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Selenium Nanoparticles Improve Physiological and Phytochemical Properties of Basil (*Ocimum basilicum* L.) under Drought Stress Conditions

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Abstract: Drought impacts on food security, land degradation and rates of biodiversity loss. Here, we aimed to investigate selenium nanoparticles (Se NPs) influenced plant resilience to drought using the morphological, physiological, and essential oil (EO) quantity and quality of basil (*Ocimum basilicum* L.) as drought proxies. Treatments included irrigation at 100% field capacity (FC100) as no stress, 80% FC as moderate water stress (FC80) and 60% FC as severe water stress (FC60), together with application of Se NPs at either 0 mg L^{-1} (control), 50 mg L^{-1}, or 100 mg L^{-1}. The highest (257 g m^{-2}) and lowest (185 g m^{-2}) dry matter yields were achieved in nil-stress and severe-water-stress conditions, respectively. Dry matter yields decreased by 15% and 28% under moderate and severe water stress, respectively. Applying Se NPs enhanced the dry matter yields by 14% and 13% for the 50 and 100 mg L^{-1} treatments, respectively. The greatest EO content (1.0%) and EO yield (1.9 g m^{-2}) were observed under severe water stress. Applying Se NPs of 50 and 100 mg L^{-1} enhanced the essential oil content by 33% and 36% and the essential oil yield by 52% and 53%, respectively. We identified 21 constituents in the EO, with primary constituents being methyl chavicol (40%–44%), linalool (38–42%), and 1,8-cineole (5–6%). The greatest methyl chavicol and linalool concentrations were obtained in FC80 with 50 mg L^{-1} Se NPs. The highest proline (17 μg g^{-1} fresh weight) and soluble sugar content (6 mg g^{-1} fresh weight) were obtained under severe water stress (FC60) for the 50 mg L^{-1} Se NP treatment. Our results demonstrate that low-concentration Se NPs increase plant tolerance and improve the EO quantity and quality of basil under drought stress.

Keywords: antioxidant activity; crop production; essential oil; soluble sugar; water restriction; water deficit; extreme event

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1. Introduction

The intensification of climate change driven by global warming is threatening the sustainability, food security, and prosperity of many agricultural communities across the world. The higher frequency and intensity of climate variability and extreme climatic events have significantly affected agricultural productivity growth over the past 60 years [1]. Stress associated with a water deficit is one of the most critical environmental factors limiting global crop and pasture growth and distribution [2,3]. The prevailing rainfall level in Iran is around 75% less than the global average, leading to more than 88% of agricultural lands in Iran being classified as in arid and semiarid climates [4]. Similar to the consequences of nutrient stress [5–7], a sub- or supraoptimal water supply results in morphological, physiological, and biochemical changes that constrain quantitative and qualitative plant growth [1,7,8]. On the basis of the severity and duration of water stress, crop production has been reported to decrease by 13–94% [9]. Water stress limits stomatal opening, reducing CO_2 uptake and photosynthesis and decreasing plants' growth [10]. Increasing reactive oxygen species (ROS) increases the lipid peroxidation of the membrane, leading to the decomposition of chlorophylls and other structural biomolecules [11,12]. In addition to negative impacts of drought stress on the plant's productivity, drought affects land degradation and biodiversity loss, which in turn have adverse effects on resource-dependent rural populations and can potentially lead to livelihood losses and subsequent migration out of affected areas. Therefore, providing new solutions to increase the adaptation and production of plants in arid and semiarid areas is needed. One of the new technologies to alleviate drought-stress effects on plant production and quality comes from harnessing advances in nanotechnology [13].

Anecdotal evidence suggests that applying stress-modulating nanoparticles (NPs) may reduce the detrimental impacts of drought and improve plant performance under otherwise-stressful conditions. Selenium (Se) is a common trace metalloid categorized among beneficial elements for plant growth [14]. The beneficial effects of Se are not directly involved in plant metabolisms, but they play a unique role in improving the vegetative and reproductive phases, especially when the plants are exposed to environmental stresses. In addition, Se NPs can modulate the negative impacts of stressful conditions through antioxidant and pro-oxidant agents [15]. It has been reported that applying Se NPs under stressful conditions prevents oxidative stress by reducing the ROS content in normal ranges and enhancing the expression of stress-responsive proteins and genes [16].

Because of the long-term adverse effects of chemical drugs on human health, medicinal compounds with natural origins are increasing daily. It has been reported that about 80% of people use herbal medicines for some part of their primary healthcare [17]. Among different medicinal and aromatic plants, the Lamiaceae family, including about 200 genera and 3200 species, widely distributed almost all over temperate and tropical regions. Most plant species belonging to the Lamiaceae family are considered medicinal and aromatic thanks to the terpenoids and phenylpropanoid compounds in their essential oils (EOs) [18]. Basil (*Ocimum basilicum* L.) is an annual herbaceous plant belonging to the Lamiaceae family. Basil is used as a fresh vegetable, a flavoring agent in many dishes, and a medicinal and aromatic plant [19]. In traditional and folklore medicine, basil is used for stomach problems such as spasms, fluid retention, head colds, kidney disorders, etc. [20]. The basil EOs have biological properties such as antiviral, antibacterial, antioxidant, anti-inflammatory, etc. characteristics [21]. The EO productivity of basil and its constituents varies, depending on the different species and environmental conditions. It has been reported that methyl chavicol, linalool, 1,8-cineole, and methyl eugenol were the main EO constituents of basil [22,23].

