0.89^{c}	144.75±1.44^{d}	76.68±0.32^{cdefg}	76.44±0.19^{defg}	76.56±0.25^{defg}
		2	0.87±0.01^{b}	0.86±0.02^{b}	0.87±0.01^{b}	172.19±1.05^{gh}	171.75±0.76^{fg}	171.97±0.90^{fg}	119.53±1.17^{fgh}	121.60±0.71^{fg}	120.56±0.91^{fgh}	77.35±0.15^{cdef}	76.99±0.37^{def}	77.17±0.25^{def}
		3	0.44±0.00^{b}	0.47±0.2^{b}	0.46±0.01^{b}	168.95±1.88^{hi}	170.47±1.01^{g}	169.71±1.39^{gh}	116.83±0.83^{ghi}	120.46±0.97^{fg}	118.65±0.90^{ghi}	75.98±0.25^{defgh}	76.10±0.10^{defgh}	76.04±0.18^{defgh}
IR	125	1	0.89±0.01^{b}	0.90±0.1^{b}	0.90±0.01^{b}	171.96±1.73^{gh}	172.63±1.65^{fg}	172.30±1.69^{fg}	119.62±0.81^{fgh}	121.35±1.40^{fg}	120.49±1.10^{fgh}	75.44±0.04^{efgh}	75.55±0.33^{efghi}	75.49±0.18^{efgh}
		2	0.94±0.03^{b}	0.96±0.03^{b}	0.95±0.03^{b}	177.41±1.87^{fg}	180.28±0.46^{ef}	178.84±1.07^{ef}	122.60±1.12^{fg}	123.39±1.19^{ef}	122.99±1.12^{fg}	73.38±0.31^{hij}	73.25±0.16^{hij}	73.32±0.23^{h,j}
		3	0.91±0.00^{b}	0.91±0.01^{b}	0.91±0.00^{b}	171.53±1.24^{gh}	170.84±1.36^{g}	171.18±1.30^{g}	119.48±1.20^{ghi}	120.95±1.18^{fg}	120.21±1.19^{ghi}	72.47±0.45^{ijk}	72.91±0.16^{ij}	72.69±0.30^{jk}
	200	1	1.00±0.03^{b}	1.02±0.02^{b}	1.01±0.03^{b}	157.49±2.43^{k}	159.75±2.36^{hi}	158.62±2.36^{i}	114.55±0.86^{hi}	115.67±1.30^{g}	115.11±1.08^{hi}	74.81±0.09^{fghi}	74.03±0.25^{ghij}	74.42±0.18^{ghi}
		2	3.39±2.71^{a}	3.60±2.82^{a}	3.49±2.77^{a}	133.20±2.24^{p}	134.64±1.16^{k}	133.92±0.68^{n}	66.84±1.43^{n}	71.48±1.30^{km}	69.17±1.37^{op}	75.02±0.09^{efghi}	74.81±0.08^{fghij}	74.92±0.09^{fghi}
		3	1.07±0.03^{b}	1.19±0.02^{b}	1.14±0.03^{b}	117.71±11.31^{r}	119.89±13.70^{m}	118.80±12.47^{o}	62.47±1.44^{n}	66.81±4.19^{m}	64.64±2.53^{p}	74.31±0.48^{ghi}	73.71±0.11^{ghij}	74.01±0.29^{ghij}
Mean			0.79±0.74^{A}	0.81±0.79^{A}	0.80±0.77	181.55±42.62^{A}	183.20±42.83^{A}	182.38±42.7^{0}	117.81±27.98^{A}	120.35±27.16^{A}	119.08±27.52	73.01±6.00^{A}	73.01±6.26^{A}	73.01±6.12
CV(%)			1.05			4.27			4.33			11.9		
Application			**	**		**	**		**	**		**	**	
Dose			ns.	ns.		**	**		**	**		**	**	
Period			*	*		**	**		**	**		**	**	
Dose*period			*	*		**	**		**	**		**	**	
Application*dose			*	*		**	**		**	**		**	**	
Aplication*period			*	*		**	**		**	**		**	**	
App*dose*period			ns.	ns.		**	**		**	**		**	**	
Year*app.			**			**			**			**		
Year*app.*dose*period			**			**			**			**		

*: p<0.05, **: p<0.01, ns.: Not significant, CV: Coefficient of variation.

