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Exogenous application of selenium or iodine improves the growth, yield and antioxidant status of *Capsicum annuum* L.

Manar S.M.F. Hassan [a] Hussein E.E. Belal [a], Alaa I.B. Abou-Sreea [b,*], Mostafa M. Rady [a]

[a] *Botany Department, Faculty of Agriculture, Fayoum University, Fayoum 63514, Egypt*
[b] *Horticulture Department, Faculty of Agriculture, Fayoum University, Fayoum 63513, Egypt*

A R T I C L E I N F O

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A B S T R A C T

Selenium (Se) and iodine (I) are not essential for plant metabolism, however, they are important to humans and animals, and therefore their presence in trace amounts in food is beneficial. Crop fertilization programs provided by Se and I allow for mineral biofortification of the crop and further accumulation of more antioxidants in the plant's edible organs. Therefore, the exogenous application of Se or I may offer a potentially interesting approach to enhancing crop yield and quality. This study aimed at investigating the effect of Se or I application on growth traits, chlorophyll content, fruit yield, and fruit quality (antioxidant capacity) of pepper plants. Growth traits (e.g., shoot length, plant leaf area, plant leaf number, shoot fresh weight, and shoot dry weight), chlorophyll content, plant fruit yield, and fruit quality traits (e.g., vitamin C, capsaicin, and β−carotene contents) were gradually increased with incremental increases in Se and I concentration, applied as a foliar spray (FrS) or through irrigation water (IrW), compared to the control. Maximum values of growth traits, chlorophyll content, and plant fruit yield were obtained with 20 or 40 mg Se L^{-1} applied as FrS or through IrW, respectively, and with 2.5 or 1.0 mg I L^{-1} applied as FrS or through IrW, respectively. While maximum values of fruit quality traits were obtained with 40 or 50 mg Se L^{-1} applied as FrS or through IrW, respectively, and with 7.5 or 5.0 mg I L^{-1} applied as FrS or through IrW, respectively. However, the Se-IrW treatments were better than the I-FrS treatments. Therefore, this report recommends the utilization of 40–50 mg Se L^{-1} applied through irrigation water to reinforce pepper plant growth and yield with high quality (antioxidant capacity).

1. Introduction

Pepper, which belongs to the Solanaceae, is second only to tomato among the most important vegetable crops. Of the approximately 30 species of pepper, *Capsicum annuum* is the most cultivated in tropical and temperate regions. It has core values related to economics, nutrition, and medical therapy. It is an essential source of natural colors and antioxidants [1]. Including *C. annuum*, climate change is harming agricultural crop yields by reducing the availability of fresh water [2, 3]. Drought stress (DSt) limits dry matter accumulation, nutrient uptake, and fruit yield of *C. annuum*. Besides, physio-biochemical and molecular processes, as well as antioxidant mechanisms are also affected by DSt [4].

Regularly, vegetables and field crops are subjected to different eco-stressors, including drought and salinity [5-9]. The negative effects of lack of water available to the plant is called “DSt”, which negatively affects plant cell metabolism and performance, and thus plant growth and productivity, and severe DSt leads the plant to not continue to survive [10, 11]. DSt is a major eco-stressor that stunts the growth and productivity of cultivated crops. DSt has adverse effects on nutrient intake, transport, and metabolism, directly contributing to plant growth and altering the assimilation partition of organs [9, 12-14]. Avoidance, tolerance, and/or escape are plant responses to DSt The increase in water uptake and decrease in leaf area, stomatal conductance, and transpiration rate is termed "avoidance". Osmotic adaptation, maintaining tissue rupture, and allowing plants to maintain growth under extreme stress is called "tolerance". Furthermore, the growth promotion that helps plant survive to the end of its life cycle is termed "escape" [15]. An enhanced understanding of the concepts of water use efficiency in agriculture through the application of good agricultural practices is important means for the effective management of available agricultural water [16]. Several strategic sustainable agricultural practices have recently been applied to improve plant self-defense systems in different crops to attenuate the adverse effects of eco-stressors, including selenium (Se; [12, 17, 18]) and iodine (I; [19-21]).