The climate crisis will result in greater global average temperatures that will result in higher frequencies and intensities of extreme events, including drought, heat waves, and flooding, which call for the development of integrated adaptations [24,25]. In the past century, average global surface temperatures have risen by 0.7 °C and, together with the increased frequencies of extreme events, will intensify adverse effects on plant performance [4]. Also, in arid and semiarid regions, the increasing consumption of chemical inputs to compensate for the yield loss in these conditions will increase production costs and environmental pollution. The higher use of chemical fertilizer in the cultivation of medicinal and aromatic plants has negative impacts on bioactive compounds and decreases the EO quality of these plants. Therefore, this study aims to investigate the effects of Se NPs as stress-modulating compounds on basil plants' morphological, physiological, and phytochemical characteristics under drought-irrigation regimes. We hypothesize that (i) the application of Se NPs will increase photosynthesis pigments under drought-stress conditions, (ii) the application of Se NPs will enhance the tolerance of basil plants by increasing osmolyte (proline and soluble sugar) concentration, and (iii) the application of Se NPs will improve the EO quantity and quality of basil plants.

2. Materials and Methods

2.1. Study Area

The study was conducted at the research farm of Shahid Bakeri Higher Education Center, Miandoab, Iran, during the 2021–2022 growing season. The physical and chemical properties of the experimental soil (depth of 0–30 cm) are shown in Table 1. This region has a semiarid climate, with a mean temperature of 12 °C and annual precipitation of 390 mm.

Table 1. Physicochemical properties of field soil (depth of 0–30 cm).

Texture	pH	Electrical Conductivity (dS m^{-1})	Organic Matter (%)	Total N (%)	Phosphorus (%)	Potassium (%)
Silty	8.25	0.88	1.30	0.13	10.33	211.6

2.2. Treatments

The study was laid out as factorial experiment based on a randomized complete block design (RCBD) with three replications. The treatments included different irrigation levels containing irrigation at 100% field capacity (FC100) as no stress, 80% FC as moderate water stress (FC80), and 60% FC as severe water stress (FC60), as well as the application of Se NPs at three concentrations, 0 mg L^{-1} (control), 50 mg L^{-1}, and 100 mg L^{-1}. Each plot contained five rows with a 40 cm distance between rows. Se NPs foliar application was performed twice each growing season, once upon seedling establishment and once three weeks later.

The basil seeds were sown with a density of 12.5 plants m^{-2}, on 21 May 2021. The first irrigation was performed immediately after sowing to ensure germination. Weeds were regularly controlled by hand. The different water stresses were applied one month after sowing.

2.3. Measurements

2.3.1. Agronomic Traits and Dry Yield

In the flowering stage, five plants were selected randomly from each plot to measure basil's agronomic traits, including canopy diameter, number of leaves, and lateral branches. To measure the dry yield of basil, 2 m^2 of each plot was randomly harvested after removing the marginal effects, on 8 August 2021.

2.3.2. Essential Oil Extraction and Analysis

Clevenger extracted the basil essential oil from the water distillation method. For this purpose, 40 g of the aerial parts of basil were poured into the Clevenger and were added with 300 mL of distilled water. The essential oil extraction was performed at a water boiling temperature for 3 h. In addition, the EO yield, as g m^{-2}, was calculated by multiplying the dry yield with EO content. After extraction of the basil EO, the required amount of sodium sulfate was added to the EO samples and kept in a refrigerator (4 °C) in darkness for chemical analysis. Moreover, the oil constituents were analyzed using GC-MS (GC-MS; Agilent 7890/5975A, USA) and GC-FID (Agilent 7990B, USA), following the previous method of Rezaei-Chiyaneh et al. [26].

2.3.3. Chlorophylls and Carotenoid

In the flowering stage, 0.5 g fresh basil leaves were homogenized in 10 mL of 80% acetone and centrifuged at 12,000 rpm for 15 min. Afterward, a UV spectrophotometer read the absorbance at 663 nm, 645 nm, and 470 nm (UV-1800, Shimadzu, Tokyo, Japan).

The content of chlorophyll a, chlorophyll b, and carotenoids was calculated by using the following equations [27]:

$$C_a = (12.25A_{663.2}) - (2.79A_{646.8})$$

$$C_b = (21.5A_{646.8}) - (5.1A_{663.2})$$

$$\text{Car} = \frac{[1000A_{470} - 1.82C_a - 85.02C_b]}{198}$$

In these equations, C_a, C_b, and Car are chlorophyll a, chlorophyll b, and carotenoids, respectively.

2.3.4. Proline

To determine the proline concentration of basil leaves, the reaction mixture containing 2000 µL of extract, 2000 µL of ninhydrin reagent, and 2000 µL of glacial acetic acid was mixed, and the absorbance was determined at 520 nm (UV-1800 Shimadzu, Tokyo, Japan) [28].

