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Sustainable Production of Tomato Plants (*Solanum lycopersicum* L.) under Low-Quality Irrigation Water as Affected by Bio-Nanofertilizers of Selenium and Copper

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Abstract: Under the global water crisis, utilizing low-quality water sources in agriculture for irrigation has offered an effective solution to address the shortage of water. Using an excess of low-quality water sources may cause serious risks to the environment, which threaten crop safety and human health. Three kinds of irrigation water (0.413, 1.44, and 2.84 dS m^{-1}) were selected under foliar-applied bio-nanofertilizers of selenium (100 mg L^{-1}) and copper (100 mg L^{-1}) in individual and/or combined application. The nanofertilizers were tested on the production of tomato under greenhouse. After harvesting, the quality of tomato yield and soil biology was evaluated. Using saline water for irrigation caused many main features in this study such as increasing the accumulation of salts, soil organic matter, and $CaCO_3$ in soil by 84.6, 32.3, and 18.4%, respectively, compared to control. The highest tomato yield (2.07 kg $plant^{-1}$) and soluble solids content (9.24%) were recorded after irrigation with low water quality (2.84 dS m^{-1}) and nano-Cu fertilization. The plant enzymatic antioxidants and soil biological activity were decreased in general due to the salinity stress of irrigation water. After 30 days from transplanting, all studied soil biological parameters (soil microbial counts and enzymes) were higher than the same parameters at harvesting (80 days) under different categories of water quality. The values of all soil biological parameters were decreased by increasing water salinity. This study was carried out to answer the question of whether the combined nanofertilizers of selenium and copper can promote tomato production under saline water irrigation. Further investigations are still needed concerning different applied doses of these nanofertilizers.

Keywords: water quality; nanofertilizers; catalase; peroxidase; hydrogenase; enzymes

1. Introduction

Conventional fertilizers have caused many environmental problems such as inducing food contamination and soil degradation due to intensive use of these mineral fertilizers and pesticides [1]. Because of the poor conventional fertilizer use efficiency (ranging from 20 to 40%), a big amount of these fertilizers leached to groundwater and then rivers, causing economic damage, eutrophication phenomena, and problems for human health [2]. Therefore, nanofertilizers are considered promising materials that display unique properties of nanoparticles at the nano-scale [3]. The term nanofertilizers indicates nanomaterials that include the plant nutrient itself or the plant nutrient as a carrier and macro-nutrient nanofertilizers, nano-zeolite, nano-hydroxyapatite, and nano-biofertilizers [4]. Many studies reported benefits that resulted from nanofertilizers applied to cultivated crops such as alfalfa [5], soybean [6], potato [7], cabbage [8], maize [9], and wheat [10]. These benefits of nanofertilizers may include improving fruit quality, productivity, and shelf life and reducing the leaching of nutrients into soil after the harvesting of crops [8,10]. The most common nutrients that are already applied as nutrient-based nanofertilizers include iron [8], copper [5,11,12], selenium [13,14], and zinc [10,15,16].

The quality of irrigation water is a limiting factor in producing agricultural crops, which have some irrigation water quality guidelines such as salinity and sodium adsorption ratio (SAR), calcium, magnesium, sodium [17], and heavy metals such as As, Cd, Cr, Cu, Pb, Fe, Mn, and Zn [18]. When the used water in irrigation contains a high content of salts and heavy metals, these cause a low quality of the water and accumulate in both agricultural soil and cultivated plants [19]. This problem was aggravated by the intensive use of wastewater (low water quality) in the irrigation of cultivated plants, which contains many transferred pollutants to the food chain of humans and animals causing potential health risks in the long term [20]. Several studies reported the problems of saline and low water quality and their impacts on cultivated plants [20,21], soil quality [22,23], and projected human health [18,19]. Many materials have been applied to remediate this low water quality such as hydrogel [24], biochar [25], magnetic bentonite [26], and nanomaterials or nanoparticles [27,28]. Nanomaterials have been used in removing pollutants from contaminated water such as arsenic [28] and chromium [29,30], whereas the role of nanofertilizers in enhancing the productivity of cultivated plants irrigated with low water quality still needs more research.

Tomato plants (*Solanum lycopersicum* L.) are considered one of the main vegetable crops worldwide due to their high dietary and commercial value, besides their nutritional value (rich in vitamin A and C, phosphorus, iron, beta-carotene, anthocyanins, and lycopene). Therefore, tomato is naturally high in antioxidants and may protect against prostate cancer and protect the human skin from UV radiation due to its high content of lycopene [31]. This crop has a long-growth season with high water requirements and could produce under different stresses such as salt stress [15,32], drought [31], copper toxicity [16], continuous irrigation using saline water [33], and nano-toxicity [34–37]. Few studies have been published about the impact of nanoparticles on cultivated tomato under low water quality irrigation such as nano-TiO_2 [38] and nano-carbon [33], whereas there are no published articles on the effect of combined applied nanofertilizers on the productivity of tomato seedlings under irrigation with low-saline water.

Therefore, the present study was based on the question of whether nanofertilizers (Cu and Se), either individual or combined, can ameliorate the impact of saline water on tomato production and quality.

2. Materials and Methods

2.1. Experimental Design

To study the effects of different applied nanofertilizers on cultivated tomato seedlings, pot experiment was carried out at an experimental farm, Kafrelsheikh University, under greenhouse conditions during the period from January to April 2020. Two kinds of nanofertilizers including biological nano-Se and nano-Cu in different combinations were foliar-applied on cultivated seedlings of tomato under three types of low water quality. The irrigation water was collected from three locations: Kafr El-Sheikh (**IW1**; represents normal irrigation water from Meet Yazid canal), El-Hamoul (**IW2**; location irrigated by Kitchener drain), and Baltim (**IW3**; location irrigated by Kitchener drain). The justification of selection of these kinds of irrigation water depended on three levels of irrigation water, i.e., good water quality (**IW1**), moderate water quality (**IW2**), and low water quality (**IW3**), as presented in Table 1 depending on the chemical properties of water according to Zaman et al. [39]. The seedlings of tomato were transplanted by the 30th of January 2020 into pots, which contained a mixture of clay soil and sand (1:3), and the capacity of each pot was 5 kg. The total number of pots was 64, where each pot had 2 tomato seedlings, and each treatment was repeated 6 times (Table 2).

Table 1. Chemical composition of soil used and irrigation water of different locations.

Soil and Water Samples from Three Locations	pH (1:2.5)	EC (dS m^{-1})	Ca^{+2}	Mg^{+2}	$CO_3{}^{-2}$	$HCO_3{}^{-1}$	Cl^-
			$mmol_c$ L^{-1}				
Soil used (1 soil: 3 sand *w/w*)	8.44	0.413	3	10	0	5	2
Kafr El-Sheikh location (**IW1**)	7.5	0.599	3	3	0	4	2
El-Hamoul location (**IW2**)	8.2	1.44	5	3.4	0	4.2	5
Baltim location (**IW3**)	8.4	2.84	6	9.4	0	5	18

Table 2. The main treatments and their details.

