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(Research Article)

Evaluate the effects of rare earth elements on sweet pepper seeds germination process, seedlings growth and plants productivity

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Abstract

This experiment was conducted to investigate the response of pepper seeds germination process and vegetative growth traits in seedlings stages as well as plant growth and productivity of open field to rare earth elements (REEs) i.e., cerium nitrate, neodymium nitrate, and praseodymium nitrate at concentrations of 0.0, 0.5, 1.0, and 1.5 ppm. Among the various REEs treatments, cerium nitrate at 0.5, 1.0, and 1.5 ppm were more significantly effective than others in increasing most of the seedling parameters and 1.5 ppm cerium nitrate exhibited the maximum effect in germination characteristics with no significant differences among 0.5, 1.0 and 1.5 ppm cerium nitrate as well as 1.5 ppm neodymium in all germination parameters in both seasons. The superiority of vegetative growth, fruit physical and total yield as well as fruit chemical content (ascorbic acid and carbohydrates) were obtained with neodymium followed by praseodymium foliar spray applications with compared to cerium or control treatments. The foliar spray treatment of 1.5 ppm neodymium nitrate exhibited an increment up to 54.1, 23.7, 29.5, and 33.1% over that observed in the control of average fruit weight, fruit diameter, fruit length, and total yield, respectively.

Keywords: Rare earth elements; Seedlings; Pepper productivity; Germination

1. Introduction

Sweet pepper (*Capsicum annuum* L.) is one of the highly favorite vegetables cultivated in Egypt for local market and exportation. Considered a high-cash crop, it has occupied an important rank in agriculture due to its high profit and nutritional value for health. Pepper fruit is well known as an excellent source of bioactive compounds i.e. ascorbic acid, carotenoids, and phenolic compounds which are the main antioxidant constituents as well as minerals such as Ca, P, K, and Fe [1-2].

The rare earth elements (REEs)/or lanthanides include 15 elements in the periodic table with atomic numbers (Z from 57 to 71) in addition to yttrium (Y) and scandium (S), they share chemical properties related to a similar external electronic configuration. REEs can be divided into two groups: light and heavy REEs, the light are La, Ce, Pr, Nr, Pm, Sm, Eu, and Gd, whereas the heavy ones are Y, Tb, Dy, Ho, Er, Tm, Yb, Lu, and Sc [3-5].

The rare earth constitutes the fifteenth most abundant component of the earth's crust [6]. The Earth's crust are comparable to common metals such as copper (Cu, 55 mg/kg^{-1}), lead (Pb, 10 mg/kg^{-1}), zinc (Zn, 70 mg/kg^{-1}) and cobalt (Co, 30 mg/kg^{-1}) [7]. The most plentiful rare earth elements are cerium and yttrium which occur more often in the earth's crust than lead, molybdenum, or arsenic however lanthanum and neodymium occur in similar quantities as lead [8]. REEs exist as oxides, silicates, carbonates, phosphates, and halogen compounds in minerals [9]. Many of these elements can compete with calcium in several calcium-mediated biological processes [10]. REEs have been used as

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fertilizers by blending seeds, immersing seeds, and spraying foliar, soil application [11]. REEs are not known to be essential elements in plants but they have been used in fertilizers in agriculture in china since 1979, the beneficial effect of these elements was evident for seed germination, root growth, chlorophyll content, plants growth, chemical composition, and resistance, improving yield and crop quality [12-14]. More than 100 crop species were treated with REEs in the form of foliar sprays, seed treatments, or as additions to solid or liquid root fertilizers or media this resulted in a mean productivity increase of 5 to 15% [15]. Many factors influence REEs distribution in plants such as application method, type of plant tissues, and the concentration of REEs in substrates [16]. From this concern, the distribution of the amount of REEs in plant tissues is ranked as follows: root>leaf>stem>flower>fruit [17]. As a percentage, the accumulation of REEs is highest in roots (88-90%), lees in stem (10-12%), and lowest in leaves as mentioned by [18]. Generally, plant response to REEs application depends on factors such as plant species, soil properties including pH, redox potential, soil texture, organic matter content, the amount of soil available REEs, mobility, and RE-availability of REEs in soil [19-21].

This study aims to use rare earth elements (REEs) as unusual fertilizer and is not widely used in the field of Egyptian agriculture, the feasibility and importance of REEs in the production of many crops have been proven through many types of research around the world, especially in China. Pepper was used in this study for its known importance and to investigate the influence of REEs on the seed germination process, seedlings' growth, and plant productivity as well as fruit quality.

2. Material and methods

The experiment was conducted in El-Kassasein Station Farm, Agriculture Research Center, Ismailia Governorate during the summer seasons of 2020 and 2021 to evaluate the effects of some rare earth elements (REEs) on the germination process, seedlings' growth stage in the nursery and the productivity of pepper plants in the open field.