2.3.5. Total Soluble Sugars

The phenol and sulfuric acid method measured the soluble sugar content of basil. Briefly, 0.5 g of fresh basil leaves were homogenized with ethanol and mixed with 98% sulfuric acid and 5% phenol, and the absorbance was spectrophotometrically read at 485 nm [29].

2.4. Phenolic Acid

Dried leaves were dissolved in 2 mL 80% MeOH and transferred to an ultrasonic bath for 30 min. The homogenates were centrifuged at 3000 rpm for 15 min and transferred to sealed jars. The extracts were crushed through fine membrane lighters and stored at 20 °C. Finally, 20 mL of the extract was injected into HPLC to separate and analyze the phenolic acid [30].

2.5. Statistical Analysis

All obtained data were analyzed by SAS (SAS Institute Inc., Cary, NC, USA) software, and the mean comparisons were analyzed by the least significant difference (LSD) test at the 95% level of probability.

3. Results

The analysis of variance results showed that the canopy diameter, number of leaves, number of lateral branches, dry yield, essential oil (EO) content, and yield were significantly impacted by the main effects of the irrigation levels and the selenium nanoparticles (Se NPs). Meanwhile, the interaction between the factors mentioned above (irrigation levels × Se NPs) significantly impacted the content of chlorophyll a, chlorophyll b, carotenoids, soluble sugars, and proline.

3.1. Agronomic Traits

Among different irrigation regimes, the highest canopy diameter (54.22 cm), number of leaves (717.56), and number of lateral branches (20.55) of basil were obtained in FC100. The lowest values of the mentioned traits were achieved in FC60. The canopy diameter, the number of leaves, and the number of lateral branches decreased by 11.9%, 7.5%, and 11.3% in moderate water stress (FC80), respectively. They were decreased by 18.7%, 11.8%, and 26.4% in severe water stress (FC60), respectively, when compared with nonstress conditions (FC100) (Table 1). Among different concentrations of Se NPs, the highest canopy diameter, the number of leaves, and the number of lateral branches were achieved after the application of 50 mg L^{-1} Se NPs which was 8.7%, 7.2% and 14.6% greater than the non-application of Se NPs, respectively (Table 2).

Table 2. The agronomic traits (canopy diameter, number of leaves, and number of lateral branches), dry yield, essential oil content, and essential oil yield of basil in different irrigation regimes and Se NPs.

	Canopy Diameter (cm)	Number of Leaves	Number of Lateral Branches	Dry Yield (g m^{-2})	Essential Oil Content (%)	Essential Oil Yield (g m^{-2})
Irrigation levels (I)						
FC100	54.22 a	717.56 a	20.55 a	256.61 a	0.68 c	1.74 c
FC80	47.78 b	663.78 b	18.22 b	218.58 b	0.84 b	1.84 b
FC60	44.11 c	633.11 c	15.11 c	184.62 c	1.03 a	1.90 a
Se nanoparticles (S)						
Control (0 mg L^{-1})	46.22 b	649.44 b	16.67 b	201.74 b	0.67 b	1.35 b
50 mg L^{-1}	50.22 a	696.22 a	19.11 a	230.77 a	0.89 a	2.05 a
100 mg L^{-1}	49.67 a	668.78 b	18.11 a	227.31 a	0.91 a	2.07 a
Source of variations			Significance			
I	**	**	**	**	**	**
S	*	*	**	**	**	**
I × S	NS	NS	NS	NS	NS	NS

Ns, * and ** indicated no significant difference, significant at 5% probability level and significant at 1% probability level, respectively. Different letters indicate significant differences at the 5% level according to LSD's test.

3.2. Dry Yield

The dry yield of basil significantly reduced with increasing drought stress levels. The plant's highest (256.61 g m^{-2}) and the lowest (184.62 g m^{-2}) dry yields were observed in FC100 and FC60, respectively. The dry yields of basil decreased by 14.8% and 28.1% in moderate and severe drought stress, respectively. Additionally, applying Se NPs in the concentration of 50 mg L^{-1} sharply increased the dry yield of basil. The dry yield of basil with 50 mg L^{-1} Se NPs enhanced by 14.4% compared with the control (non-application of Se NPs) (Table 2).

3.3. Essential Oil Content

The EO productivity of basil was enhanced by increasing drought-stress levels. Among different irrigation regimes, the maximum EO content of basil (1.03%) was recorded under severe water stress (FC60), while the lowest EO content (0.68%) was related to the non-stress conditions (FC100). The EO productivity of basil was enhanced by 23.53% and 51.5% under moderate and severe water stress, respectively (Table 1). In addition, the application of Se NPs in the concentration of 50 and 100 mg L^{-1} enhanced the EO content of basil by 32.8% and 35.8% when compared with the control (Table 2).

3.4. Essential Oil Yield

Among different irrigation levels, the highest (1.90 g m^{-2}) and lowest (1.74 g m^{-2}) EO yields of basil plants were obtained under severe water stress (FC60) and non-stress (FC100) conditions. Compared with the non-stress conditions, the EO yields of basil enhanced by 5.8% and 9.2% in FC80 and FC60, respectively. Interestingly, the application of Se NPs in concentrations of 50 and 100 mg L^{-1} enhanced the EO yields of basil by 51.8% and 53.3%, respectively, when compared with the control (Table 2).