Treatments		Definition of Treatment	Nanofertilizer Type	Source of Irrigation Water
T1		**Control**	**No Adding Nanofertilizers**	**Irrigation Using Tap Water**
T2 T3 T4	**IW1**	Good water quality	Nano-Se Nano-Cu Nano Se + Cu	Irrigation from Meet Yazid canal at Kafr El-Sheikh location
T5 T6 T7	**IW2**	Moderate water quality	Nano-Se Nano-Cu Nano Se + Cu	Irrigation from Kitchener drain at El-Hamoul location
T8 T9 T10	**IW3**	Low water quality	Nano-Se Nano-Cu Nano Se + Cu	Irrigation from Kitchener drain at Baltim location

Nano-copper or nano-selenium applied at **100 mg L^{-1}** concentration (**nano-Cu; nano-Se**). Combined application of both nano-selenium and -copper (**Nano Se + Cu**).

2.2. Applied Nanofertilizers and Irrigation Water

Biological selenium and copper nanoparticles were produced at Agricultural Microbiology Lab., Soil, Water and Environment Research Institute, Agricultural Research Center, Giza, Egypt. High-resolution transmission electron microscope (HR-TEM, Tecnai G20, FEI, Amsterdam, The Netherlands) was used, and selenium nanoparticles of 100–300 nm and copper nanoparticles of 350–500 nm were biosynthesized and analyzed by Nanotechnology and Advanced Material Central Lab, Agriculture Research Center (ARC). These nanofertilizers were applied at rate of 100 mg L^{-1} for each nanofertilizer, where this dose was foliar-applied after irrigating plants with studied water. Each nanofertilizer was applied 3 times with 2 weeks interval starting from the first of March.

Each irrigation was applied for each pot at rate of 250 mL as normal irrigation water (**IW1**). The irrigation with **IW1** continued until 24 February 2020 using the same rate of 250 mL for each pot, and the interval was 5 days. Starting from 16 March, the irrigation amount increased to 500 mL for each pot due to the increase of temperature in greenhouse. On the 23rd of March, a dose of NPK (20:20:20) at rate of 5 g was dissolved in 500 mL and applied for each pot to support seedlings against stress on cultivated plants. Due to the high temperature in greenhouse up to 40 °C, the amount of water irrigation increased to 1000 mL for each pot during April until harvesting (on the 21st of April 2020). The diseases (e.g., powdery mildew) were controlled by foliar application of pesticides (Mancodex M 80%) and micron sulfur 80%.

2.3. Vegetative Growth Parameters and Harvesting

At harvest, soil samples (from cultivated pots), water (which was used in irrigation), and plant samples (fruits and leaves) were collected for analysis. Soil samples were collected as a composite sample for chemical and biological measurements. Water samples also were collected and filtered for chemical analysis, where plant samples were divided into fruits and leaves. The vegetative growth parameters included plant fresh weight, stem length, number of leaves and branches per plant, and leaf area. The quality of tomato fruits was also evaluated including firmness (kg cm^{-2}), fruit yield per plant (kg $plant^{-1}$), soluble solids content (SSC, %), vitamin C, and the pH of fruits. The chlorophyll content and some enzymatic antioxidants in leaves were also determined. Plant, water, and soil samples were measured at the Central Lab for Environmental Studies at Kafrelsheikh University, which is accredited by ISO/IEC 17025-2017. Plant samples were gathered from each pot to measure fresh weight, vegetative parameters, and plant enzymes. Yield of fruits and its quality and chlorophyll content, using SPAD 501 chlorophyll meter (Minolta, Co., Ltd., Osaka, Japan) and leaf area (cm^2), were also measured in Physiology and Breeding of Horticultural Crops Laboratory, Department of Horticulture, Faculty of Agriculture, Kafrelsheikh University, Kafr El-Sheikh, Egypt, an accredited lab by ISO/IEC 17025-2017.

2.4. Measuring of Plant Enzymes

Plant enzymes were measured using 0.5 g leaf material, which was homogenized at 0–4 °C in 3 mL of 50 mM TRIS buffer (pH 7.8), containing 1 mM EDTA-Na2 and 7.5% polyvinylpyrrolidone. The homogenates were centrifuged at 12,000 rpm, 20 min, 4 °C, and the total soluble enzyme activities in the supernatant were measured spectrophotometrically [40]. All measurements were carried out at 25 °C using the model UV-160A spectrophotometer (Shimadzu, Japan). The enzyme assays were tested three times. Activity of catalase (CAT), polyphenol oxidase (PPO), and peroxidase (POX) was determined spectrophotometrically according to Aebi [41], Malik and Singh [42], and Hammerschmidt et al. [43], respectively.

2.5. Soil Sampling, Chemical and Biological Analyses

After harvesting, soil samples were taken out from all pots, then air-dried and passed through a 2 mm sieve. Different physico-chemical characteristics of used soils were evaluated according to Page et al. [44]. Soil salinity was measured in an extract of 1:5 (soil: water) solution by an EC meter (Mi170, Rocky Mount, NC, USA), whereas soil pH was measured in a suspension of 1:2.5 by a pH meter (JENWAY 3510, Staffordshire, UK). Total $CaCO_3$ was measured using a Collins calcimeter, whereas soil organic matter (SOM) was measured by the loss on ignition method using a muffle furnace at 400 °C for 4 h. The available trace metals (Cu, Se, and Zn) were extracted using the method of AB-DTPA or "ammonium bicarbonate–diethylene triamine penta-acetic acid". The studied nutrients were measured using the instrument of atomic absorption spectrometry (AAS) (GBC Avanta E, Victoria, Australia).

Soil samples from the rhizosphere (10 g) were taken and then were transferred into a glass bottle. These bottles contained 90 mL of sterile distilled water and were prepared for shaking for 0.5 h at 150 rpm. The total bacteria, actinomycetes, and fungi counts were estimated using soil extract agar media, Jensen's agar medium, and Martin's agar medium, respectively [45]. The previous population of microbes was expressed as CFU (log 10) g^{-1} dry soil at 30 and 80 days after transplanting and at harvest, respectively. According to Casida et al. [46], dehydrogenase (DAH) activity in used soil samples was estimated, and the results were expressed as mg TPF g^{-1} soil day^{-1}. The activity of urease enzyme in soil samples was determined according to Pancholy and Rice [47]. Both soil enzymes were determined after 30 days from transplanting and at harvest.

2.6. Plant Analyses and Nutrient Uptake

At harvest, plant samples were collected from pots. The entire plants were washed with tap water, distilled water, and then dried at 65 °C for 48 h. Plant samples were ground to a fine powder using a stainless-steel grinder and stored in plastic bag until analyses. In a muffle furnace, 1.0 g of plant materials was dried to ash at 450 °C for 5 h. The digested materials were extracted using 20% hydrochloric acid. Trace metals including Cu, Zn, and Se were measured using AAS. The mobilization of elements in soil-to-plant system was expressed as bioaccumulation factor (BAF). Bioaccumulation factor (BAF) was calculated to determine the efficiency of the plant at accumulating a trace element from the soil [48] as follows:

BAF = metal concentration in plant tissues (mg kg^{-1})/AB-DTPA-extractable metal concentration in the surface soil layer (mg kg^{-1}) [49].