2.1. Preparation of Rare Earth Elements (REEs) solutions

Three elements of REEs *i.e.*, Praseodymium nitrate Pr $(NO_3)_3$, Cerium nitrate Ce $(NO_3)_3$, and Neodymium nitrate Nd $(NO_3)_3$ in powder form were brought from Nuclear Materials Authority, Kattamia, Cairo, Egypt, obtained thru (SIGMA, Chemical Company, Saint Louis, USA). The treatments were prepared by weighted 0.0005, 0.001, and 0.015g, from each powder and dissolved in 1000 ml distilled water to reach the concentration of 0.5, 1.0, and 1.5 ppm respectively in addition to tap water (0 concentrates) the control treatment.

2.2. Effect of REEs solutions on germination process and seedlings stage

Seeds of sweet pepper (*Capsicum annum* L.) cv. California Wonder were sown in seedlings trays in the second and third week of February during the summer seasons of 2020 and 2021, respectively. Seedlings trays (84 cells) were divided into two groups and all filled with a mixture of peat moss and vermiculite 1:1 (v/v) which it's physical and chemical properties were shown in Table 1. The seedlings trays of 1st group were irrigated by three concentrates of REEs *i.e.*, 0.5, 1.0, and 1.5 ppm beside the control treatment (tap water) resulting in ten treatments. The number of germination seeds of 1st group was counted every day after 5 days of cultivation, until the seventh day when there were no more germinated seeds whereas the emergence of cotyledon leaves to 3 mm was considered as a germination process according to Odoemena [22]. After the appearance of the first true leaf, other agricultural practices were done in trays through the nursery stage according to the recommendation of the Ministry of agriculture. Both groups (either the first treated group or the second untreated group) continued in the nursery for 45 days.

The experiment was arranged in a randomized complete block design with three replicates as follow:

Table 1 Physical and chemical properties of seedlings growth media

Parameters	**Physical properties**			**Chemical properties**						
	B.D (g/cm^3)	**T.P.S (%)**	**T.W.H. (%)**	**pH**	**E.C (dS/m)**	**C/N ratio**	**T.O.C (%)**	**N (%)**	**P (%)**	**K (%)**
Growth media	92.80	80.00	4.27	6.80	0.21	70.32	22.67	0.38	0.02	0.07

B.D: Bulk density **T.P.S:** Total pore space **T.W.H.C:** Total water holding capacity **T.O.C:** Total organic carbon

2.2.1. *Germination process*

The parameters used to compare the germination process were as follows:

- Mean Germination Time (MGT).
- Mean Germination Rate (GI).
- Coefficient of Velocity of Germination (CVG).

The details, and calculation methods of each parameter are shown in Table 2.

Table 2 Germination parameters, formulas, description of variables and references considered to evaluate the effect of REEs concentrations on sweet pepper (*Capsicum annum L.*)

Parameter	**Formula**	**Description**	**Notes and references**
Mean germination time (MGT) or Mean length of time or Sprouting index or Emergence index	$MGT = \sum NiTi / \sum Ni$	Ni = Number of germinated seeds per day, Ti = Number of days from the start of the count (the number corresponding to the ith interval)	It is the average length of time required for maximum germination of a seed lot (It is the inverse of mean germination rate). The lower the MGT, the faster a population of seeds has germinated [23-27].
Mean germination rate (MGR)	$MGR = \sum Ni / \sum NiTi$		That is the mean germination time, used to evaluate seedling emergence [24], and is defined as reciprocal of the mean germination time (1/MGT) as Ranal and Santana [26] and CVG/100 as Scott et al. [28].
Coefficient of velocity of germination (CVG)	$CVG = 100 \times \Sigma Ni / \Sigma NiTi$		The CVG gives an indication of the rapidity of germination. It increases when the number of germinated seeds increases and the time required for germination decreases. heoretically, the highest CVG possible is 100. This would occur if all seeds germinated on the first day. Scott et al. [28], Jones and Sanders [29] as well as Moghadam and Alaei [27].

2.2.2. *Seedlings vegetative growth traits*

Seedlings traits, *i.e.,* length (cm), fresh weight (g) and dry weight (g) as well as number of leaves/seedling were recorded after the end of 45th day. Ten seedlings were taken from each treatment and dried at 70 ºC till constant weight, to determined the average dry weight of whole seedlings using the standard methods as illustrated by A.O.A.C. [30] and total leaf chlorophyll content were measured using Minolta chlorophyll meter SPAD-501.