Selenium is considered an antioxidant mineral essential to plants. Plant growth and productivity are negatively affected in Se-poor agricultural lands [17, 22, 23]. The practical role of Se as an essential trace element for plants is still in the field of research. The toxicity range of Se is limited, and thus its use should be in small amounts because it can be toxic. In recent papers [11, 17, 24], however, Se has desirable influences on cellular metabolism

* Corresponding author.
E-mail address: aib00@fayoum.edu.eg (A. Abou-Sreea); Tel.: +20-84-010-074-677-89
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when applied in lower doses. Particularly in stressed plants, Se enhances plant growth, osmoregulating substances, and different (enzymatic and non-enzymatic) antioxidants. These positive Se outcomes lead to reducing the undesirable influences of DSt on photo-system II and enhancing photosynthesis [17, 25, 26]. Therefore, Se has antioxidant significance under eco-stresses, especially DSt and salinity [17, 27]. To offset its deficiency in the edible parts of food crops, Se has been applied to plants as foliar spraying or to soil with irrigation water to attenuate the stress damage in plants and to boost plant growth and development, especially under DSt [17, 28].

Iodine (I) is an essential nutrient for human health. It is involved in the synthesis of thyroid hormones, which play a dominant role in growth and metabolism [29] and the development of most organs, especially the brain [30]. There is no enough information available on the influence of I on plant morphology, physiology, biochemical characteristics, and plant productivity as I is not essential for plants. Thus, little papers have explored I positive influences on plant growth and productivity [19, 31-33].

There are no works so far for the foliar application of Se (Se-FrS) or I (I-FrS) and adding Se or I in irrigation water (Se-IrW or I-IrW, respectively) for pepper plants grown under DSt. Therefore, this research aimed at assessing the potential positive influences of Se-FrS or I-FrS and also of Se-IeW or I-IrW on modulating growth, fruit yield, and antioxidant levels of DSt-exposed pepper plants. The hypothesis for this study is that Se-FrS or I-FrS and Se-IeW or I-IrW would enhance the plant performance by promoting plant growth, yield, and antioxidant levels of DSt-exposed pepper plants.

Among the recently revealed cathode materials, the cation-disordered rocksalt Li-excess (DRX) cathode materials have an intense attraction due to their characteristics [11-14]. The DRX cathode materials can deliver energy densities over about 1000 (Wh/kg) [15]. Urban et al. [16] reported a considerable cation disordering and Li excess in the rocksalt structure (NaCl-structure) lead to DRX materials that can produce high capacities compared to other commercial materials [16]. The cation disordering which means the random distribution of Li and transition metal (TM) at the cation sublattice 4a sites creates zero-TM channels. Such channels have no TMs in the face-sharing octahedra and act as the main channel for Li diffusion [16-18]. It is suggested that the existence of the d0 transition metal is vital for creating disordered rocksalt phases [17]. In 2015, Yabuuchi et al. [19] reported the niobium-based high-capacity cathode material, $Li_{1.3}Nb_{0.3}Mn_{0.4}O_2$ that delivers high noticeable reversible capacities up to 300 mAh.g^{-1}. The output high capacity refers to applying a Mn^{2+}/Mn^{4+} redox couple that utilizes a redox reaction of two electrons ($2e^-$) [12, 19]. Recently, Kamel et al. [20] reported the optical, magnetic, and thermodynamic properties of this compound. Since most studies are directed toward electrochemistry performance, there are few concerning fundamental studies such as thermal and dielectric properties. Furthermore, the thermal analysis for cathode materials of LIBs is very important to understand their behavior at elevated temperatures [21]. This work aimed to throw light on the thermal analysis up to 995 °C, FTIR spectra, and the electrical properties of LNMO at different temperatures as well as different frequencies.

2. Experimental part

2.1. *Plant Material and Growth Conditions*

Three pot experiments were performed in the Experimental Farm (29° 17'N; 30° 53'E) of the Faculty of Agriculture, Fayoum University, Egypt. Thirty-five-day-old C. annuum seedlings (cultivar "Top Star Hybrid") were procured from Egyptian Ministry of Agriculture nurseries. The uniform healthy seedlings were gently washed and transplanted into 216 plastic containers (32 cm diameter, 30 cm depth) at a rate of 1 seedling per container. Before transplantation, each container was filled with approximately 8 kg of growth medium (GM) suggested in [34]. The suggested GM consisted of 16.67% crushed corn grains, 33.33% vermiculite, and 50.00% peat moss with adding humic acid at a rate of 250 mg L^{-1} of the medium. The GM also received a fungicide (e.g., Moncut SC) at a rate of 125 mg L^{-1} of the medium (Central Glass Co., Ltd., Tokyo, Japan). In addition, the GM was supplied with fertilizer ingredients; ammonium nitrate, calcium superphosphate, potassium sulfate, and magnesium sulfate were added at a rate of 415, 500, 333, and 833 mg L^{-1} of the medium, respectively, and iron, zinc, and manganese were also added at a rate of 333mg L^{-1} of the medium each. To regulate the pH of the GM, CaCO3 was added at a rate of 1250 mg L^{-1} of the medium. Finally, a leguminous compost was added to the GM components at a rate of 2%.