Table 2: Effects of nanofertilizer doses applied at different stages on ascorbic acid peroxidase activity (APX) (EU/mg protein) and aatalase activity (CAT), proline (µg/ml), MDA (nmol/ g) in sweet corn.

Application	Dose	Period	APX (EU/mg protein)			Catalase activity (CAT)			Proline (µg/ml)			MDA (nmol/ g)		
			2020	2021	Mean	2020	2021	Mean	2020	2021	Mean	2020	2021	Mean
ZN	125	1	0.68±0.03^{fghij}	0.65±0.03^{fghi}	0.67±0.03^{fghi}	8.58±0.11^{g}	14.01±0.11^{gh}	11.30±0.11^{k}	4.07±0.22^{fgh}	4.09±0.32^{efg}	4.08±0.27^{fg}	1.19±0.02^{b}	1.17±0.02b	1.18±0.02b
		2	1.32±0.14^{ef}	1.36±0.16^{ef}	1.34±0.15^{ef}	15.62±1.42^{d}	22.52±0.12^{d}	19.07±0.76^{e}	6.12±0.10^{cde}	6.14±0.03^{cd}	6.13±0.07^{cde}	1.39±0.01^{b}	1.40±0.01b	1.39±0.01b
		3	0.74±0.04^{fghij}	0.78±0.05^{fghi}	0.76±0.05^{fghi}	11.54±2.37^{f}	14.56±0.33^{fgh}	13.05±1.31^{ij}	4.34±0.06^{fg}	4.33±0.02^{ef}	4.34±0.04^{f}	1.23±0.01^{b}	1.25±0.02b	1.23±0.01b
	200	1	0.60±0.03^{fghij}	0.59±0.02^{fghi}	0.60±0.02^{fghi}	8.34±0.05^{g}	12.34±0.53^{hi}	10.34±0.29^{km}	3.66±0.02^{gh}	3.64±0.07^{fg}	3.65±0.04^{g}	1.14±0.02^{b}	1.13±0.02b	1.13±0.02b
		2	0.55±0.02^{ghij}	0.56±0.02^{ghi}	0.55±0.02^{ghi}	8.19±0.04^{g}	10.92±0.04^{ij}	9.56±0.04^{kmn}	3.58±0.04^{h}	3.52±0.03^{gh}	3.55±0.04^{g}	1.05±0.05^{b}	1.05±0.04b	1.05±0.04b
		3	0.51±0.01^{ghij}	0.49±0.01^{ghi}	0.50±0.01^{ghi}	8.04±0.09^{g}	10.81±0.04^{ij}	9.42±0.06^{kmn}	2.58±0.69^{i}	2.84±0.65^{h}	2.71±0.62^{b}	0.99±0.01^{b}	0.96±0.03b	0.97±0.02b
MO	125	1	0.40±0.02^{ghij}	0.38±0.01^{ghi}	0.39±0.01^{ghi}	6.55±0.09^{gh}	9.80±0.34^{ijk}	8.17±0.21^{no}	1.53±0.07^{jk}	1.72±0.05^{ij}	1.62±0.06^{ijk}	0.87±0.03^{b}	0.85±0.00b	0.85±0.02b
		2	0.47±0.01^{ghij}	0.41±0.01^{ghi}	0.44±0.01^{ghi}	6.72±0.07^{gh}	10.37±0.03^{ijk}	8.54±0.05^{mno}	1.71±0.12^{jk}	1.85±0.09^{i}	1.78±0.10^{ij}	0.92±0.01^{b}	0.87±0.02b	0.89±0.02b