2.3. Effect of REEs solutions on pepper plant development (Open field)

Table 3 Soil physical and chemical analyses

Soil physical analyses				**Soil chemical analyses**																
Text.	**Sand (%)**	**Silt (%)**	**Loam (%)**	**pH**	**E.C. (dSm^{-1})**	**$CaCo_3$ (%)**	**Soluble cations (M/L)**				**Soluble anions (M/L)**			**Macro elements (ppm)**			**Micro Elements (ppm)**			
							Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	HCO^{-3}	Cl^{-2}	SO_4^{-2}	N	P	K	Fe	Cu	Zn	Mn
Sandy loam	80.3	2.0	17.6	8.4	0.2	5.2	1.0	0.5	0.3	0.2	0.2	0.5	1.3	40	66	40	3.0	0.8	1.0	1.5

Open field data recorded

45-old day's healthy seedlings (2nd untreated group) were selected and transplanted in the open field at 25cm apart on one side of the ridge. The plot area was (9.8 m^2) including 4 ridges (3.5m length and 0.7m width) in a randomized complete block design with three replicates each replicate including 10 spraying treatments. The first REEs treatment started 30 days after sowing and repeated each 15 days interval 5 times. The uniform cattle manure 20 m^3/feddan was added to the soil before 3days from transplanting, other cultural practices were applied according to the recommendation of the Ministry of Agriculture, Egypt. Soil samples analyses were carried out according to the procedures described by Chapman and Pratt [31] and the average of the obtained data are shown in Table 3.

2.3.1. *Vegetative growth traits*

A sample of five plants were chosen and taken randomly from each plot at the flowering stag in order to determine plant height (cm), plant leaf area (cm^2) as well as both plant fresh weight (g) and dry weight (g) where the plants were dried at 70 Cº till constant weight as illustrated by A.O.A.C. [30], and total leaf chlorophyll content at the fourth upper leaves using Minolta chlorophyll meter SPAD-501 was recorded as SPAD units.

2.3.2. *Fruit yield and its quality*

A sample of five sweet pepper fruits at edible stage were randomly taken from each plot at the third picking to determine the following data: fruit length (cm), fruit diameter (cm) and average fruit weight (g) in addition to total fruit yield (total weight of picked fruits throughout the picking season in kg per plant converted to ton/feddan).

2.3.3. *Fruit chemical content*

Total ascorbic acid (Vitamin C, mg/100g fresh weight) content was determined using 2, 6 dichlorophenol indophenols method as described by Ranganna [32].

Total Carbohydrates were determined colorimetrically according to A.O.A.C. [30].

2.4. Statistical analysis

All data were subjected to statistical analysis according to the procedures reported by Snedecor and Cochran [33] using Statistix 8 program, the means were compared by L.S.D multiple range tests at the 0.05 level of probability in the two seasons.

3. Results and discussion

3.1. Effect of REEs solutions on germination process and seedlings stage

3.1.1. *Germination process*

Irrigation of pepper seeds with different REEs treatments prior to germination significantly affected germination-related characteristics, such coefficient of velocity of germination (CVG) and mean germination time (MGT) as shown in Table 4 and Fig. 1. The improvement of the nine REEs treatments (T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8, and T_9) over untreated control seeds was 0.18, 1.01, 3.91, 11.79, 12.80, 13.63, 3.20, 3.91 and 4.80%, respectively in 1st season and 0.89, 8.46, 13.17, 15.49, 17.06, 25.67, 13.58, 13.86 and 15.36% in 2nd season for CVG, as well as the time needed to germinate MGT (the time required to the onset of the germination)) recorded for each treatment which in general, were lower than the control value, and these decreased reached 0.16, 0.84, 3.71, 10.47, 11.31, 11.99, 3.04, 3.71, and 4.56% in T1, T2, T3, T4, T5, T6, T7, T8, and T9, respectively in 1st season and 0.87, 7.90, 11.71, 13.46, 14.64, 20.49, 12.00, 12.15 and 13.32% in 2nd season compared to control. It is remarkable from the data (Table 4) that applications T4, T5, T6 (Ce, 0.5, 1.0, and 1.5 ppm) were more efficient to obtain the best results for both CVG and MGT parameters in two seasons than the control with no significant differences between them. Concerning MGR the percentage improvement overall the control were 0.00, 0.00, 5.88, 11.76, 11.76, 11.76, 0.00, 5.88 and 5.88% in 1st season and 0.00, 6.67, 13.33, 13.33, 13.33, 20.00, 13.33, 13.33 and 13.33% in 2nd season respectively. In general Ce at different concentrations was equalized in the first season, but the superiority was achieved for a high level of 1.5 ppm in the second one for MGR. These results might be parallel to those obtained by Sobarzo-Bernal et al. [34] where authors found that Ce has a stimulating effect on germination and initial growth in tomatoes and can be an alternative to accelerate the production time of tomato seedlings in seedbeds. The stimulatory effect of the application of different REEs treatments on the germination rate might be consistent with that obtained by other researchers. In rice, significant increases in seed germination were found when seeds were treated with 2.5 to 20 μg/mL $Ce(NO_3)_3$ [35]. In our study Ne in concentrate 1.5 ppm was able to stimulate the CVG parameter and lower the time required to the onset of the germination MGT as previously calculated above. Several studies proved the favorable effect of $(NO_3)_3$ on seed germination of various plants where Nd-treated seeds appeared with higher GR reaching 15% [36] and reached 22% [37] than the control treatment. It was mentioned that REEs can stimulate the seed germination process when used at an appropriate concentration through improved water absorption and permeability of the cytoplasmic membrane of seed cells during imbibition [38], besides, encouraging the oxygen evolution rate which triggers greater metabolic activity resulting in generating energy for rapid growth as mentioned by [39] and there have acting synergically with phytohormones which support the germination process [40].