2.7. Statistical Analyses

Soil parameters and studied elements were performed using descriptive statistical analyses with the SPSS statistics package 18 (IBM Corp., Armonk, NY, USA) and Microsoft Excel (Microsoft Corp., Redmond, WA, USA). The two-tailed Pearson correlation coefficient was calculated to understand the correlations among soil variables. Data on element concentrations were evaluated using analysis of variance (ANOVA) at $p < 0.05$ and the Duncan test. Processing with XLSTAT software, principal component analysis (PCA) was used to clarify the general distribution patterns or similarities of soil variables and elements in the collected samples.

3. Results

3.1. Vegetative Growth under Bio-Nanofertilization

The obtained results of almost all studied vegetative growth parameters have a similar trend as presented in Table 3. This trend includes the dominant impact of nano-Cu under good water quality (**IW1**), whereas under moderate (**IW2**) and low water quality (**IW3**), nano-Se and combined nano-Cu and -Se, respectively, were more effective. The highest stem length (69.8 cm) was obtained under irrigation with moderate water quality and combined nano-Se. The highest chlorophyll content (79.7 SPAD) was recorded after nano-Se application and irrigation using low water quality. The branch number per plant was the only vegetative growth parameter that recorded a non-significant effect among all studied properties.

Table 3. Response of tomato vegetative growth parameters and chlorophyll content to different treatments applied.

Treatments		Plant Stem Length (cm)	Plant Fresh Weight (g/Plant)	Leaf Area (cm^2/Plant)	Branch No./Plant	No. of Leaves/Plant	Chlorophyll Content (SPAD)
T1	Control	65.3 b	250.5 a	64.92 b	4.0 a	15.3 a	50.5 f
T2	**IW1**	61.3 cd	211.9 b	71.50 a	2.5 a	16.3 a	61.6 e
T3	**IW1**	65.2 b	211.4 b	65.71 b	3.0 a	15.2 a	63.5 e
T4	**IW1**	54.3 e	186.0 c	60.43 cd	2.4 a	13.3 bc	54.1 f
T5	**IW2**	69.8 a	172.2 d	52.64 e	3.5 a	13.4 bc	66.4 d
T6	**IW2**	63.2 c	184.4 c	52.68 e	2.9 a	14.6 b	71.2 c
T7	**IW2**	58.7 d	159.8 e	51.52 e	2.1 a	12.7 bc	76.2 b
T8	**IW3**	59.8 d	169.6 d	61.90 c	2.1 a	14.2 b	79.7 a
T9	**IW3**	59.7 d	203.9 b	67.65 b	2.3 a	13.5 bc	65.5 d
T10	**IW3**	67.8 ab	163.4 e	61.97 c	3.0 a	12.8 bc	67.8 d
F-test		**	**	**	NS	*	**

For more details about T1 to T2, please refer to Table 2; **IW1**, **IW2**, and **IW3** = irrigation water from Kafr El-Sheikh, El-Hamoul, and Baltim locations. Different letters in same column show significant differences between each group of treatments according to Duncan's test at $p \leq 0.05$. Note: (*) and (**) means that there is a significant at differ at less than 0.05 and 0.01 probability level, respectively.

3.2. Tomato Yield and Its Quality

All studied tomato yields and their quality were significant in their response to different water quality and nanofertilizers except fruit pH (Table 4). The highest values of fruit yield (2.07 kg plant^{-1}) and soluble solids content (9.24%) were obtained under irrigation using low water quality (**IW3**) and with 100 mg L^{-1} of nano-Cu applied, whereas the highest value of vitamin C content (mg 100 g^{-1} FW) was resulted under low water quality (**IW3**) and with combined 100 mg L^{-1} of nano-Se and nano-Cu. The highest value of fruit firmness (511 kg cm^{-2}) was recorded under foliar-applied nano-Cu and irrigation using good water quality. Some studied parameters achieved the highest values under nano-fertilization and low water quality (**IW3**) such as fruit yield and vitamin C content. Under each category of water quality in general, the dominant impact of nano-Cu could be noticed under irrigation using low water quality for fruit yield and SSC measurements while nano-Se under moderate water quality and the combined nano-Se and Cu under good water quality.

Table 4. Fruit yield and quality response to bio-nanofertilization and irrigation using low-quality water.

Treatments		Fruit pH	SSC (%)	Vitamin C (mg 100 g^{-1} FW)	Firmness (kg cm^{-2})	Fruit Yield (kg Plant^{-1})
T1	Control	4.45 a	5.38 d	41.6 b	430.0 c	1.82 bc
T2	**IW1**	4.54 a	7.44 b	33.2 d	389.0 d	1.83 bc
T3	**IW1**	4.48 a	8.70 ab	34.9 d	511.0 a	1.55 d
T4	**IW1**	4.60 a	8.84 ab	38.4 c	396.7 d	1.90 b
T5	**IW2**	4.06 a	7.95 b	42.7 b	494.7 ab	2.05 a
T6	**IW2**	4.31 a	5.78 cd	39.6 c	383.7 d	1.75 c
T7	**IW2**	4.48 a	6.11 c	45.9 a	482.3 b	1.62 d
T8	**IW3**	4.33 a	7.18 b	41.6 b	444.3 c	2.00 a
T9	**IW3**	4.31 a	9.24 a	44.8 a	350.7 e	2.07 a
T10	**IW3**	4.42 a	8.46 ab	46.0 a	335.0 e	0.85 e
F-test		NS	**	**	**	**

For more details about T1 to T2, please refer to Table 2. Soluble solids content (SSC). **IW1**, **IW2**, and **IW3** = irrigation water from Kafr El-Sheikh, El-Hamoul, and Baltim locations. Different letters in same column show significant differences between each group of treatments according to Duncan's test at $p \leq 0.05$. Note: (**) means that there is a significant at differ at less than 0.05 and 0.01 probability level, respectively, whereas NS means not significant.

3.3. Enzymatic Antioxidants

Three enzymatic antioxidants (i.e., CAT, POX, and PPO) were measured to evaluate whether cultivated tomato under low water quality experienced stress in the presence of two nanofertilizers in individual and in combined application or not (Figure 1). Under good water quality, the combined nanofertilizers showed the highest values of PPO and CAT activities, whereas the highest value of POX was recorded after applying nano-Cu under low water irrigation. The decrease in values of measured plant enzymes in general for almost all treatments may refer to the oxidative stress resulted from the low quality of irrigation.