The containers were randomly arranged in an open (net) greenhouse under natural conditions; average temperature 26 ± 3 °C, humidity 65 ± 5%, day/night photoperiod 11/13 h, and natural sunlight intensity. Fifteen days after transplantation (DAT), the containers were divided into two groups (for selenium; Se and iodine; I treatments), each containing 108 containers. Each group was divided into two sub-groups (for foliar spray and soil application through irrigation water) each group contained 54 pots (9 pots/replicates for each one of 6 treatments). Each sub-group was divided into 6 treatments; 0, 10, 20, 30, 40, and 50 mg for Se L^{-1}, and 0, 1.0, 2.5, 5.0, 7.5 and 10.0 mg for I L^{-1}. Foliar spraying of Se and I was performed three times; at 15, 30, and 45 DAT. For soil treatments, Se and I at the indicated concentrations were added to the irrigation water three times and applied at the same times as the three foliar sprays. For foliar spraying, a solution of Se or I was applied in an average of 30 mL per plant (20 mL per plant at 15 DAT, 30 mL per plant at 30 DAT, and 40 mL per plant at 45 DAT) each time the spray was done.

The main study was conducted three times simultaneously in the same period. The treatments of each trial were arranged in a completely randomized design and the trials were continued until harvest (80-94 DAT). The weight method was utilized to water plants daily, where the containers were weighed and watered up to the soil field capacity, by replacing the amount of water transpired and evaporated. The containers were rotated every 2 days throughout the trial duration to avoid bias and systematic error produced by fluctuations in the local environmental conditions.

2.2. *Sampling and replicates of estimations*

Pepper plant samples were taken 60 DAT. The plant shoot was used for vegetative growth traits, while the upper fully-expanded leaves were utilized for biochemical determinations and determinations of antioxidants. Pepper fruits were obtained at harvest stage (80-94 DAT) to evaluate fruit yield per plant. All samples were collected at 8.00 am (11 ± 1 °C) in the shortest possible time to avoid the fluctuations in environmental factors influencing sample tissues. The samples were then quickly transported to laboratories for various analyses. Samples from 3 replicates were used to measure all growth and yield traits and to determine antioxidants.

2.3. *Evaluation of plant growth and yield traits and yield quality*

At 60 DAT, plant growth traits were evaluated as follows: leafy areas were measured by scanning using a Leaf Area Meter LI-3100C (LI-COR, Lincoln, NE, USA). Shoot fresh weights were taken, and then shoot dry weights were recorded after drying at 70 °C for 48 h until constant weights were obtained.

At the harvest stage (80-94 DAT), fruits were collected and counted for each plant. Average fruit yield was assessed for each plant. The quality was evaluated in fresh fruits; vitamin C (ascorbate) contents (mg 100g^{-1} FW) was measured following the Okamura [35] method with a modification of Law et al. [36]. Capsaicin contents were estimated in pepper fruit samples according to the colorimetric estimation suggested by Reddy [37]. The HPLC method was used to assess the content of β−Carotene as described by Mejia et al. [38].

2.4. *Evaluation of total chlorophyll content*

Total chlorophyll content was determined using the fully-extended first and second upper leaves of each plant. Extraction of fresh leaf samples was done using pure acetone as a solvent and the total chlorophyll (mg g^{-1} FW) was evaluated [39].

2.5. *Statistical analysis*

The experiments were arranged in a completely randomized design. The data (3 replicates for all determinations) were analyzed statistically utilizing one-way-ANOVA, after testing for homogeneity of error variances following the Gomez and Gomez [40] procedures. Combined analysis of the data of the three trials was carried out and significant differences between treatments were compared at $p \leq 0.05$ by Duncan's multiple range test. The GLM procedure of Gen STAT (version 11) (VSN International Ltd., Oxford, UK) was applied.

3. Results

In this study, different concentrations of selenium (Se; 0, 10, 20, 30, 40, or 50 mg L^{-1}) and iodine (I; 0, 1.0, 2.5, 5.0, 7.5, or 10.0 mg L^{-1}) were applied, as foliar spraying or through irrigation water, to evaluate their influences on growth and yield traits, chlorophyll content, and fruit quality (antioxidant capacity) of hot pepper plants.