3.1.2. *Seedlings vegetative growth traits*

As regards the effect of REEs as applications, the results showed that increasing seedling length (SL), number of leaves per seedling (NL/S), and both fresh and dry weight of seedling (SFW/SDW) as well as total chlorophyll in seedling stage (SLC) comparing to distilled water, was obtained as a result of most different treatments in this study. However, the 1.5 ppm cerium nitrate solution was more effective than other treatments, which reflected the highest values on SL, NL/S, SFW, SDW, and SLC in both seasons followed by cerium at 1.0 ppm for SL,

NL/S and SFW with no significant differences between them in both seasons as well as SDW

Table 4 Influence of some rare earth elements on germination process of pepper seed during the two growing seasons of 2020 and 2021

Treatments	CVG		MGT		MGR	
	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season
T0	16.88	14.65	5.92	6.83	0.17	0.15
T1	16.91	14.78	5.91	6.77	0.17	0.15
T2	17.05	15.89	5.87	6.29	0.17	0.16
T3	17.54	16.58	5.70	6.03	0.18	0.17
T4	18.87	16.92	5.30	5.91	0.19	0.17
T5	19.04	17.15	5.25	5.83	0.19	0.17
T6	19.18	18.41	5.21	5.43	0.19	0.18
T7	17.42	16.64	5.74	6.01	0.17	0.17
T8	17.54	16.68	5.70	6.00	0.18	0.17
T9	17.69	16.90	5.65	5.92	0.18	0.17
L.S.D at 0.05	2.11	2.11	0.45	0.51	0.01	0.02

CVG: Coefficient of germination velocity (%), MGT: mean germination time, MGR: mean germination rate.T0= tap water (control) T1= Pr (NO3)3 at 0.5 ppm T2= Pr (NO3)3 at 1.0 ppm T3= Pr (NO3)3 at 1.5 ppm T4= Ce (NO3)3 at 0.5 ppm T5= Ce (NO3)3 at 1.0 ppm T6= Ce (NO3)3 at 1.5 ppm T7= Nd (NO3)3 at 0.5 ppm T8= Nd (NO3)3 at 1.0 ppm T9= Nd (NO3)3 at 1.5 ppm.

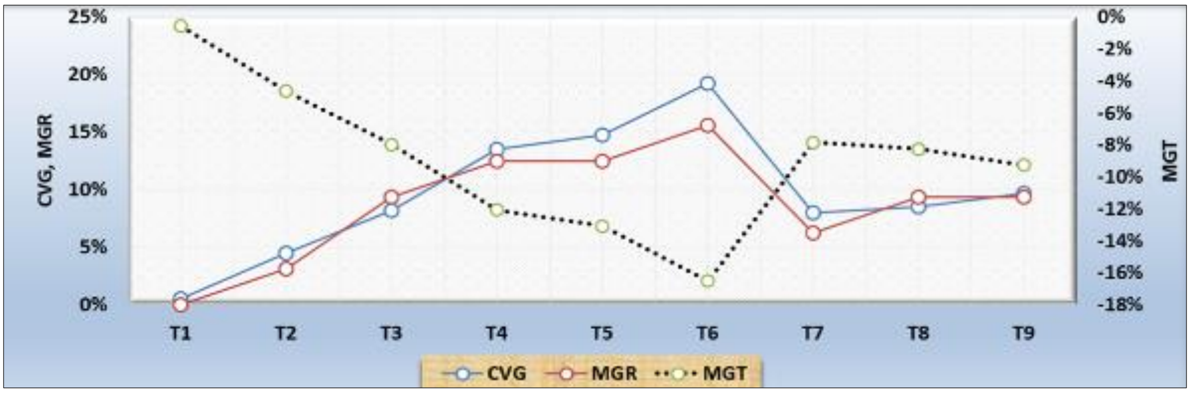

Figure 1 The increment percentage of CVG, MGT and MGR as affected by the nine ERRs treatments compared to the untreated control (average of both seasons)

Table 5 Influence of some rare earth elements on pepper seedlings vegetative growth traits during the two growing seasons of 2020 and 2021