		3	0.49±0.01^{ghij}	0.47±0.00^{ghi}	0.48±0.01^{ghi}	7.46±0.55^{g}	10.47±0.07^{ijk}	8.96±0.30^{mn}	2.04±0.02^{ij}	2.02±0.05^{i}	2.03±0.03^{i}	0.96±0.01^{b}	0.91±0.01b	0.93±0.01b
	200	1	0.32±0.00^{ghij}	0.34±0.01^{ghi}	0.33±0.01^{ghi}	4.84±1.14^{hi}	8.85±0.40^{jk}	6.85±0.72^{op}	1.20±0.20^{km}	1.38±0.16^{ijk}	1.29±0.18^{jkm}	0.80±0.02^{b}	0.83±0.02b	0.81±0.02b
		2	0.29±0.02^{hij}	0.31±0.02^{ghi}	0.29±0.02^{hi}	3.97±0.03^{i}	7.71±0.52^{km}	5.84±0.27^{pr}	0.99±0.04^{kmn}	1.05±0.10^{jkm}	1.02±0.07^{km}	0.75±0.04^{b}	0.76±0.02b	0.75±0.03b
		3	0.21±0.05^{ij}	0.26±0.02^{hi}	0.24±0.03^{hi}	3.46±0.07^{i}	4.78±0.41^{n}	4.12±0.24^{r}	0.72±0.29^{mn}	0.78±0.22^{km}	0.75±0.25^{mn}	0.65±0.04^{b}	0.72±0.03b	0.68±0.04b
BO	125	1	0.14±0.02^{j}	0.19±0.01^{i}	0.17±0.01^{i}	3.34±0.02^{i}	0.77±0.07^{o}	2.05±0.0^{5s}	0.29±0.04^{n}	0.38±0.08^{m}	0.33±0.06^{n}	0.49±0.07^{b}	0.52±0.05b	0.51±0.06b
		2	3.32±0.25^{b}	3.37±0.18^{b}	3.34±0.21^{b}	33.02±0.02^{a}	34.42±0.08^{b}	33.73±0.05^{b}	7.90±1.02^{b}	8.71±1.04^{b}	8.30±0.90^{b}	1.54±0.04^{b}	1.63±0.02b	1.59±0.03b
		3	4.51±1.41^{a}	4.57±1.51^{a}	4.54±1.46^{a}	33.45±0.41^{a}	37.96±2.90^{a}	35.71±1.57^{a}	9.23±0.10^{a}	9.65±0.50^{a}	9.44±0.29^{a}	3.91±2.48^{a}	3.97±2.54a	3.94±2.51a
	200	1	2.41±0.19^{c}	2.38±0.10^{c}	2.40±0.14^{c}	26.10±3.22^{b}	33.79±0.07^{b}	29.94±1.64^{c}	6.65±0.31^{c}	6.74±0.48^{c}	6.70±0.39^{c}	1.49±0.01^{b}	1.54±0.02b	1.52±0.01b
		2	2.14±0.08^{cd}	2.14±0.08^{cd}	2.14±0.08^{cd}	22.29±0.04^{c}	28.12±0.07^{c}	25.20±0.06^{d}	6.34±0.03^{cd}	6.31±0.03^{cd}	6.33±0.03^{cd}	1.44±0.02^{b}	1.48±0.01b	1.46±0.01b
		3	1.54±0.06^{de}	1.61±0.06^{de}	1.57±0.06^{de}	20.57±2.73^{c}	24.39±1.34^{d}	22.48±1.82^{e}	6.28±0.02^{cd}	6.20±0.04^{cd}	6.24±0.03^{cde}	1.42±0.00^{b}	1.45±0.03b	1.44±0.02b