3.1. Effects of Se and I on growth traits

Shoot length (SL), plant leaf area (PLA), plant leaf number (PLN), shoot fresh weight (SFW), and shoot dry weight (SDW) were gradually increased with incremental increases in Se and I concentration, applied as a foliar spray (FrS) or through irrigation water (IrW), compared to the control (Tables 1 and 2). Maximum values were obtained with 20 or 40 mg Se L^{-1} applied as FrS or through IrW, respectively, and with 2.5 or 1.0 mg I L^{-1} applied as FrS or through IrW, respectively. Thereafter, the growth traits were reduced by increasing the concentrations of Se or I up to 40 mg L^{-1} and 5 mgL^{-1}, respectively. Applications of Se at 40 mg L^{-1} through irrigation water (Se-IrW) and I at 2.5 mg L^{-1} as a foliar spray (I-FrS) were the best treatments conferring the best growth traits of pepper plants. The Se-IrW (at 40 mg L^{-1}) and I-FrS (at 2.5 mg L^{-1}) increased SL, PLA, PLN, SFW, and SDW by 23.8 and 8.7%, 29.4 and 12.2%, 31.5 and 11.2%, 54.0 and 39.1%, and 56.0 and 28.7%, respectively. Furthermore, the Se-IrW treatment was better than I-FrS, specially fruit quality under Se applied as IrW (Tables 1 and 2).

3.2. Effects of Se and I on chlorophyll content

As shown in Tables 1 and 2, chlorophyll content was gradually increased with progressive increases in Se and I concentration, applied as a foliar spray (FrS) or through irrigation water (IrW), compared to the control. Maximum chlorophyll values were obtained with 20 or 40 mg Se L^{-1} applied as FrS or through IrW, respectively, and with 2.5 or 1.0 mg I L^{-1} applied as FrS or through IrW, respectively. Then, chlorophyll content was decreased by increasing the concentrations of Se or I. Applications of Se at 40 mg L^{-1} through irrigation water (Se-IrW) and I at 2.5 mg L^{-1} as a foliar spray (I-FrS) were the best treatments giving the best chlorophyll content of pepper plant leaves. The Se-IrW (at 40 mg L^{-1}) and I-FrS (at 2.5 mg L^{-1}) increased chlorophyll content by 35.0 and 21.5%, respectively. Moreover, the Se-IrW treatment was better than I-FrS (Tables 1 and 2).

Table 1. Effect of selenium (Se) levels applied as foliar sppray (FrS) or through irrigation water (IrW) on growth, yield, and fruit quality of hot pepper plant (cv. Top Star Hybrid)

S-treatments	Treatment types/Parameters									
	FrS	IrW	FrS	IrW	FrS	IrW	FrS	IrW	FrS	IrW
	Shoot length (cm)		Leaf area (cm^2)		Leaf number plant^{-1}		Shoot FW (g)		Shoot DW (g)	
S-0	78.0±6.1bc	77.8±5.7c	0.221±0.018c	0.221±0.018d	26.0±2.3b	26.0±2.3d	69.6±5.9c	69.6±6.0e	8.36±0.56c	8.36±0.55e
S-10	81.9±6.5b	81.0±6.3c	0.235±0.019b	0.234±0.019d	26.9±2.3b	27.5±2.3cd	79.2±6.4b	76.8±6.8d	8.98±0.64b	9.28±0.68d
S-20	87.1±7.3a	86.3±6.9b	0.252±0.022a	0.253±0.021c	29.5±2.4a	29.0±2.5c	98.0±7.6a	83.2±6.8c	11.12±0.80a	10.92±0.84c
S-30	76.3±5.5c	90.5±7.1b	0.220±0.018c	0.267±0.023b	24.5±2.2c	31.5±2.6b	71.6±5.6c	93.6±7.6b	7.36±0.54d	12.28±0.88b
S-40	69.9±5.0d	96.3±7.7a	0.212±0.018cd	0.286±0.025a	18.5±1.7d	34.2±2.9a	53.9±4.8d	107.2±8.4a	6.16±0.48e	13.04±0.98a
S-50	52.8±4.8e	72.3±5.9d	0.205±0.015d	0.191±0.015e	17.5±1.4d	19.5±1.6e	40.8±4.2e	59.6±4.8f	4.56±0.36f	6.56±0.41f
	TChl content (mg g^{-1} FW)		Fruit yield plant^{-1} (g)		Vitamin C (mg 100 g^{-1} fruit FW)		Capsaicin (mg Kg^{-1} fruit FW)		β−Carotene (mg Kg^{-1} fruit FW)	
S-0	2.46±0.08c	2.46±0.08e	395±28c	395±28e	124.2±4.2e	124.2±4.2f	170.3±4.8e	170.3±4.8f	121.4±3.8e	121.4±3.8f
S-10	2.74±0.10b	2.68±0.09d	466±34b	426±31d	151.1±4.9d	143.5±4.8e	194.8±5.4d	195.2±5.3e	144.5±4.2d	145.0±4.4e
S-20	3.04±0.13a	2.89±0.09c	528±39a	463±34c	214.6±6.4c	170.8±5.1d	251.0±7.2c	224.3±5.9d	197.3±5.7c	171.3±4.9d
S-30	2.33±0.08c	3.11±0.12b	334±24d	512±39b	230.3±7.3b	201.3±5.9c	288.4±8.5b	260.4±7.4c	225.5±7.1b	194.8±6.1c
S-40	2.04±0.06d	3.32±0.15a	242±21e	556±42a	252.6±8.4a	233.2±7.2b	309.2±9.2a	288.6±8.3b	250.1±7.9a	228.8±7.4b
S-50	1.88±0.05e	1.89±0.06f	184±14f	364±25f	106.7±3.2f	261.4±8.7a	102.4±3.4f	314.6±9.5a	104.1±2.9f	256.2±8.2a