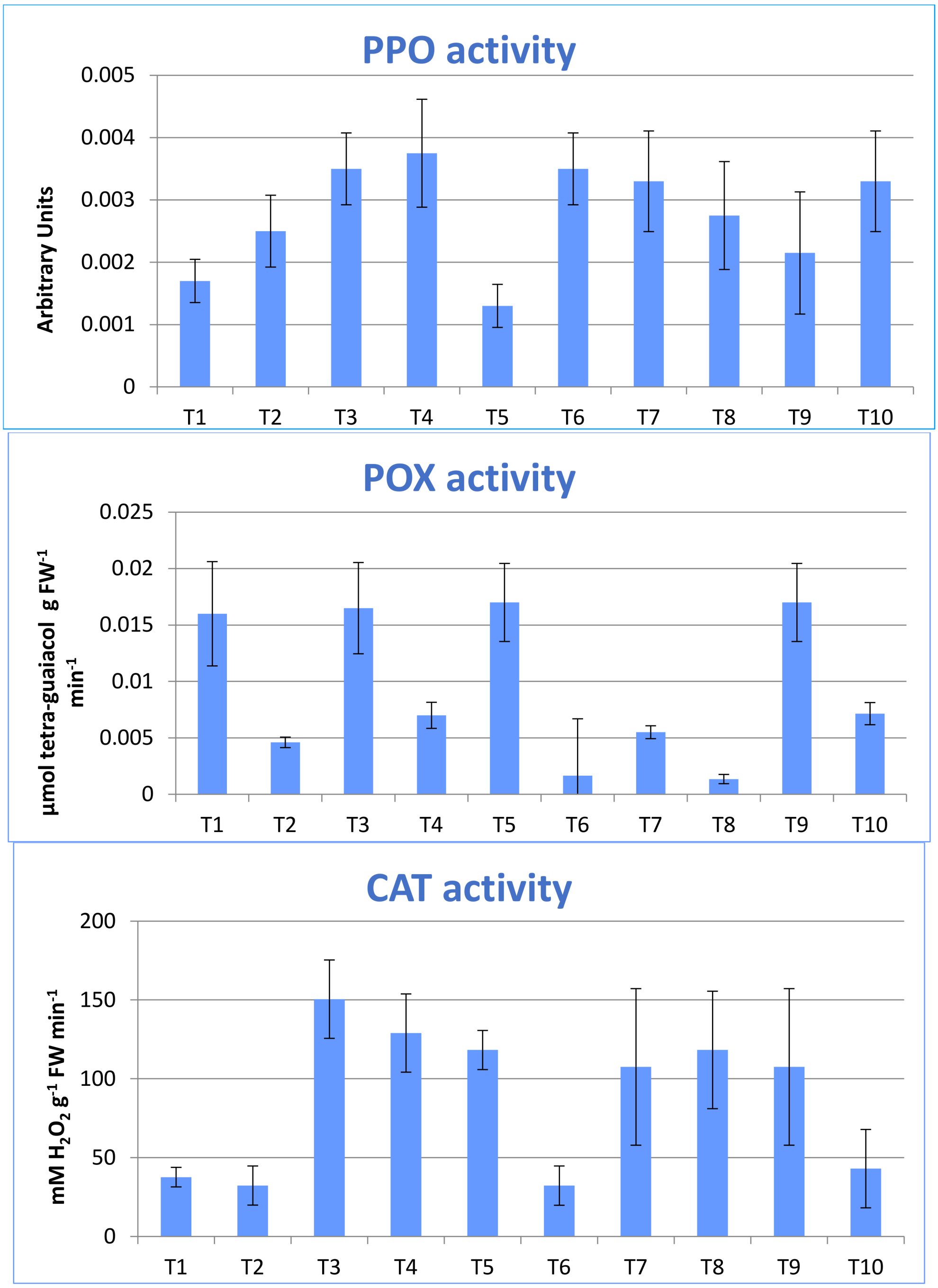

Figure 1. The impact of irrigation water at different quality on the antioxidant enzymatic activities in the presence of Se and Cu nanofertilizer including polyphenol oxidase (PPO), peroxidase (POX), and catalase (CAT) (for more details about T1 to T2, please refer to Table 2).

3.4. Bio-Nanofertilization and Soil Biological Activity

The impact of applied irrigation water at different quality on the total counts of bacteria, actinomycetes, and fungi in the presence of the Se and Cu nanofertilizer is presented in Figure 2. The microbial count was measured after 30 days from the transplantation of the tomato and at harvesting (after 80 days). The microbial accounts of bacteria, fungi, and actinomycetes were higher after 30 days from transplanting and decreased in all treatments at harvest due to the harmful effect of low water irrigation quality. The microbial counts can be ordered as follows: bacteria > actinomycetes > fungi, where the highest microbial count for the three previous microbes was achieved under irrigation using good water quality and nano-Se. A remarkable decrease was observed in all studied microbes under low water quality (Baltim location) compared to other irrigation treatments. The combined foliar application of nanofertilizers recorded the lowest counts in all microbes compared to other nanofertilizers.