Treatments	Seedling length (cm)	No. leaves/ Seedling	Seedling fresh weight (g)	Seedling dry weight (g)	Seedling leaf chlorophyll (spad)
	1st Season				
T0	11.68	4.53	1.67	0.23	29.04
T1	11.82	4.73	1.78	0.28	29.44
T2	11.86	4.78	2.01	0.30	30.61
T3	11.88	5.19	2.05	0.34	31.33
T4	12.87	6.17	2.85	0.43	37.06
T5	12.94	6.81	3.15	0.46	37.20
T6	13.07	7.20	3.36	0.50	40.08
T7	12.36	5.77	2.17	0.35	30.72
T8	12.68	5.99	2.37	0.38	30.90
T9	12.58	6.27	2.61	0.41	32.23
L.S.D at 0.05	0.37	0.35	0.24	0.03	1.93
	2nd Season				
T0	9.46	4.82	1.57	0.31	28.88
T1	9.96	5.09	1.91	0.33	29.16
T2	10.45	5.25	1.99	0.35	29.28
T3	11.03	5.35	2.14	0.38	31.50
T4	12.77	5.56	2.85	0.54	33.43
T5	13.30	6.50	3.14	0.56	33.48
T6	13.43	6.90	3.68	0.57	39.94
T7	10.64	5.43	2.33	0.39	30.12
T8	11.42	5.65	2.69	0.45	31.35
T9	12.09	6.17	2.80	0.48	32.02
L.S.D at 0.05	0.61	0.52	0.18	0.04	2.05

T0= tap water (control) T1= Pr (NO3)3 at 0.5 ppm T2= Pr (NO3)3 at 1.0 ppm T3= Pr (NO3)3 at 1.5 ppm T4= Ce (NO3)3 at 0.5 ppm, T5= Ce (NO3)3 at 1.0 ppm T6= Ce (NO3)3 at 1.5 ppm T7= Nd (NO3)3 at 0.5 ppm T8= Nd (NO3)3 at 1.0 ppm T9= Nd (NO3)3 at 1.5 ppm.

Trait in 2nd season. Therefore, the application of Ce, especially at a concentration of 1.5 ppm, produced superior seedlings parameters compared with the control. Meanwhile, the values of the above measurements were relatively approximated and not statics in praseodymium-treated seedlings and control treatment in two seasons. Similarly, a positive response of seedlings length was estimated by neodymium application, meanwhile, in the case of seedling dry weight, the result achieved by the high concentrates (1.0, 1.5 ppm) of neodymium was relatively close to cerium applied at levels 0.5 ppm (T4) and 1.0 ppm (T5) in the average of both seasons Fig. 2. Many of studies were summarized on the increment relative to Ce applications on fresh and dry seedlings biomass as [35] and [41-43] in some vegetable crops as spinach, maize, and lettuce. They stated that Ce significantly increased the initial growth variables of the seedlings. Generally, it was concluded that the role of REEs at low concentrations in producing healthy seedlings growth depends on consist strong root system through promoting the formation of adventitious roots besides affecting cell differentiation, root morphogenesis, and absorption of minerals and metals [38]. In the current study, the positive effect of Ce on the total chlorophyll content in pepper seedlings stage was also assessed whereas 1.5 ppm Ce exhibited higher leaf chlorophyll content in both seasons. It is assumed that the role of Ce in encouraging leaf chlorophyll content may be returned to use a suitable amount of Ce which positively affects the absorption of light energy, its transformation, electron transport rate, and photophosphorylation [44-45]. Nevertheless, Ce may play an indirect role in chlorophyll formation; hence it could enter into the chloroplast and bind easily to chlorophyll, replacing Mg^{2+} and forming Ce-chlorophyll as stated by Honge et al. [46]. Such stimulatory effects of cerium nitrate on seedlings' growth traits can be attributed to Ce enhancing photosynthetic activity, antioxidant activity, and secondary metabolites which resulted in healthy growth [47-51]. Current results also showed that Nd at high concentrations could induce seedlings' growth including the number of leaves per seedling (NL/S), fresh weight (SFW), and dry weight (SDW). It was reported that REEs treatment including Nd at appropriate concentration can promote seedlings' root growth and activity which considers the main organ that absorbs water and nutrients due to the vigor of seedlings' growth [52-54]. The extent of variation for chlorophyll Fig. 3 was from 1.17% – 37.36% for all types and concentrations of REEs (average of both seasons), with 5 REEs solutions showing a significant positive effect. In general, the three different concentrations of both Ce and Nd exhibited significant positive increments in SL, NL/S, SFW, and SDW in both seasons Table 5. As for the average values of both seasons Fig. 3, the changes in these traits ranged from 3.03-25.35% (SL), 5.03-50.8% (NL/S), 13.89-117.28% (SFW), and 12.96-98.15% (SDW) for all studied types of REEs Fig. 3 over control treatment.