S-0 (Control) = Pepper plants irrigated at 100% moisture at soil field capacity and not treated with Se; Se, Se-10, Se-20, Se-30, Se-40, or Se-50= Pepper plants irrigated at 100% of soil field capacity and foliar sprayed with or fed through irrigation water at 0, 10, 20, 30, 40, or 50 mg selenium L^{-1}, respectively; FW= Fresh weight; DW= Dry weight; TChl= Total chlorophylls.

Table 2. Effect of Iodine (I) levels applied as foliar spray (FrS) or through irrigation water (IrW) on growth, yield, and fruit quality of hot pepper plant (cv. Top Star Hybrid).

I-treatments	Treatment types/Parameters									
	FrS	IrW	FrS	IrW	FrS	IrW	FrS	IrW	FrS	IrW
	Shoot length (cm)		Leaf area (cm^2)		Leaf number plant^{-1}		Shoot FW (g)		Shoot DW (g)	
I-0	78.0±6.1bc	77.8±5.7b	0.221±0.018bc	0.221±0.018b	26.0±2.3bc	26.0±2.3b	69.6±6.0c	69.6±5.9b	8.36±0.56c	8.36±0.55b
I-1.0	80.3±6.3b	83.8±6.5a	0.229±0.019b	0.240±0.019a	26.9±2.3b	28.7±2.4a	84.8±6.8b	75.6±6.8a	9.28±0.64b	9.01±0.63a
I-2.5	84.8±6.8a	71.0±6.1c	0.248±0.021a	0.198±0.016c	28.9±2.5a	22.7±1.9c	96.8±7.2a	61.6±5.2c	10.76±0.76a	8.08±0.48b
I-5.0	75.5±7.3c	51.3±5.0d	0.214±0.018c	0.152±0.012d	25.6±2.3c	19.4±1.5d	67.2±5.2c	56.8±4.4d	8.04±0.55c	7.00±0.46c
I-7.5	75.0±5.8c	35.5±3.2e	0.195±0.016d	0.126±0.009e	22.4±2.0d	14.2±1.1e	57.2±4.5d	48.4±3.2e	7.32±0.44d	5.76±0.44d
I-10	52.9±4.5d	25.0±1.9f	0.155±0.013e	0.111±0.007f	17.5±1.5e	10.7±0.8f	40.4±2.8e	41.2±2.4f	5.76±0.36e	4.32±0.32e
	TChl content (mg g^{-1} FW)		Fruit yield plant^{-1} (g)		Vitamin C (mg 100 g^{-1} fruit FW)		Capsaicin (mg Kg^{-1} fruit FW)		β−Carotene (mg Kg^{-1} fruit FW)	
I-0	2.46±0.08c	2.46±0.08b	395±28c	395±28b	124.2±4.2e	124.2±4.2d	170.3±4.8e	170.3±4.8d	121.4±3.8e	121.4±3.8d
I-1.0	2.68±0.09b	2.81±0.11a	449±32b	434±32a	174.2±4.9d	159.6±5.5c	201.4±5.7d	201.2±6.0c	151.3±4.5d	162.3±4.9c
I-2.5	2.99±0.12a	2.21±0.06c	512±38a	332±24c	205.8±6.0c	195.4±7.2b	246.2±6.9c	250.2±7.4b	194.7±5.4c	210.2±6.2b
I-5.0	2.21±0.06d	2.04±0.05d	352±26d	204±14d	224.7±7.0b	239.9±8.0a	270.5±7.7b	288.7±8.6a	219.8±6.3b	239.7±7.2a
I-7.5	1.94±0.05e	1.64±0.03e	284±21e	153±12e	248.6±8.2a	120.4±3.8d	299.4±8.9a	161.3±4.2d	246.6±7.6a	112.4±3.6de
I-10	1.64±0.04f	1.23±0.02f	202±18f	111±08f	102.4±3.0f	102.4±3.1e	155.1±3.9f	122.5±3.4e	111.2±3.2f	104.4±3.2e