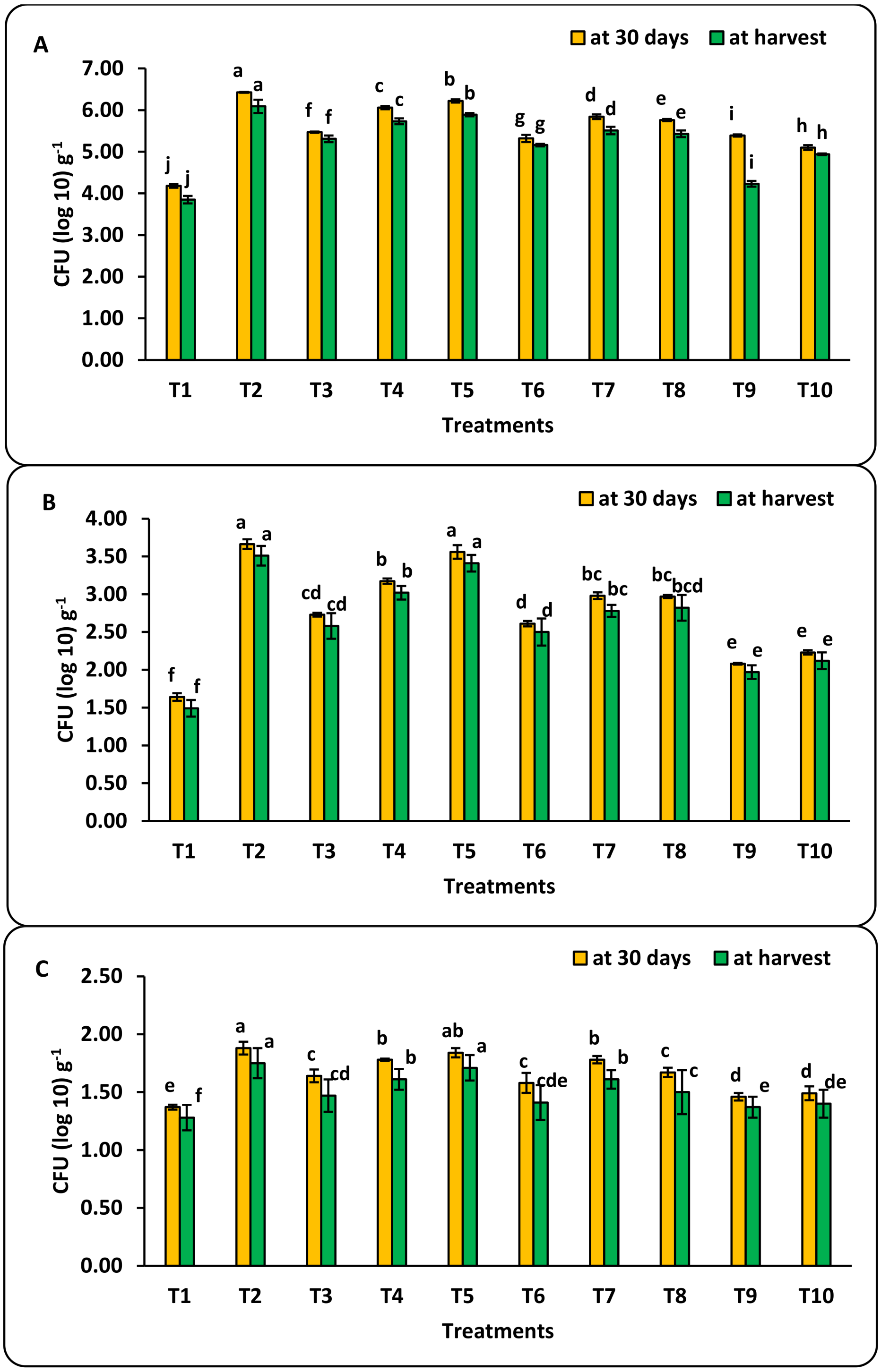

Figure 2. The impact of irrigation water at different quality on the total counts of bacteria (**A**), actinomycetes (**B**), and fungi (**C**) in the presence of Se and Cu nanofertilizer. All values calculated as a colony-forming unit (CFU) (for more details about T1 to T2, please refer to Table 2). Different letters in same column show significant differences between each group of treatments according to Duncan's test at $p \leq 0.05$.

Soil samples were analyzed after 30 and 80 days from transplanting to evaluate the impact of different irrigation and nanofertilization treatments on soil dehydrogenase and urease (Figure 3). The values of both enzymes decreased with the decreasing quality of irrigation water, where the lowest values of dehydrogenase and urease were obtained under irrigation with a low quality of irrigation water (Baltim location), and the opposite is correct. In general, nano-Se can lead to the highest values of both enzymes under different quality of irrigation water. There was a significant positive correlation between the enzyme activities and the quality of irrigation water, where the highest values of enzymes were observed at 30 days and before applying this water. There was a significant difference among the three locations and different treatments of nanofertilizers.

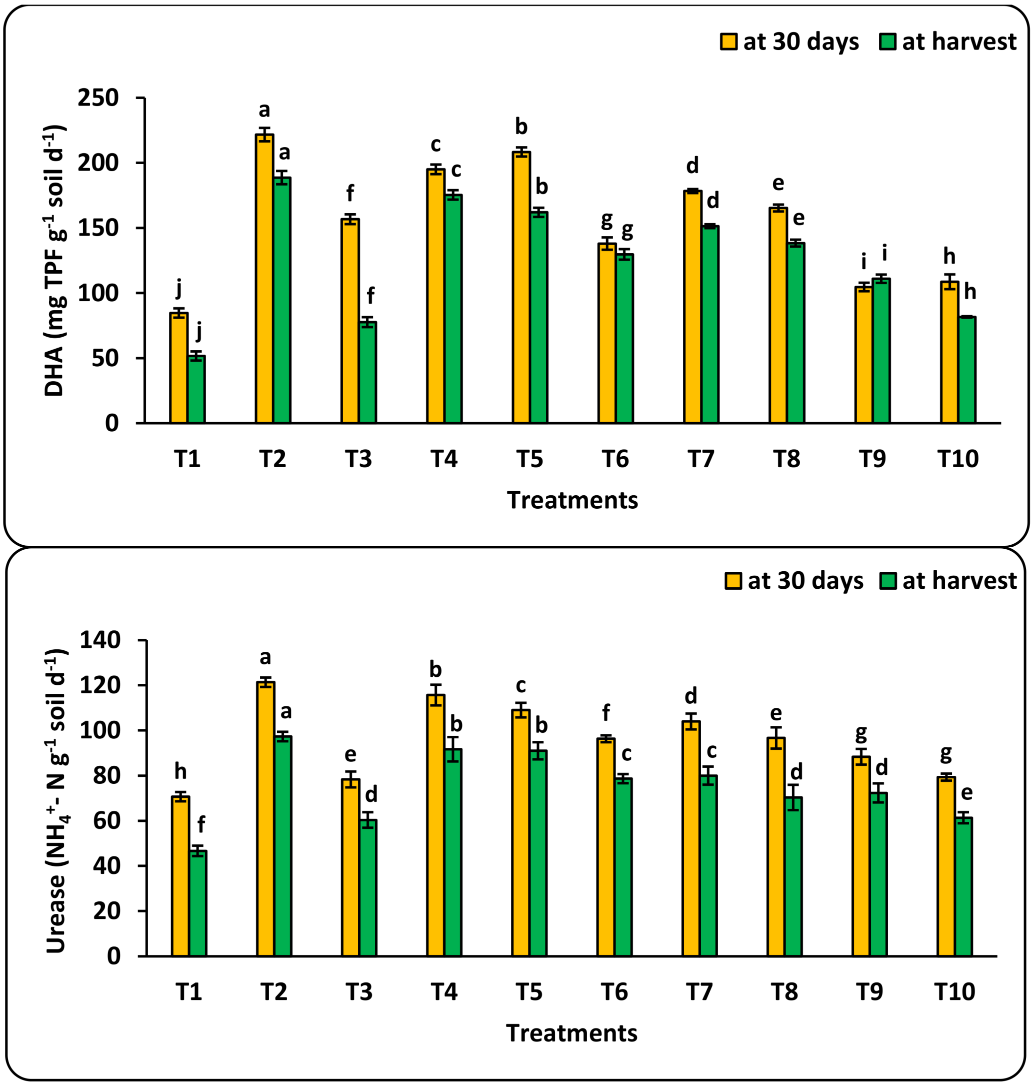

Figure 3. The impact of irrigation water at different quality on soil enzyme activities including dehydrogenase (DHA) and urease in the presence of Se and Cu nanofertilizer. Where triphenylformazan is TPF (for more details about T1 to T2, please refer to Table 2). Different letters in same column show significant differences between each group of treatments according to Duncan's test at $p \leq 0.05$.