3.5. Essential Oil Constituents

According to the GC-MS and GC-FID analysis, 21 constituents were identified in basil EO, the major constituents being methyl chavicol (39.74–43.61%), linalool (37.78–41.51%), and 1,8-cineole (4.83–6.15%). The maximum content of methyl chavicol and linalool was obtained under moderate water stress (FC80) following the application of 50 mg L^{-1} Se NPs. In addition, the maximum content of 1,8-cineole was recorded under severe water stress (FC60) treated with 50 mg L^{-1} Se NPs. Additionally, the lowest content of the three mentioned constituents was measured under non-stress conditions (FC100) without applying Se NPs (Table 3).

3.6. Phenolic Compounds

The main phenolic compounds of the basil plant include comaric (522.07–687.97 ppm), chlorogenic acid (310.68–395.83 ppm), caffeic acid (212.41–282.49 ppm), and gallic acid (110.18–178.12 ppm). The respective maximum contents of comaric, caffeic acid, and gallic acid were obtained under moderate water stress (FC80) following 50 mg L^{-1} Se NPs. In addition, the maximum contents of chlorogenic acid, rosmaric acid, quercetin, and apigenin were recorded under severe water stress (FC60) with 50 mg L^{-1} Se NPs. On average, the content of gallic acid, caffeic acid, chlorogenic acid, rutin, comaric, rosmaric acid, quercetin, cinnamic acid, and apigenin enhanced by 24%, 10%, 6%, 10%, 8%, 14%, 2%, 11%, and 17% after the application of 50 mg L^{-1} Se NPs and 14%, 7%, 11%, 24%, 7%, 11%, 11%, 10%, and 19% after the application of 100 mg L^{-1} Se NPs, respectively (Table 4).

3.7. Chlorophyll Content

The maximum concentrations of chlorophyll a (0.56 mg g^{-1} fresh weight) and chlorophyll b (0.23 mg g^{-1} fresh weight) in the basil plant were obtained under non-stress conditions (FC100) treated with 50 mg L^{-1} Se NPs. In contrast, the lowest contents of chlorophyll a (0.3 mg g^{-1} fresh weight) and chlorophyll b (0.11 mg g^{-1} fresh weight) were recorded in FC60 without Se NPs. The concentrations of chlorophyll a and chlorophyll b were reduced by 16.7% and 14.3% under moderate water stress (FC80) and by 31.5% and 28.6% under severe water stress (FC60), respectively. Additionally, the concentration of photosynthesis pigments was enhanced by 21.9% and 42.9% with the application of 50 mg L^{-1} Se NPs and 12.2% and 35.7% with the application of 100 mg L^{-1} Se NPs, respectively, when compared with the control (Figure 1A,B).

3.8. Carotenoid Content

Applying 50 mg L^{-1} Se NPs under moderate water stress (FC80) produced the highest carotenoid concentration in the basil plant. However, the lowest concentration of carotenoid was observed in FC100 without the application of Se NPs. Under moderate and severe water stress, carotenoid concentration enhanced by 35.9% and 45.5% compared with non-stress conditions. In addition, the application of 50 and 100 mg L^{-1} Se NPs increased the carotenoid concentration by 44.9% and 31.6%, respectively, compared with the control (Figure 2).

3.9. Soluble Sugar Content

Applying 50 mg L^{-1} Se NPs under severe water stress (FC60) produced the maximum soluble sugar content in the basil plant. However, the lowest soluble sugar content was obtained in FC100 without applying Se NPs. Under moderate and severe water stress, carotenoid concentration enhanced by 35.3% and 41.5%, respectively, compared with nonstress conditions. In addition, the soluble sugar content of basil increased by 65.4% and 27.1% after the application of 50 and 100 mg L^{-1} Se NPs, respectively (Figure 3).

3.10. Proline

The highest proline concentration (16.87 μg g^{-1} fresh weight) was obtained under severe water stress (FC60) treated with 50 mg L^{-1} Se NPs. In addition, the lowest proline concentration (9.1 μg g^{-1} fresh weight) was related to the non-stress conditions without applying Se NPs. Under moderate and severe water stress, the proline concentration enhanced by 17.4% and 35.9%, respectively, compared to non-stress conditions. In addition, the proline concentration of basil increased by 41.1% and 18.4% after the application of 50 and 100 mg L^{-1} Se NPs, respectively (Figure 4).

Table 3. The essential oil constituents of basil in different irrigation regimes and Se NPs.