IR	125	1	0.99±0.01^{efgh}	1.01±0.03^{efgh}	1.00±0.02^{efgh}	13.92±0.61^{def}	17.05±0.58^{ef}	15.48±0.60^{gh}	5.91±0.01^{cde}	5.93±0.02^{d}	5.92±0.01^{de}	1.35±0.01^{b}	1.35±0.02b	1.35±0.01b
		2	1.07±0.05^{efg}	1.12±0.03^{efg}	1.09±0.04^{efg}	14.38±0.05^{de}	19.05±1.75^{e}	16.71±0.90^{g}	5.98±0.05^{cde}	6.00±0.04^{cd}	5.99±0.04^{de}	1.37±0.01^{b}	1.37±0.00b	1.37±0.01b
		3	0.95±0.01^{efghi}	0.95±0.02^{efghi}	0.95±0.01^{efghi}	13.17±0.01^{def}	15.84±0.64^{fg}	14.51±0.32^{hi}	5.85±0.03^{de}	5.86±0.02^{d}	5.85±0.02^{de}	1.34±0.01^{b}	1.32±0.01b	1.33±0.01b
	200	1	0.24±0.09^{hij}	0.27±0.07^{hi}	0.25±0.07^{hi}	3.76±0.37^{i}	5.47±4.10^{mn}	4.61±2.23^{r}	0.75±0.42^{mn}	0.84±0.41^{km}	0.80±0.41^{mn}	0.66±0.16^{b}	0.68±0.14b	0.67±0.15b
		2	0.92±0.02^{efghi}	0.91±0.02^{efghi}	0.92±0.02^{efghi}	13.08±0.04^{def}	15.07±0.03^{fgh}	14.08±0.04^{hi}	5.37±0.71^{e}	5.82±0.02^{d}	5.59±0.36^{e}	1.28±0.02^{b}	1.29±0.01b	1.28±0.02b
		3	0.87±0.01^{efghij}	0.86±0.04^{efghi}	0.87±0.03^{efghi}	12.98±0.05^{ef}	15.00±0.02^{fgh}	13.99±0.03^{hi}	4.44±0.03^{f}	4.45±0.06^{e}	4.45±0.04^{f}	1.24±0.01^{b}	1.27±0.01b	1.25±0.01b
Mean			1.07±1.07^{A}	1.08±1.09^{A}	1.08±1.08	12.64±8.67^{B}	16.00±9.63^{A}	14.32±9.09	4.06±2.51^{A}	4.18±2.57^{A}	4.12±2.54	1.23±0.76^{A}	1.24±0.78A	1.23±0.77
CV(%)			1.00			1.58			1.62			1.61		
Application			**	**		**	**		**	**		**	**	
Dose			**	**		**	**		**	**		*	*	
Period			**	**		**	**		**	**		*	*	
Dose*period			**	**		**	**		**	**		*	*	
Application*dose			ns	ns		**	**		**	**		ns.	ns.	
Aplication*period			**	**		**	**		**	**		*	*	
App*dose*period			**	**		**	**		**	**		**	*	
Year*app.			**			**						**		
Year*app.*dose*period			**			**						**		