3.5. Uptake of Nutrients and Bioaccumulation

The physico-chemical changes in soil at harvest due to irrigation using saline water are tabulated in Table 5. The observed increase in soil salinity (up to 0.892 dS m^{-1}), soil organic matter (up to 13.1 g kg^{-1}), and soil carbonate (116 g kg^{-1}) could be attributed to the applied saline water, which resulted from continued irrigation using saline water. The bioaccumulation factor (BAF) was calculated based on metal availability and its uptake by a particular plant (Figures 4 and 5). This index is a useful tool to interpret metal accumulation and mobilization in plants [48,50]. The BAF is a significant indicator of the plant capability uptake of metals. The BAF factors of soil to plant are greater than 1 indicating that the studied metals tend to be accumulated in the plant's tissues [51]. In this study, all heavy metal BAFs were greater than 1 for tomato crop (Figure 6). According to the BAF, one could classify plants into accumulators, hyperaccumulators, and excluders based on the concentration of accumulated metals (>5 mg kg^{-1}, <5 mg kg^{-1} and >1 mg kg^{-1}, and <1 mg kg^{-1}, respectively) [52]. Based on these criteria, tomato plants were hyperaccumulators for Cu, Se, and Zn in all locations. The crop was an accumulator for all other metals in all water treatments.

Table 5. Physico-chemical characterization of soil samples after harvesting of tomato.

Soil Treatments		pH	EC (dS m^{-1})	TDS (mg kg^{-1})	$CaCO_3$ (g kg^{-1})	OM (g kg^{-1})
T1	Control	8.41	0.482	236	98	9.9
T2	**IW1**	8.55	0.430	231	109	8.6
T3		8.41	0.578	294	95	8.1
T4		8.50	0.498	250	111	9.9
T5	**IW2**	8.39	0.610	305	111	11.1
T6		8.23	0.649	323	99	9.6
T7		8.38	0.808	404	105	7.9
T8	**IW3**	8.30	0.830	415	103	0.64
T9		8.37	0.788	400	112	10.1
T10		8.33	0.892	450	116	13.1

EC, electric conductivity; TDS, total dissolved solids; OM, organic matter.

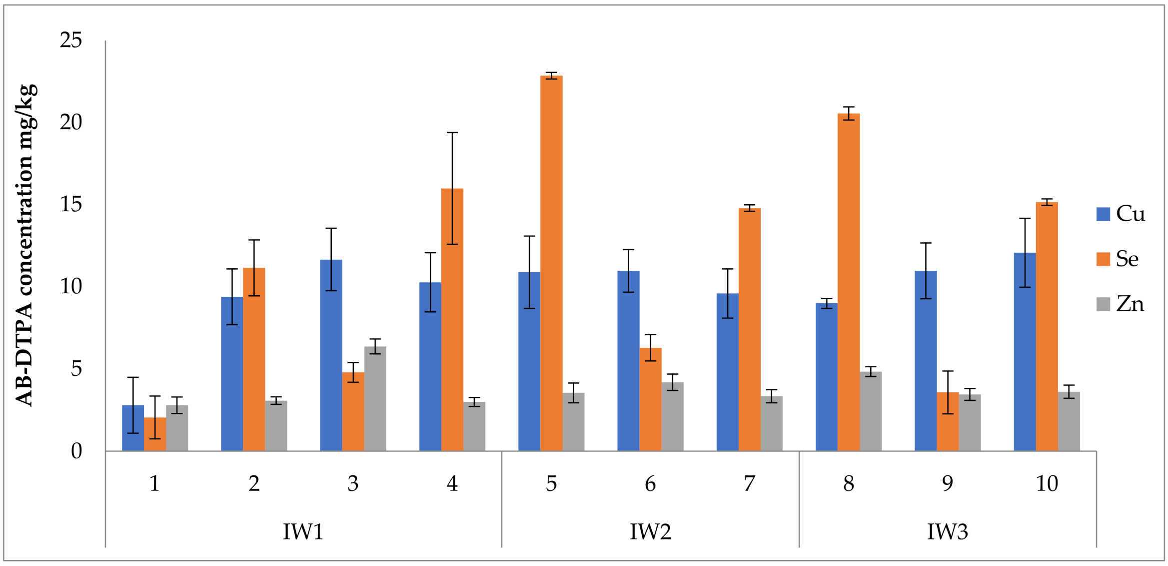

Figure 4. Descriptive statistics for AB-DTPA concentrations (mg kg^{-1}) of copper (Cu), selenium (Se), and zinc (Zn) in mg kg^{-1} at different treatments (for more details about **IW1**, **IW2**, and **IW3**, please refer to Table 2), ammonium bicarbonate–diethylenetriaminepentaacetic acid (AB-DTPA) procedure for extraction of trace elements.

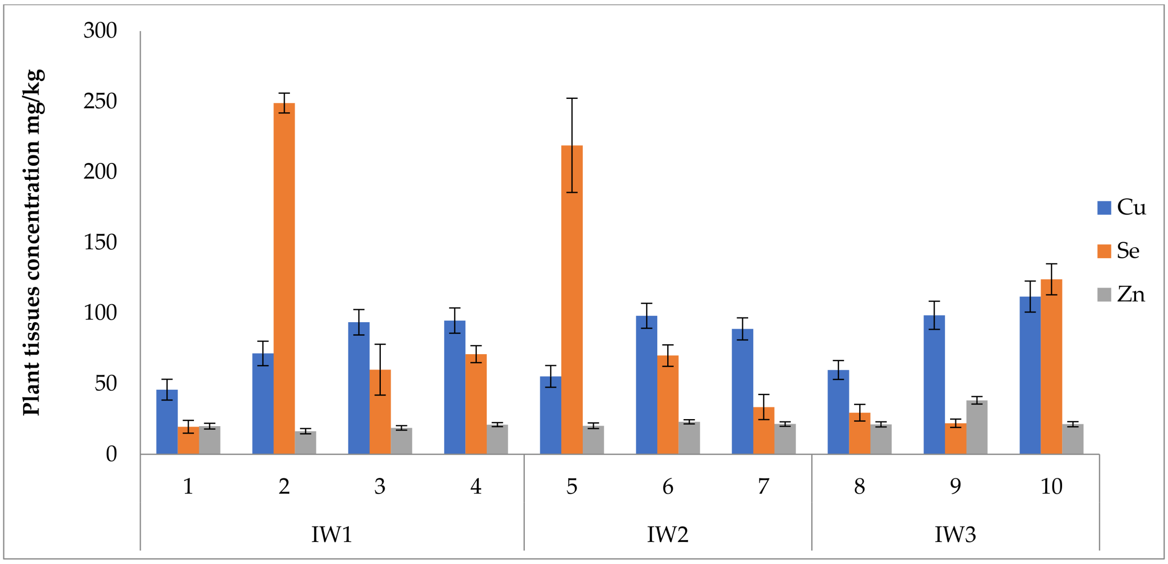

Figure 5. Plant tissue concentrations of copper (Cu), selenium (Se), and zinc (Zn) in mg kg^{-1} at different treatments (for more details about **IW1**, **IW2**, and **IW3**, please refer to Table 2).