No.	Components	RI [a]	Treatments								
			FC100+ Control	**FC100+ 50 mg L^{-1} Se**	**FC100+ 100 mg L^{-1} Se**	**FC80+ Control**	**FC100+ 50 mg L^{-1} Se**	**FC100+ 100 mg L^{-1} Se**	**FC60+ Control**	**FC100+ 50 mg L^{-1} Se**	**FC100+ 100 mg L^{-1} Se**
1	α-Pinene	925	0.21	0.18	0.18	0.21	0.2	0.19	0.17	0.22	0.17
2	Sabinene	964	0.12	0.1	0.09	0.12	0.11	-	0.09	0.13	0.09
3	β-Pinene	968	0.26	0.23	0.21	0.27	0.25	0.24	0.22	0.28	0.21
4	Myrcene	981	0.08	0.1	0.06	0.09	0.08	0.08	0.07	0.09	0.06
5	**1,8-Cineole**	**1024**	**4.83**	**5.43**	**4.91**	**5.87**	**5.81**	**5.54**	**5.61**	**6.15**	**5.83**
6	**Linalool**	**1097**	**37.78**	**38.89**	**38.09**	**39.09**	**41.51**	**41.09**	**38.12**	**39.23**	**40.06**
7	Terpinen-4-ol	1177	1.18	0.83	0.91	0.55	0.61	0.34	0.56	0.19	0.57
8	**Methyl chavicol**	**1195**	**39.74**	**42.45**	**42.62**	**42.80**	**43.61**	**43.08**	**41.93**	**42.35**	**41.42**
9	Neral	1234	0.38	0.5	-	-	0.29	-	0.59	0.53	0.11
10	Geraniol	1249	0.72	0.92	0.1	0.21	0.1	-	0.55	-	0.05
11	α-Copaene	1369	0.07	0.09	0.08	0.07	0.07	-	0.09	-	0.08
12	β-Cubebene	1383	0.39	0.21	0.16	0.52	0.14	0.19	0.21	0.23	0.14
13	Methyl eugenol	1395	3.02	1.65	2.96	2.63	2.23	1.91	2.17	1.36	2.98
14	trans-Caryophyllene	1414	2.16	1.64	1.53	1.58	1.24	1.52	1.55	1.87	1.43
15	(*E*)-β-Farnesene	1433	0.05	0.06	0.05	0.07	0.07	0.06	0.06	0.08	0.06
16	α-Humulene	1447	0.84	0.67	0.64	0.7	0.58	0.62	0.67	0.8	0.63
17	Germacrene D	1475	1.46	0.96	1.02	0.88	0.79	0.98	0.23	0.82	0.99
18	α-Bisabolene	1498	0.08	0.09	0.09	0.08	0.08	0.09	1.12	0.11	0.08
19	cis-α-Bisabolene	1532	1.83	0.91	1.47	1.66	0.83	1.67	1.59	0.77	1.51
20	Caryophyllene oxide	1578	0.12	0.13	0.11		0.12	0.07	0.14	0.09	-
21	α-Bisabolol	1674	0.05	-	0.05	-	0.13	0.05		0.07	0.06
	Total identified (%)		95.37	96.44	95.33	97.4	98.85	97.72	95.74	95.37	96.53

[a] RI, linear retention indices on the DB-5 MS column, experimentally determined using homologue series of n-alkanes. Bold values show the main components.

Table 4. The phenolic compounds of basil in different irrigation regimes and Se NPs.

No.	Components	ppm								
		FC100+ Control	FC100+ 50 mg L^{-1} Se	FC100+ 100 mg L^{-1} Se	FC80+ Control	FC80+ 50 mg L^{-1} Se	FC80+ 100 mg L^{-1} Se	FC60+ Control	FC60+ 50 mg L^{-1} Se	FC60+ 100 mg L^{-1} Se
1	Gallic acid	110.18	122.34	119.75	118.20	178.12	159.63	147.43	167.09	149.93
2	Caffeic acid	219.56	212.41	242.25	230.75	282.49	262.46	251.63	274.11	243.82
3	Chlorogenic acid	310.68	341.91	360.55	322.60	342.91	393.54	390.28	395.83	384.31
4	Rutin	42.72	43.36	49.78	42.23	53.38	59.16	43.38	44.29	50.20
5	Comaric	522.07	597.11	578.21	632.29	687.97	639.87	533.39	540.95	593.23
6	Rosmaric acid	31.01	33.58	32.79	35.56	38.78	39.59	37.90	46.56	43.76
7	Quercetin	51.67	57.11	67.56	69.97	59.81	69.16	79.75	89.17	86.10
8	Cinnamic acid	4.50	5.65	5.39	6.72	7.45	7.98	8.12	8.34	8.01
9	Apigenin	19.75	22.30	23.37	21.29	23.11	24.68	21.39	27.61	26.54