I-0 (Control) = Pepper plants irrigated at 100% moisture at soil field capacity and not treated with I; I-0, I-10, I-25, I-50, I-75, or I-100= Pepper plants irrigated at 100% of soil field capacity and foliar sprayed with or fed through irrigation water at 0, 1.0, 2.5, 5.0, 7.5, or 10.0 mg iodine L^{-1}, respectively; FW= Fresh weight; DW= Dry weight; TChl= Total chlorophylls.

3.3. Effects of Se and I on pepper fruit yield

Tables 1 and 2 show that plant fruit yield was gradually increased with gradually increases in Se and I concentration, applied as a foliar spray (FrS) or through irrigation water (IrW), compared to the control. Maximum plant fruit yields were obtained with 20 or 40 mg Se L^{-1} applied as FrS or through IrW, respectively, and with 2.5 or 1.0 mg I L^{-1} applied as FrS or through IrW, respectively. Then, plant fruit yield was decreased by increasing the concentrations of Se or I. Applications of Se at 40 mg L^{-1} through irrigation water (Se-IrW) and I at 2.5 mg L^{-1} as a foliar spray (I-FrS) were the best treatments giving the best fruit yield of pepper plants. The Se-IrW (at 40 mg L^{-1}) and I-FrS (at 2.5 mg L^{-1}) increased plant fruit yield by 40.8 and 29.6%, respectively. Moreover, the Se-IrW treatment was better than I-FrS (Tables 1 and 2).

3.4. Effects of Se and I on pepper fruit quality (antioxidant capacity)

Fruit vitamin C (F-vit), capsaicin (Cpn), and β−Carotene (β−Crt) were gradually increased with incremental increases in Se and I concentration, applied as a foliar spray (FrS) or through irrigation water (IrW), compared to the control (Tables 1 and 2). Maximum values were obtained with 40 or 50 mg Se L^{-1} applied as FrS or through IrW, respectively, and with 7.5 or 5.0 mg I L^{-1} applied as FrS or through IrW, respectively. Thereafter, the fruit quality traits were reduced by increasing the concentrations of Se or I. Applications of Se at 50 mg L^{-1} through irrigation water (Se-IrW) and I at 7.5 mg L^{-1} as a foliar spray (I-FrS) were the best treatments conferring the best fruit quality traits of pepper plants. The Se-IrW (at 50 mg L^{-1}) and I-FrS (at 7.5 mg L^{-1}) increased F-vit, Cpn, and β−Crt by 110.5 and 100.2%, 84.7 and 75.8%, and 111.0 and 103.1%, respectively. Furthermore, the Se-IrW treatment was better than I-FrS (Tables 1 and 2).

4. Discussion

All obtained findings were significantly increased with 40−50 mg Se L^{-1} applied through irrigation water (Se-IrW), which exceeded 2.5−7.5 mg I L^{-1} applied as a foliar spray (I-FrS), which in turn surpassed other I concentrations (Tables 1 and 2). Se-IrW at 40−50 mg L^{-1} and I-FrS at 2.5−7.5 mg L^{-1} enabled pepper plants to confer the highest growth traits (e.g., shoot length, plant leaf area, plant leaf number, shoot fresh weight, and shoot dry weight), chlorophyll content, plant fruit yield, and fruit quality traits (e.g., vitamin C, capsaicin, and β−carotene contents) (Tables 1 and 2).