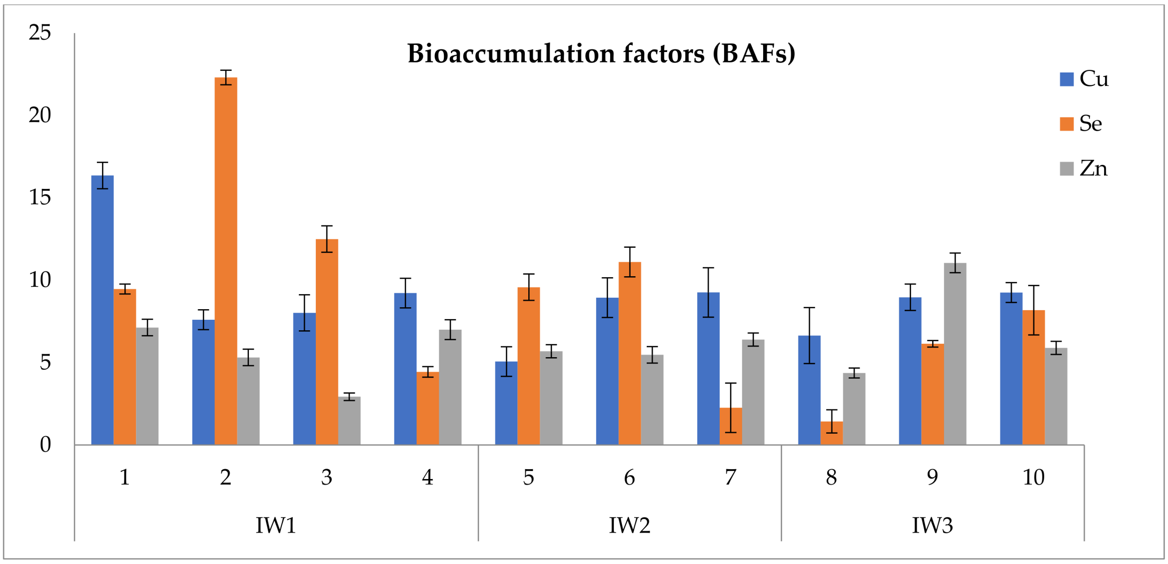

Figure 6. Bioaccumulation factors (BAFs) of copper (Cu), selenium (Se), and zinc (Zn) in mg kg^{-1} at different treatments (for more details about **IW1**, **IW2**, and **IW3**, please refer to Table 2).

4. Discussion

4.1. Tomato Growth, Yield, and Its Quality

The production of tomato crop needs many growth factors especially proper and enough nutrients as well as the quality of irrigation water. When the cultivated tomato suffers from a problem in supplying nutrients or irrigation water, plant production will decline due to the stressful conditions. Under the global water crisis, there is an urgent need to utilize low-quality water sources in agricultural irrigation as an effective method for water shortage [53]. The main problems of low-quality water are represented by high levels of heavy metals, salts, and other pollutants, which may bring many environmental risks to soil and cultivated plants and consequences for human health. Results indicate that using low-quality water (**IW2** and **IW3**) from the Kitchener drain (more details in [48]) for irrigation revealed many risks for cultivated tomatoes. The current results corroborate the findings of a great deal of reuse of remediated low water quality using nanofertilizers through irrigation.

Tomato fruit production was higher under irrigation with low-quality irrigation water as compared to control and good quality. The fruit yield under water quality categories increased as follows, compared to control: 4.4, 12.6, and 13.7% for good (**IW1**), medium (**IW2**), and low water quality (**IW3**), which were achieved using combined nanofertilizers (Se and Cu), nano-Se, and nano-Cu, respectively. This also accords with our earlier studies, which showed that Kitchener drain water is rich in nutrients that are higher than those from Kafr El-Sheikh to Baltim [48]. Along with the Kitchener drain (40 km), there is a strong possibility to use only the water of the Kitchener drain near the Mediterranean Sea (near Baltim) as a main source for irrigation water in these areas. In spite of the high quality of tomato fruits under the low quality of irrigation water in Baltim, the accumulation of heavy metals may threaten human health. Ma et al. [54] found that irrigation with wastewater led to an accumulation of some heavy metals such as Cr and Pb [54].

4.2. Irrigation Water Stress on Tomato Production

Low irrigation water quality causes stress on cultivated tomato plants, which was reflected by enzymatic antioxidants. Shoaib et al. [55] observed elevation in the antioxidant enzyme activities such as SOD, POX, and CAT which are strongly correlated to salt endurance in many plants [55]. In general, the role of nano-Cu is sometimes dominant as in the case of CAT activity, which increased by 250-fold compared to control (**IW1**). On the other hand, nano-Se was often dominant under low-quality water irrigation (**IW2** and **IW3**). The highest values of CAT, PPO, and POX activities could be noticed under the good quality of irrigation water, whereas the lowest values, in general, belonged to the low quality of irrigation water. These results agree with the findings of other studies, which confirm that low water quality from the Kitchener drain causes stress on cultivated plants [48]. The role of nano-Se or nano-Cu in improving tomato growth has been discussed in some recent studies such as nano-Se under salinity stress [56], nano-Cu under salinity stress [57–59], and both nano-Se and nano-Cu for biotic stress on tomato [60]. Soil enzyme activities are responsible for the biogeochemical cycles of many elements and are particularly sensitive to soil ecological changes; hence they have been commonly utilized as indicators to assess soil health and the level of contamination among the many soil properties [54]. It was found that irrigation with mine wastewater caused negative effects on the soil enzyme activity especially at the flowering stage due to the accumulation of heavy metals. Based on the biological impact of Se or Cu in ameliorating the stress on cultivated plants, these elements are components or co-factors of many plant enzymes such as CAT and POX, which work as enzymatic antioxidants.

4.3. Soil Biology and Stress of Irrigation Water

Continuous irrigation using low water quality may lead to an accumulation of heavy metals, salts, and pollutants, which threaten soil biology including soil microbial counts and enzymes. In a recent study, soil biological assessments were conducted twice after 30 and 80 days from the transplantation of tomato. The observed increase in these soil biological activities could be attributed to the absent impact of saline irrigation water after 30 days from transplantation, which was realized after 80 days as the oxidative stress of low water quality. These results are consistent with those of other studies and suggest that continuous saline water irrigation leads to adverse effects on the quality of soil by reducing the bioavailability of nutrients and decreasing soil microbial activities as well as tomato growth [33]. The most obvious finding to emerge from the analysis of soil biological activities is that nano-Se achieved the highest values of soil microbial counts and studied enzymes compared to control in general under different categories of water quality. A high significant correlation could be found among the soil biological parameters in the Supplementary Material (Table S1). Taken together, these results suggest that there is an association between nanofertilizers and soil biological activities, which mainly depends on the quality of irrigation water. Concerning the distinguished impacts of different fertilizers on soil biology including enzymatic activities and soil microbial community, it could be referred to the studies of Samuel et al. [61,62] and Bungau et al. [63].