Table 3: Effects of nanofertilizer doses applied at different stages on total chlorophyll content (mg/g), chlorophyll-a (mg/g), chlorophyll-b (mg/g) in sweet corn.

Application	Dose	Period	Total Chlorophyll Content (mg/g)			Chlorophyll-a (mg/g)			Chlorophyll-b (mg/g)		
			2020	2021	Mean	2020	2021	Mean	2020	2021	Mean
ZN	125	1	3.45±0.05^{fghi}	3.52±0.07^{efgh}	3.48±0.06^{efghi}	1.97±0.02^{cdefgh}	1.99±0.06^{bcdef}	1.98±0.03^{cdefg}	1.54±0.01^{cd}	1.50±0.01^{cdefg}	1.52±0.01^{cdef}
		2	3.56±0.04^{efghi}	3.60±0.01^{efgh}	3.58±0.02^{efghi}	2.00±0.01^{cdefgh}	2.08±0.03^{bcdef}	2.04±0.02^{cdefg}	1.54±0.01^{cd}	1.53±0.01^{cdefg}	1.53±0.01^{cdef}
		3	3.34±0.05^{efghi}	3.37±0.03^{fghi}	3.35±0.04^{fghij}	1.92±0.02^{cdefgh}	1.92±0.01^{bcdef}	1.92±0.01^{cdefg}	1.45±0.04^{cd}	1.44±0.02^{cdefg}	1.45±0.03^{cdef}
	200	1	3.28±0.01^{efghi}	3.23±0.07^{fghi}	3.26±0.04^{fghij}	1.89±0.01^{cdefgh}	1.88±0.00^{bcdef}	1.89±0.01^{cdefg}	1.35±0.05^{cd}	1.32±0.09^{cdefg}	1.33±0.07^{cdef}
		2	3.66±0.03^{efgh}	3.64±0.01^{efgh}	3.65±0.03^{efghi}	2.10±0.01^{cdefgh}	2.16±0.02^{bcdef}	2.13±0.02^{bcdefg}	1.56±0.01^{cd}	1.57±0.02^{cdefg}	1.57±0.02^{cdef}
		3	1.97±0.11^{m}	1.97±0.07^{k}	1.97±0.09^{m}	0.97±0.15^{h}	0.97±0.11^{f}	0.97±0.13^{cdefg}	0.82±0.04^{d}	0.80±0.08^{g}	0.81±0.06^{f}
MO	125	1	2.91±0.04^{ghijkm}	2.89±0.01^{ghijk}	2.90±0.02^{ghijkm}	1.82±0.00^{defgh}	1.80±0.02^{cdef}	1.81±0.01^{cdefg}	1.12±0.03^{cd}	1.12±0.01^{defg}	1.12±0.02^{def}
		2	3.20±0.06^{fghij}	3.14±0.06^{fghij}	3.17±0.06^{fghij}	1.87±0.01^{defgh}	1.86±0.01^{bcdef}	1.86±0.01^{cdefg}	1.26±0.05^{cd}	1.21±0.02^{defg}	1.23±0.04^{cdef}
		3	3.76±0.04^{efg}	3.73±0.06^{efgh}	3.74±0.05^{efgh}	2.17±0.05^{cdefg}	2.21±0.03^{bcdef}	2.19±0.04^{bcdefg}	1.58±0.01^{cd}	1.60±0.01^{cdefg}	1.59±0.01^{cdef}
	200	1	2.82±0.02^{ghijkm}	2.84±0.01^{ghijk}	2.83±0.02^{ghijkm}	1.79±0.01^{defgh}	1.78±0.00^{cdef}	1.78±0.01^{cdefg}	1.08±0.01^{cd}	1.08±0.01^{defg}	1.08±0.01^{def}
		2	3.06±0.08^{fghijk}	2.96±0.03^{ghijk}	3.01±0.06^{ghijk}	1.85±0.02^{defgh}	1.83±0.01^{bcdef}	1.84±0.02^{cdefg}	1.18±0.02^{cd}	1.14±0.01^{defg}	1.16±0.02^{def}
		3	3.82±0.02^{efg}	3.83±0.02^{efg}	3.82±0.02^{efg}	2.27±0.05^{cdefg}	2.34±0.03^{bcdef}	2.30±0.05^{bcdefg}	1.62±0.04^{cd}	1.62±0.02^{cdefg}	1.62±0.03^{cdef}