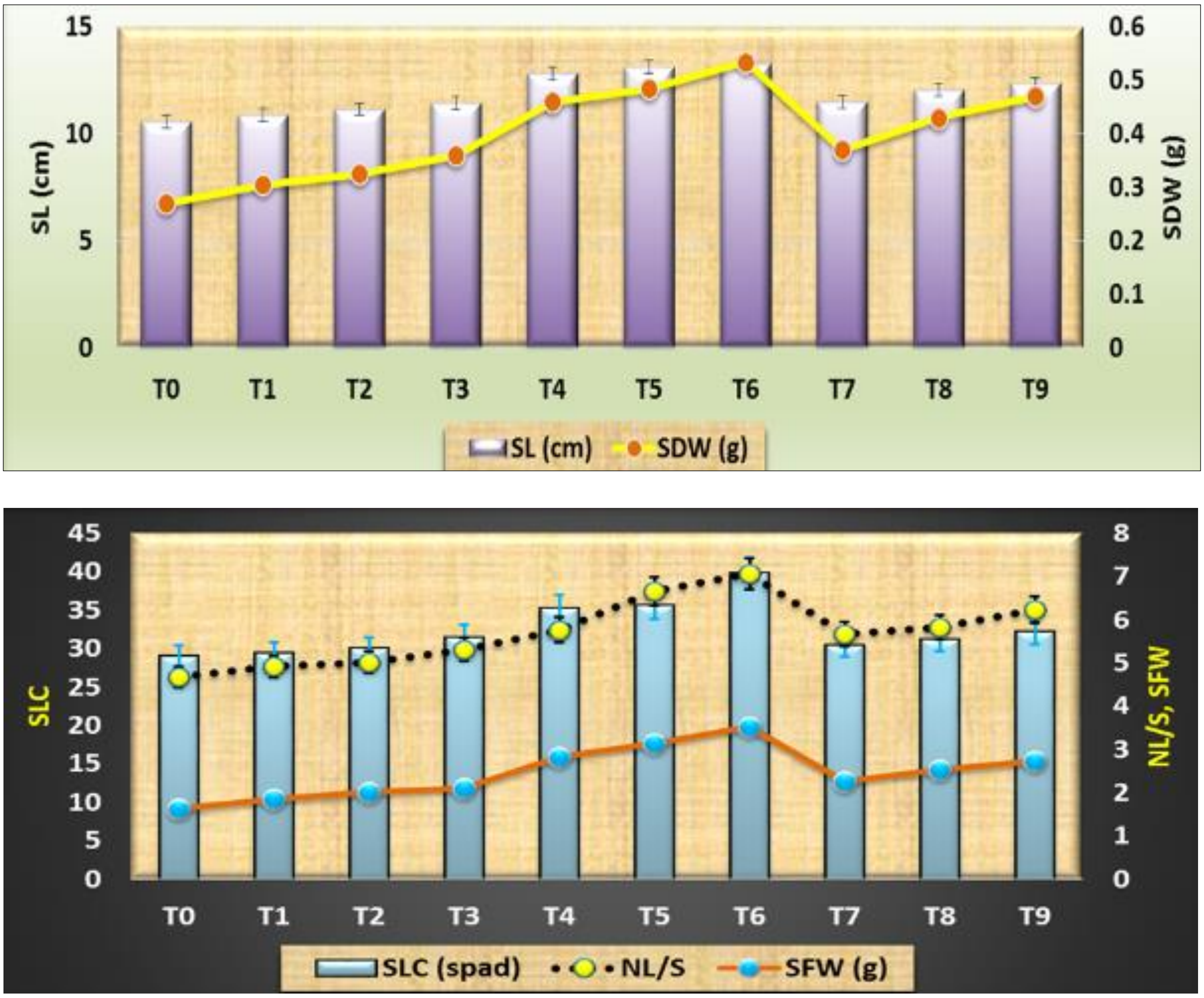

Figure 2 Pepper seedling vegetative growth traits as affected by some rare earth elements as average of 2020 and 2021 seasons