4.4. Nutrient Bioaccumulation and Stress of Irrigation Water

After harvesting, soil samples were collected from each treatment to evaluate the chemical composition of the soil. It is interesting to note that only the low water quality (2.84 dS m^{-1}) led to an increase in the accumulation of salinity, soil organic matter, and $CaCO_3$ in soil by 84.6, 32.3, and 18.4%, respectively, compared to control. These values were the highest values of soil salinity, soil organic matter, and calcium carbonate content at harvesting as affected by the combined application of nanofertilizers using Se and Cu. The increase in salts and nutrients was reported as by Akbar et al. [64]; however, Waheed et al. [65] found that EC values were within permissible standard limits. On the other hand, they found that irrigation with wastewater, which contained a variety of organic compounds from urban communities, greatly increased organic matter levels, and organic matter addition is one of the most prevalent reasons for using wastewater in irrigation. It could summarize the main factors implied in the suggested sustainable production of tomato plants from this study and other published articles including soil properties (soil pH, salinity, nutrient availability, and soil texture), climatic conditions (mainly temperature, CO_2, and light), different soil management approaches including weed control and plant pathogens, application of proper fertilizers, using a suitable irrigation system, etc. (Figure 7).

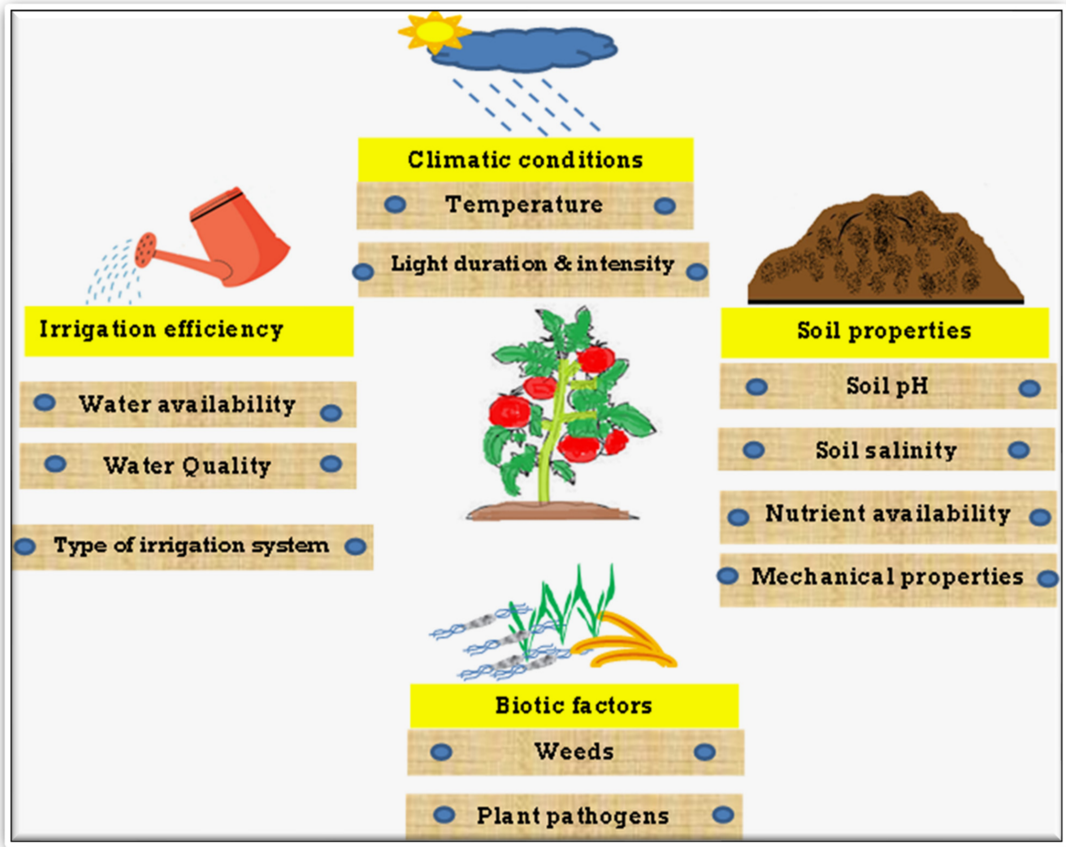

Figure 7. A scheme summarizing the main factors implied in sustainable production of tomato plants including climatic conditions, soil properties, biotic factors, irrigation efficiency and management of the soil, fertilizers, etc. This drawing scheme was provided by our colleague Dr. **Tamer Elsakhawy**, SWERI, Egypt.

5. Conclusions

The water crisis is a serious problem in several places all over the world, which need alternative sources. Therefore, the water of the Kitchener drain, as one of the biggest drains in the north Delta of Egypt, was used for irrigation in many rural areas in the Nile Delta of Egypt. However, the continued use of the low-quality water has led to the accumulation of a significant amount of salts and a high content of heavy metals and other toxins, which causes many environmental problems. In the current study, three types of water quality were used in the irrigation of tomato under greenhouse conditions. Two bio-nanofertilizers of Se and Cu were applied to promote the growth and production of cultivated tomato under water salinity stress. The most important finding is the crucial role of bio-nano-Cu in enhancing the yield and quality of tomato fruits under irrigation with low water quality. In addition, the low quality of irrigation water led to the accumulation of salts, organic matter, and $CaCO_3$ in the soil. Due to the salinity stress of irrigation water, plant enzymatic antioxidants and soil biological activity decreased. After 30 days from transplanting, all studied soil biological parameters (soil microbial counts and enzymes) were higher than the same parameters at harvesting after 80 days under different water qualities. The soil biological parameters were also decreased by increasing water salinity, which is considered an important issue for future research.

Therefore, the use of a bio-nanofertilizer is promising in enhancing the productivity and quality of cultivated crops, especially under stress conditions. However, there are still many unanswered questions concerning different applied doses of these nanofertilizers for further studies that could take the following variables into account: the expected impact of low water quality of irrigation on the yield of other crops, on the one hand, and its impact on soil biological parameters under applied nanofertilizers, on the other hand.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14063236/s1, Table S1: Correlations among all studied parameters in the current study.

Author Contributions: Conceptualization and visualization, M.M.S., M.A.K. and H.E.-R.; resources, A.E.-H., S.E.-M. and H.E.-R.; methodology, F.E, A.E.-D.O., Y.B. and H.E.-R.; software, K.B., J.P., F.E. and A.E.-D.O.; validation, A.E.-H., F.E. and H.E.-R.; investigation, M.M.S. and H.E.-R.; data curation, K.B. and F.E.; writing—original draft preparation, review, and editing, M.M.S., F.E., A.E.-D.O. and H.E.-R.; funding acquisition, K.B. and J.P. All authors have read and agreed to the published version of the manuscript.

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