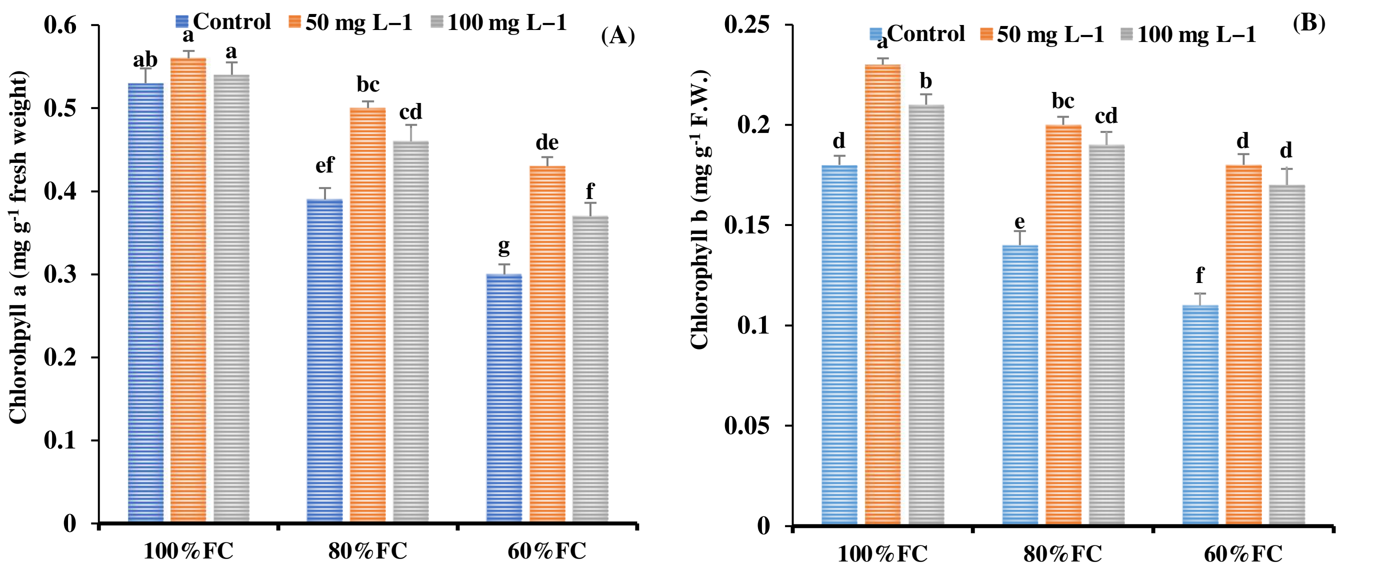

Figure 1. The content of chlorophyll a (**A**) and chlorophyll b (**B**) of basil in different irrigation regimes and Se NPs. Different letters indicate significant differences at the 5% level according to LSD's test.

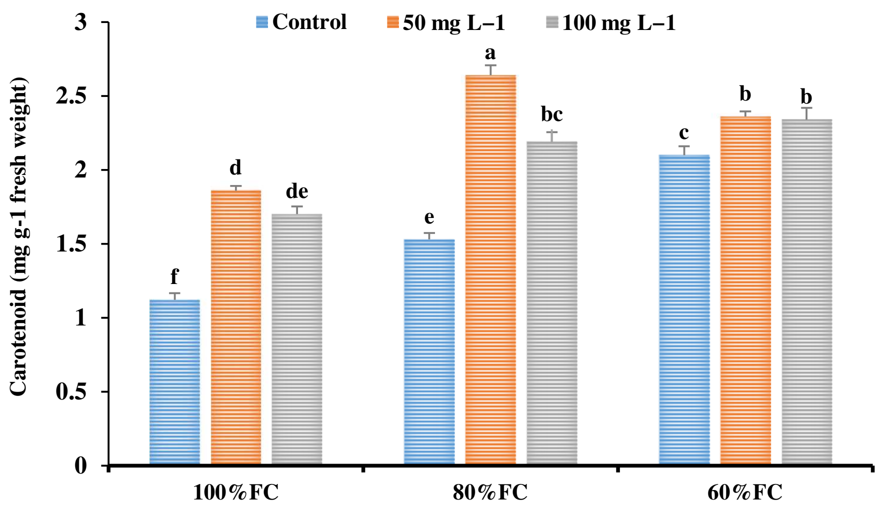

Figure 2. The content of the carotenoid of basil in different irrigation regimes and Se NPs. Different letters indicate significant differences at the 5% level according to LSD's test.

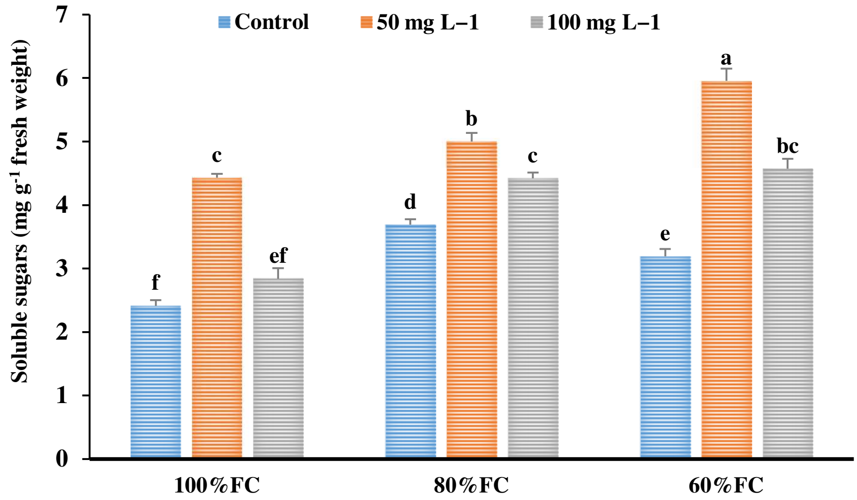

Figure 3. The soluble sugar content of basil in different irrigation regimes and Se NPs. Different letters indicate significant differences at the 5% level according to LSD's test.