BO	125	1	2.16±0.07^{km}	2.15±0.07^{jk}	2.16±0.07^{hi}	1.22±0.10^{gh}	1.13±0.03^{ef}	1.18±0.06^{fg}	0.88±0.01^{d}	0.90±0.01^{fg}	0.89±0.01^{ef}
		2	2.71±0.04^{hijkm}	2.77±0.02^{hijk}	2.74±0.03^{hijkm}	1.75±0.03^{defgh}	1.73±0.01^{cdef}	1.74±0.02^{cdefg}	1.06±0.02^{cd}	1.02±0.02^{efg}	1.04±0.02^{def}
		3	4.01±0.14^{def}	4.10±0.11^{def}	4.05±0.13^{def}	2.40±0.04^{bcdefg}	2.46±0.02^{bcdef}	2.43±0.03^{bcdef}	1.72±0.04^{cd}	1.71±0.01^{cdefg}	1.72±0.02^{cdef}
	200	1	2.39±0.15^{jkm}	2.45±0.13^{ijk}	2.42±0.14^{jkm}	1.38±0.03^{fgh}	1.31±0.11^{def}	1.34±0.07^{efg}	0.95±0.03^{cd}	0.94±0.02^{efg}	0.95±0.02^{ef}
		2	4.43±0.06^{cde}	4.43±0.03^{cde}	4.43±0.04^{cde}	2.53±0.04^{bcdef}	2.63±0.04^{bcdef}	2.58±0.04^{bcdef}	1.78±0.01^{bcd}	1.76±0.07^{cdefg}	1.77±0.03^{cdef}
		3	2.62±0.04^{ijkm}	2.71±0.05^{hijk}	2.66±0.04^{ijkm}	1.62±0.12^{efgh}	1.60±0.14^{cdef}	1.61±0.13^{defg}	0.99±0.01^{cd}	0.99±0.01^{efg}	0.99±0.01^{def}
IR	125	1	4.83±0.05^{bcd}	4.85±0.10^{bcd}	4.84±0.07^{bcd}	2.61±0.04^{bcde}	2.76±0.08^{bcde}	2.69±0.06^{bcde}	1.81±0.01^{bcd}	1.87±0.01^{cdef}	1.84±0.01^{cdef}
		2	5.20±0.09^{bc}	5.21±0.10^{bc}	5.21±0.09^{bc}	2.88±0.03^{bcd}	2.99±0.02^{bc}	2.94±0.03^{bcd}	2.00±0.09^{bcd}	2.03±0.11^{bcd}	2.01±0.10^{bcd}
		3	4.95±0.03^{bc}	5.01±0.05^{bcd}	4.98±0.04^{bcd}	2.83±0.01^{bcd}	2.89±0.03^{bcd}	2.86±0.02^{bcd}	1.87±0.03^{bcd}	1.89±0.01^{cde}	1.88±0.02^{cde}
	200	1	5.44±0.04^{b}	5.43±0.06^{b}	5.43±0.05^{b}	3.05±0.21^{bc}	3.10±0.10^{bc}	3.08±0.15^{bc}	2.14±0.04^{bc}	2.26±0.04^{bc}	2.20±0.04^{bc}
		2	7.40±1.92^{a}	7.45±1.99^{a}	7.43±1.96^{a}	5.58±2.20^{a}	5.35±3.10^{a}	5.47±2.61^{a}	4.56±2.22^{a}	4.98±1.81^{a}	4.77±1.96^{a}
		3	5.55±0.05^{b}	5.61±0.10^{b}	5.58±0.08^{b}	3.50±0.16^{b}	3.47±0.07^{b}	3.48±0.11^{b}	2.88±0.05^{b}	2.86±0.04^{b}	2.87±0.04^{b}
Mean			3.77±1.30^{A}	3.79±1.31^{A}	3.78±1.30	2.25±0.98^{A}	2.26±1.03^{A}	2.26±1.00	1.61±0.86^{A}	1.63±0.90^{A}	1.62±0.87
Application			2.9			2.25			1.86		
Dose			**	**		**	**		**	**	
Period			*	ns.		*	ns.		*	*	
Dose*period			**	**		**	*		*	**	
Application*dose			**	**		**	*		*	**	
Aplication*period			**	**		**	*		**	**	
App*dose*period			**	**		**	*		*	**	
Year*app.			**	*		*	ns.		*	*	
Year*app.*dose*period			**			**			**		
Application			**			**			**		