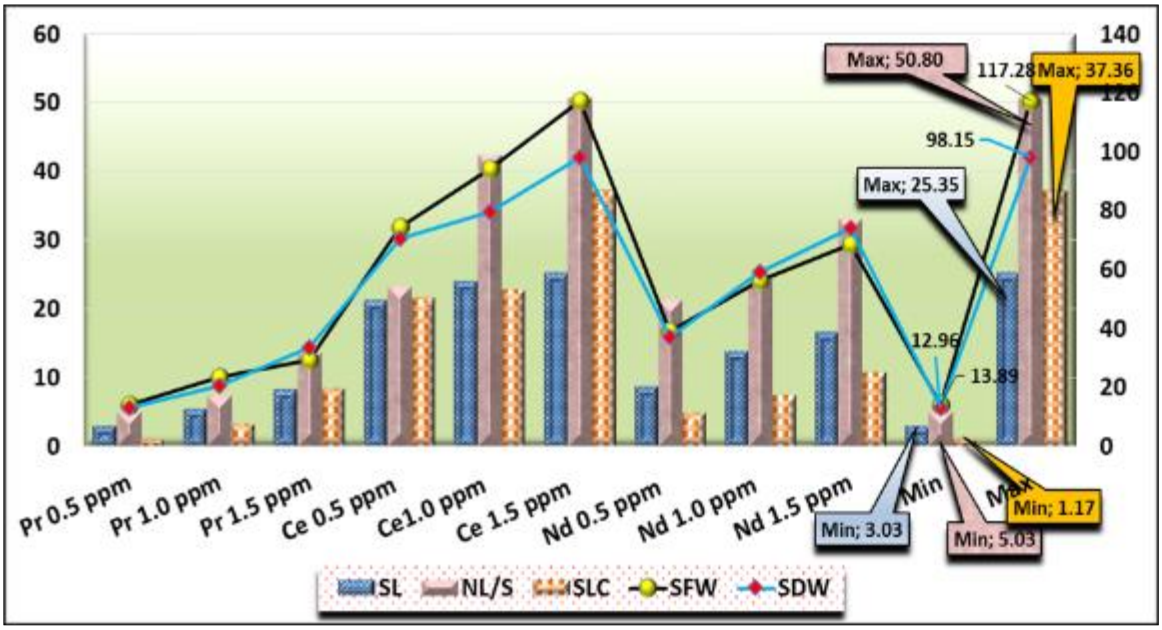

Figure 3 Changes percentage of seedling traits (average of 2020 and 2021 seasons) as affected by some rare earth elements over control

3.2. Effect of REEs solutions on pepper plant development (Open field)

3.2.1. Vegetative growth traits

The simulative effect of REEs i. e., Nd and Pr on pepper vegetative growth expressed as plant height (PH), leaf area (LA), plant fresh (PFW), and dry weight (PDW), as well as chlorophyll leaf content (Ch), were shown in Table 6 and Fig. 4. All applications of Nd significantly produced the maximum vegetable plant growth parameters especially the high level 1.5 ppm (T9). The favorable effect was also clear by Pr treatments (T1, T2, and T3) respectively next to Nd applications. Meanwhile, cerium at different concentrations was the worst in terms of vegetative growth results compared to the other two substances Nd and Pr. As for the average values of both seasons Fig. 4. The extent of variation for the vegetative traits ranges from 8.5-66.7% (PH), 4.4-31.2% (LA), 6.3-59.2% (PFW), 7.0-58.4% (PDW) and 2.8-43.6% (Ch) for all studied types of REEs over the control treatment. In the treatment with 1.5 ppm Nd the relative growth exhibited increments up to 66.7, 59.2, 58.4, 43.6, and 31.2% over that observed in the control of PH, PFW, PDW, Ch, and LA, respectively Fig. 5. The positive effects of REEs on pepper plant growth may be returned to the fact that using a suitable concentration of REEs could stimulate plant growth and development because they have similar physiological effects as some mineral nutrients [54-55] in additive; REEs stimulate the photosynthetic capacity [56]. It was reported that neodymium (Nd) is an effective fertilizer for improving plant nutrition and healthy growth [38], significantly promotes growth, increases the chlorophyll content, and accelerates the photosynthesis rate and accumulation of organic substances, thereby enhancing plant fresh and dry mass [57-58]. As for REEs role inside the plant, it was mentioned that REEs stimulate growth, by inducing cell growth and biosynthesis of certain secondary metabolites i.e., alkaloids, carotenoids, and flavonoids, and their effect on plant physiology [59] and [38]. As shown in the current study that REEs were induce pepper chlorophyll leaf content, it possibility may return that most of the REEs adhered to the cell wall [60] or bound to the cell membrane [61], and the free radical reaction was in equilibrium [62], which increased the stability of the membrane [63] and activity of the corresponding enzyme [64], thus stimulating and compensating the chlorophyll content. Furthermore, [54] deduced that the change in chlorophyll leaf content was caused by two reasons the change in total chlorophyll content, and the change in chlorophyll structure so, significant changes were observed in the chlorophyll content in plant leaves under different concentrations of REEs. The REE application can have a beneficial effect by improving the growth, height, and dry weight of plants when supplied in an appropriate concentration [65] and [38]. It has been concluded that rare earth has been shown to enhance the transformation of inorganic phosphate into organic phosphate compounds. Furthermore, higher amounts of phosphatide and energy-rich phosphate could be detected in treated plants. On this basis, it was assumed that these changes reflect on vigor of plant growth [66].

3.2.2. *Fruit yield and its quality*

Data presented in Table 7 and Fig. 6. Show the effect of REEs applications, *i.e.,* 3-rare earth elements in three different concentrations on yield and fruit quality traits of pepper. It is clearly illustrated that all REEs applications increased average fruit weight (AFW), fruit diameter (FD), fruit length (FL), and total yield (TY) compared with the control. The effect of Ce at concentrates 0.5 and 1.0 ppm resulted in insignificant increases in fruit diameter in both seasons. Similarly, Ce foliar spray at 1.0 ppm on total yield in the first season as shown in Table 6. Nd at all concentrations exhibited the maximum values for all studied yield traits than the other used REEs (Pr or Ce) with no significant differences among the three concentrations’ effects for

Table 6 Influence of some rare earth elements on pepper plant vegetative growth during the two growing seasons of 2020 and 2021