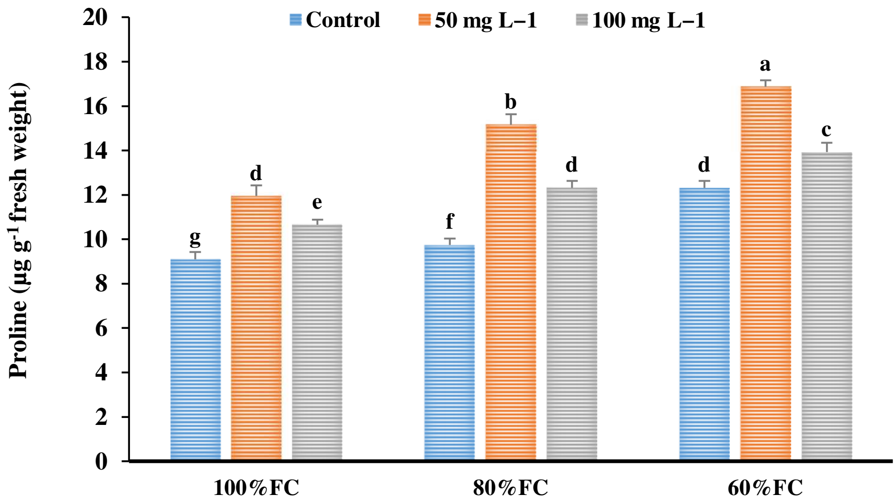

Figure 4. The proline concentration of basil in different irrigation regimes and Se NPs. Different letters indicate significant differences at the 5% level according to LSD's test.

4. Discussion

Plant productivity depends on various vital factors, such as soil fertility, good quality irrigation water, etc. During the crop growth cycle, a plant has to constantly face several biotic and abiotic stresses that negatively affect the morphological, physiological, biochemical, and molecular changes in plants, ultimately decreasing productivity. Recently, there has been an increased interest in using nanotechnology in the agriculture sector for managing abiotic stresses and improving plant performance under these conditions. However, the excessive use of nanofertilizers in high concentrations will cause toxicity in plants and negatively affect plant growth. Also, the excessive application of nanoparticles may be destructive to humans and the environment owing to the fast accumulation of nanoparticles in the tissues of alive bodies. This obligates the researchers to find the correct method and doses of nanoparticles for different plants. The study aimed to investigate the advantages and disadvantages of applying different doses of Se NPs for basil productivity and its quality under drought stress conditions.

The study demonstrated that basil's agronomic traits and dry yield were reduced under moderate and severe water stress. Water limitation negatively impacts the plant's morphological, physiological, and chemical processes. In this situation, the photosynthesis rate of plants decreases in water-stress conditions owing to reducing the leaf area, closing the stomata, reducing the conductivity of the stomata, the lipid peroxidation of membranes, and reducing the synthesis of protein and chlorophyll, which lead to decreasing plants productivity [31]. Similarly, Ostadi et al. [4] noted that the dry yield of sage (*Salvia officinalis* L.) decreased by 30% and 35% under moderate and severe water stress, respectively. Javanmard et al. [32] reported that the fresh and dry weight of balangu (*Lallemantia iberica*) reduced by 14.9% and 15.3% under moderate water stress (60% FC), and by 33.9% and 34.2% under severe water stress (30% FC), respectively.

On the other hand, applying Se NPs, especially in the concentration of 50 mg L^{-1}, enhanced canopy diameter, the number of leaves, lateral branches, and basil's dry yield. One of the positive effects of using selenium nanoparticles, especially in low concentrations, is the increase in plant root growth [33]. Therefore, the increase in plant productivity after applying Se NPs could be attributed to the improvement of root growth, which will lead to an increase in the absorption of nutrients, the rate of photosynthesis, and the plant's growth characteristics. It has been reported that applying Se NPs, especially in a low concentration, is vital for increasing stomatal conductance and Rubisco activity and for the efficiency of photosynthetic system II, which will enhance the photosynthesis rate and plant productivity [34,35]. Kiumarzi et al. [36] reported that applying Se NPs increased the fresh and dry weight of pineapple mint (*Mentha suaveolens* Ehrh.).

Our results showed that the EO content and main EO constituents of basil, such as methyl chavicol, linalool, and 1,8-cineole, enhanced under water-stress conditions. Compared with plants whose economic performance is reduced under drought stress, the performance of medicinal and aromatic plants is enhanced under stressful conditions through the biosynthesis of secondary metabolites. The biosynthesis of secondary metabolites in medicinal and aromatic plants is known as one of the defensive mechanism systems for increasing the adoption of these plants in the face of stressful conditions [37]. Under drought stress conditions, the photosynthesis rate of plants decreased because of closing stomata and the lower absorption of CO_2, which led to the accumulation of NADPH+H^+ in plant cells. The biosynthesis of secondary metabolites, such as EO compounds, alkaloids, phenolics, etc., through the consumption of NADPH+H^+ increases plant efficiency under stressful conditions [4]. Amani Machiani et al. [38] concluded that the essential oil content of thyme (*Thymus vulgaris* L.) and the main EO constituents of this plant, such as thymol and γ-terpinene, enhanced under moderate drought stress.