*:p<0.05, **:p<0.01, ns.: Not significant, CV: Coefficient of variation.

Lipid peroxidation activity (MDA) (nmol/ g TA)

MDA levels were affected by application, dose, period and their interactions. The highest value was found in the 3rd period of nano-BO-125 ppm fertilizer, while the lowest value was found in the 1st period of nano-BO-125 ppm fertilizer (Table 2). Chattha *et al.* (2022) found that potassium reduced MDA and oxidative damage in tomato plants under salt stress. The results achieved in this study are consistent with their findings.

Total chlorophyll content (mg/g)

The total chlorophyll content was affected by application, period and dose. The highest value was found in the 1st period of nano-IR-200 ppm application, while the lowest value was found in the 3rd period of nano-ZN-200 ppm fertilizer application. Nano-IR, nano-ZN, nano-MO and nano-BO were observed to be advantageous in that order (Table 3). The results reported by Kumawat *et al.* (2006), Ashrafuzzaman *et al.* (2000) and Turan *et al.* (2009) are also consistent with the results reported in the present study.

Chlorophyll-a (mg/g)

Chlorophyll content was affected by application, period, dose and year in the first year. In the 2nd year, only application, period and dose were significant. Upon examining the averages for 2 years, the highest value of 5.47±2.61 mg/g was found during the 2nd period of applying nano-IR-200 ppm. The lowest value of 0.97±0.13 mg/g was obtained during the 3rd period of applying nano-ZN-200 ppm fertilizer (Table 3). Nano-IR was found to be more useful when compared to Nano-ZN, Nano-MO and Nano-BO in terms of fertilizer types. Insufficient fertilizer results in plant stress. Hence, findings reported in previous studies on stress align with the results achieved in this study (Agastian and Kingsley, 2000; Kaya *et al.,* 2003).

Chlorophyll-b (mg/g)

The chlorophyll content was significantly affected by application, period, dose and their interactions. The highest value was found in the 2nd period of nano-IR-200 ppm application, while the lowest value was found in the 3rd period of nano-ZN-200 ppm fertilizer application. Nano-IR was found to be more useful than Nano-ZN, Nano-MO and Nano-BO. Upon examining the averages for 2 years, the highest value of 5.47±2.61 mg/g was found during the 2nd period of applying nano-IR-200 ppm. The lowest value of 0.97±0.13 mg/g was obtained during the 3rd period of applying nano-ZN-200 ppm fertilizer (Table 3). Nano-IR was found to be more useful when compared to Nano-ZN, Nano-MO and Nano-BO in terms of fertilizer varieties. Insufficient fertilizer results in plant stress. Hence, findings reported in previous studies on stress align with the results achieved in this study (Agastian and Kingsley, 2000; Kaya *et al.,* 2003).

Total carotenoid content (mg/g)

The carotenoid content was significantly affected by application, year*application and year*application period*dose interactions. The highest value was found in the 2nd period of nano-IR-200 ppm application (3.60±2.82 mg/g), while the lowest value was found in the 3rd period of nano-ZN-200 ppm fertilizer application (0.16±0.06 mg/g). Nano-IR was found to be more useful than nano-ZN, nano-MO and Nano-BO (Table 1). The present findings are supported by the results of a study carried out by Yakit and Tuna (2006).

CONCLUSION

Given the results of the present study, Nano-ZN-125 ppm application yielded the highest total phenolic and flavonoid content. It was also found that the time of application and dose of the fertilizers had a significant effect on the total phenolic content. The 3rd period of Nano-BO-125 ppm application yielded the highest proline content in maize plants. Nano-ZN-125 ppm fertilizer yielded the highest antioxidant capacity. Considering the total antioxidant capacity, the 200-ppm dose of Nano-BO and Nano-IR fertilizers was more effective than the 125-ppm dose. Nano-BO-125 ppm fertilizer showed the highest catalase activity. Considering the total carotenoid content, the best result was obtained in the 2nd period of Nano-IR-200 ppm fertilizer. It was determined in the present study that Nano-ZN-125 ppm application provided higher plant height than Nano-MO-125 ppm fertilizer. In the present study, Nano-ZN-125 ppm fertilizer yielded the highest total phenolic and flavonoid content. This effect is influenced by factors such as the type of fertilizer, time of application and dose.

Conflict of interest: None.

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