The positive effect of Se on yield and yield quality of pepper plants, in this study, is very important for human health due to the increased fruit content of antioxidants with regard to the agricultural crop foods produced in Se-deficient soils in many areas, including Egypt (Table 1). Se applied through irrigation water (Se-IrW) was better than Se applied as foliar spraying and significantly improved pepper plant growth performance (Table 1). Regarding Se concentrations on growth traits, yield, chlorophyll content, and yield quality, 40−50 mg L^{-1} was the most effective. The increase occurred by Se-IrW in plant growth traits indicates that Se-IrW improved the underground (root) growth of pepper reflecting the improved shoot growth. It has been reported that the root tip cell mitotic division can be increased by Se thereby the increase root growth, which positively reflects in shoot growth. They added that, possibly by the increase in starch content in chloroplasts, Se at low concentrations increases plant growth [41]. It has been demonstrated that Se at proper concentrations enhanced plant growth, and balanced hormonal and nutrient contents within plants leading to improved plant root and shoot growth [18, 42, 43]. However, as shown in this study (Table 1), high Se concentrations induced negative impacts on pepper plant growth traits and reduced pepper shoot biomass. This negative finding by high Se concentrations can be attributed to changes in the permeability of cellular membranes losing essential ions and causing respiration disturbance and water uptake [44]. In this study, the increased fruit yield of pepper plants by Se-IrW could be due to the increase in chlorophyll content and shoot biomass (Table 1). It has been reported that Se induces positive impacts on physiological, biochemical, and molecular processes and enhanced photosynthetic efficiency in plants. However, higher doses of Se lead to phytotoxic impacts on the cellular physio-biochemical and molecular processes [45]. In this study, pepper plants showed increases in the antioxidant activity of fruits. In this regard, it has been elucidated that the increased plant antioxidant activity might be, at least partially, explained by the increased concentrations of phenolic compounds [45, 46]. In addition, it has been demonstrated that a proper concentration of Se markedly improves the photosynthetic pigments by increasing the antioxidant activity and delaying the leaf tissue senescence in *Brassica oleracea* plants [47]. In this study, Se led to significant increases in fruit antioxidants (e.g., vitamin C, capsaicin, and β−Carotene). This result was a positive reflection of increased chlorophyll content and growth traits on fruit yield and its content of antioxidants (Table 1).

Earlier research work revealed that Se has a double effect on plant growth; at a lower concentration, it improves the growth of flue curd tobacco but its higher concentration reduced the growth [48]. Jiang et al. [49] also found the same trend in maize plants where the application of high Se dose considerably reduces the root and shoot growth of maize plant. The same results were confirmed as well by Hawrylak-Nowak et al. [50] on cucumber plants. Toxic effects of high Se application were also found by Dhillon and Dhillon [51] and Ramos et al. [52] in different plants. Reduction in plant growth parameters could be due to the reduction in photosynthetic activity and chlorophyll content [53]. Higher selenium concentration reduces net photosynthetic rate (A), which ultimately leads to a reduction in biomass production. In this regard, Noreen and Ashref [54], Siddiqi et al. [55], Abbasi et al. [56] found a significant reduction in the transpiration rate of sunflower, safflower and maize, respectively. Se was found toxic when 10 or above 10 mg kg^{-1} was applied in growth medium for tomato plants [57, 58]. Naseem et al. [59] observed that maize membrane stability index, relative water contents, the accumulation of Se in shoots, growth, physiological, water relation, and gas exchange parameters, dry matter and the antioxidant activities also decreased as the Se level increased and vice versa. Destruction in antioxidant activity with higher Se was also proved by Jiang et al. [49]. Such destruction in antioxidant activity may be because of the production of reactive oxygen species (ROS) [60] which adversely affect the antioxidant activity, water relation, and gas exchange parameters, which are important for normal plant growth [61] and also damages the proteins and DNA and could interfere with natural cellular functioning in plants, resulting in cellular death. Jiang et al. [49] assured that high concentration of Se competes with micronutrients like Fe and Zn in plants and disrupts their uptake.

On the other hand, Nawaz et al. [62] found that low Se concentration enhanced the stomatal and photosynthetic cells of garlic. So, the increase in photosynthetic activities was due to the positive effect of Se on photosynthesis. Also Xia et al. [63] observed that Se was at low levels gave the highest value of relative water content in Hordeum vulgare plants which might be due to the improvement in membrane stability [64]. Iron concentration in roots was only increased with lowest Se concentration [65]. Enzyme activities, plant height and root length, transpiration rate, photosynthetic rate, and stomatal conductance were also improved in maize plants exposed to low Se level [59].