Interestingly, applying Se NPs enhanced the EO content and improved EO quality by increasing basil's main EO constituents. The increasing EO productivity through the application of Se NPs could be explained by the role of the aforementioned NPs in improving root growth and higher nutrient uptake, which leads to increasing EO precursor compositions and intermediate EO compounds such as acetyl coenzyme A, NADPH, and ATP. In addition, applying Se NPs could increase the chlorophyll content by modulating the adverse effects of drought stress. Increasing the chlorophyll concentration is vital for improving the photosynthesis rate and producing sufficient carbohydrates for the growth of cells and the production of EO-secreting glands. In this way, it can increase EO content in the plant. In accordance with the results of the present study, Azimi et al. [39] noted that the application of Se NPs improved the EO quality of *Dracocephalum moldavica* L. by increasing the content of geranyl acetate, geraniol, geranial, and z-citral.

The EO yield of basil enhanced under severe water stress and Se NPs. The EO yield of plants is calculated from the dry matter yield productivity and EO content, and it directly relates to these two mentioned indicators. Therefore, the increasing EO yield of basil could be attributed to enhancing plant EO productivity under severe water stress and applying Se NPs.

Phenolic compounds have antioxidant activities that they collect and reduce reactive oxygen species (ROS), thereby preventing the oxidation of vital biomolecules and inhibiting oxidative stress or mitigating its impacts on plant cells. The results of this study demonstrated that the application of Se NPs, especially at lower concentrations, improved basil plants' phenolic compounds under water-stress conditions. The increasing phenolic compounds through the application of Se NPs could be attributed to enhancing nutrient availability, which enhances the activity of enzymes involved in the biosynthesis of phenolic compounds [40]. In addition, Li et al. [41] reported that the Se NPs affect JA productivity by adjusting the alpha-linolenic acid pathway, which induces the synthesis of phenolics and flavonoids in the celery (*Apium graveolens*) plant. These authors noted that the content of the apigenin, rutin, *p*-coumaric acid, and ferulic acid of the celery plant enhanced by 58.4%, 66.2%, 80.4%, and 68.2% after the application of Se NPs.

The content of chlorophyll a and chlorophyll b decreased under both moderate and severe water stress. Exposing the plant to drought stress seems to enhance the content of reactive oxygen radicals (ROS) compounds, which leads to an increase in the lipid peroxidation of the membranes and, ultimately, the decomposition of chlorophylls in the leaves [42]. In addition, the decreasing chlorophyll content under water-stress conditions may be due to the decreasing nutrient absorption that negatively affects the biosynthesis of chlorophyll [43]. Javanmard et al. [32] reported that the content of chlorophyll a and b in *Lallemantia iberica* leaves decreased under moderate and severe water deficits. In contrast to chlorophylls, the carotenoid concentration was enhanced under drought-stress conditions. The actions of enzymatic and nonenzymatic antioxidant systems usually suppress the oxidative damage of drought stress in plant tissues. The nonenzymatic antioxidants include carotenoids (xanthophylls and carotenes), ascorbates, and alpha-tocopherol, which enhance plant tolerance in the face of stressful conditions by decreasing the activity of ROS compounds [44].

Moreover, the concentration of chlorophylls and carotenoids was enhanced by applying Se NPs. It seems that applying stress-modulating NPs such as Se NPs reduced the adverse effects of water stress and the lipid peroxidation of membranes, thereby affecting the content of chlorophyll and carotenoids in plant cells. Similarly, Seliem et al. [45] showed that the application of Se NPs enhanced the content of chlorophyll a and b in the *Chrysanthemum morifolium* Ramat leaves.

Our results showed that the osmolyte (proline and soluble sugar) concentration enhanced under water-deficit conditions. The accumulation of soluble sugars and proline in response to environmental stress is related to the osmotic regulation or protection of cell membranes. During this physiological process, plant cells absorb osmolyte metabolites such as amino acids (especially proline), soluble sugars, etc., which reduces osmotic potential and maintains the turgescence pressure of plant cells at a high level. Therefore, the increasing proline and soluble sugars under water stress maintain the ROS levels within normal ranges (detoxification of ROS), decreasing lipid peroxidation, stabilizing the membranes and improving cell turgor [46]. In addition, the application of Se NPs enhanced the content of soluble sugars and proline, which may be due to the central role of Se NPs in decreasing chlorophyll decompositions and increasing the photosynthesis rate, which enhances the carbohydrate and other biomolecule content under water-stress conditions. It has been reported that the application of Se NPs enhanced the photosynthesis rate by modulating the negative impacts of drought stress and the upregulation of genes related to light-harvesting complex II [47].

5. Conclusions

Water stress is one of the leading abiotic stress factors that disrupt plant growth and development and thus lead to productivity loss. Using selenium under water stress conditions can cause plants to adapt to drought. The study demonstrated that the application of Se NPs modulates the negative impacts of water-stress conditions by improving chlorophylls, carotenoids, and osmolytes (proline and soluble sugars). In addition, the application of Se NPs enhanced the EO content and main EO constituents of the basil plant, such as linalool, methyl chavicol, and 1,8-cineol. We conclude that applying Se NPs, especially in low concentrations, increased plant tolerance and improved the essential oil quantity and quality of the basil plant under water-stress conditions.

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