For iodine (I), physio-biochemical mechanisms of I interaction on plant uptake of essential nutrients have not been explored. Also, in some reports [66, 67], the impact of I on photosynthesis machinery, including chlorophyll content, is not predicted. However, in this report, the element I significantly improved the growth, yield, yield quality (antioxidant capacity), and photosynthesis parameters, including chlorophyll content. Previous reports indicate a synergistic or antagonistic I effect on plant mineral nutrition [31]. Reports by Smoleń & Sady and Blasco et al. [31, 68] explored that by adding I to irrigation water (a cost-effective and beneficial method), KIO3 provides a significant increase in plant growth (biomass) as it optimizes soil nutrient levels. It also increases antioxidant amounts to enhance plant growth and productivity [69, 70]. On the other hand, through foliar spraying, IO_3^- (lower toxicity to plants) is transported from plant leaves to roots and edible parts and is reduced to I− [32, 71]. The lower IO_3^- toxicity can be elucidated based on that the IO_3^- is an alternative substrate to many enzymes, including nitrate reductase [72], or it activates IO_3^- reductase through its stimulation of other responses connected with redox signaling and I metabolism in plants, besides the IO_3^- reduction. As also reported by Weng et al. and Blasco et al. [73, 74], the addition of IO_3^- in nutrient solutions increases leaf vegetable biomass. The concentration ranges of $00.5–2 \times 10^{-3}$ M KIO_3 added to the plant nutrient solutions lead to significant increases in plant biomass [75, 76]. Positive influences of I on food crop biomass have been observed [77]. Although the global concentration of I averages at 2.6 mg per kg soil [78], applications of I up to 10 mg per kg soil enhance plant growth and productivity [79, 80]. In most cases, I application as IO_3^- is better than I^-, particularly for the synthesis of the antioxidant compounds [69,74]. KIO_3 supplementation (7.88 μM IO_3^-) increases the contents of vitamin C and phenolics in plants [33, 70]. KIO3 application (20 and 40 μM IO_3^-) increases AsA, GSH, and phenolic accumulations and antioxidant potential [74, 81]. In this report, the beneficial impact of I application on pepper plants may be related to its inclusion in plant proteins, thus stimulating plant growth, development, productivity, and fruit yield [67, 82].

Landini et al. [83] applied high I-concentrations from 5,000 to 20,000 μM in tomato plants grown hydroponically and observed that, despite toxicity symptoms as chlorosis and leaf tip burn, the plants produced fruits; therefore, they showed that tomato plants are resistant to high concentrations of iodine.

Smoleń et al. [84] noticed a negative correlation in lettuce between iodine concentrations and those of K, Ca, S, Mg, Na, Fe, Zn, Mn, Cu, and B. High concentrations of iodine could change the specific root transporters for IO_3^-, affect the uptake of K and P or trigger an antagonistic interaction that may explain the decrease of these elements in basil plants leaves [85]. Higher iodine content in plant tissues can activate detoxifying mechanisms which increase oxidizing enzymes activity and alter concentrations of Cu, Fe, and Mn in tissue [86]. However, Mackowiak et al. [87] suggested that IO_3^- might stimulate reductase activity in the root, which could affect the bioavailability of mineral nutrients, and induce other responses related to redox signaling to counteract the effect of IO_3^-.

Phytotoxic symptoms noticed in cowpea after potassium iodide and iodate foliar application may be due to smaller unit of leaf mass in comparison with cabbage since similar dosages were applied. Slight defoliation, chlorosis, and necrotic spots on the older leaves were visible still after foliar spray of both I fertilizers at 10 kg I ha^{-1}. However, eventual plant death was observed with 15 kg I ha^{-1} of potassium iodide. Iodide toxicity has been due to its photo-oxidation to free I in the presence of light, resulting in chlorophyll destruction [71]. This is also shown on butter head lettuce [88] and spinach [89, 73].

5. Conclusion

Selenium (Se) and iodine (I) are not essential for plant metabolism, however, they are important to humans and animals, and therefore their presence in trace amounts in food is beneficial. Crop fertilization programs provided by Se and I allow for mineral biofortification of the crop and further accumulation of more antioxidants in the plant's edible organs. Therefore, exogenous application of Se (through irrigation water) and/or I (as a foliar spray) may offer an interesting approach to improve crop growth, yield, and quality. Se or I application succeeded in increasing pepper plant growth, fruit yield, chlorophyll content, and fruit quality (antioxidant capacity). Providing irrigation water with Se (at 40−50 mg L^{-1}) should, in the future, be widely used to promote crop growth, yield, and yield quality.

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Author Contributions

All authors contributed to this work. Manar S.M.F. Hassan cultivation the crop and prepared the samples and completed the experimental measurements. Both Alaa I.B. Abou-Sreea and Mostafa M. Rady shared writing and followed the performance of the experiments. Hussein E.E. Belal helped the first author complete the sample preparation. A. Hassen with M. Kamel completed the paper writing, analyzing the data, and validation. A. Hassen followed the revision and submission of the manuscript for publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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