Treatments	Plant height (cm)	Leaf area (cm^2)	Plant fresh weight (g)	Plant dry weight (g)	Chlorophyll (spad)
	1st Season				
T0	40.16	183.25	175.26	72.50	40.67
T1	50.37	198.00	195.65	107.47	51.75
T2	55.00	210.06	205.50	114.08	53.19
T3	57.43	219.18	224.98	116.33	56.69
T4	41.26	192.86	182.54	82.64	43.00
T5	44.76	194.58	188.27	86.80	42.45
T6	44.95	201.93	192.93	91.71	47.78
T7	63.50	225.83	244.60	118.00	58.00
T8	67.12	232.07	246.20	121.77	58.43
T9	68.56	246.05	276.33	125.35	59.29
L.S.D at 0.05	4.14	8.64	13.42	5.53	3.17
	2nd Season				
T0	43.74	196.33	162.00	88.50	47.99
T1	58.04	216.72	204.20	111.15	57.39
T2	59.08	224.52	209.46	116.00	58.75
T3	62.16	231.17	234.17	119.63	61.29
T4	49.80	203.42	175.93	89.65	48.14
T5	51.53	208.17	191.00	94.61	51.49
T6	52.70	210.89	203.06	109.08	53.93
T7	66.11	239.99	237.00	124.93	63.78
T8	70.66	245.07	245.33	125.17	67.41
T9	71.33	252.00	260.67	129.67	68.06
L.S.D at 0.05	3.40	8.18	7.45	4.37	3.67

T0= tap water (control) T1= Pr (NO3)3 at 0.5 ppm T2= Pr (NO3)3 at 1.0 ppm T3= Pr (NO3)3 at 1.5 ppm T4= Ce (NO3)3 at 0.5 ppm, T5= Ce (NO3)3 at 1.0 ppm T6= Ce (NO3)3 at 1.5 ppm T7= Nd (NO3)3 at 0.5 ppm T8= Nd (NO3)3 at 1.0 ppm T9= Nd (NO3)3 at 1.5 ppm.

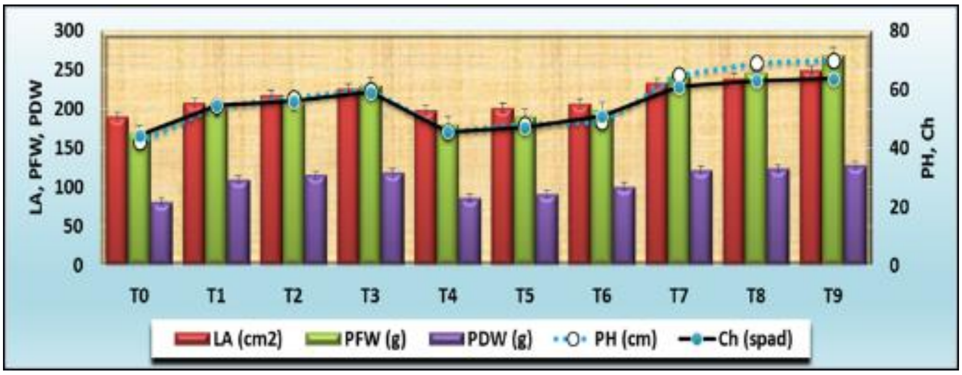

Figure 4 Pepper vegetative growth traits in open field as affected by some rare earth elements as average of 2020 and 2021 seasons

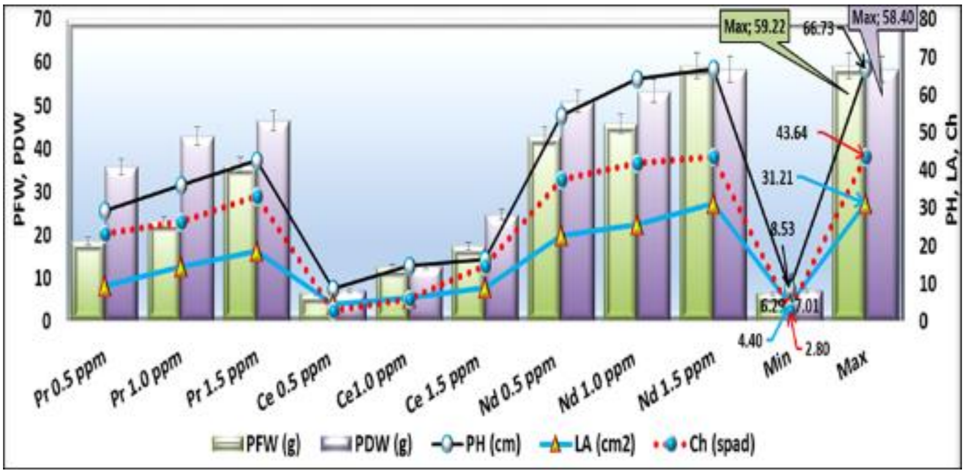

Figure 5 Changes percentage of vegetative growth traits (average of 2020 and 2021 seasons) as affected by some rare earth elements over control

Table 7 Influence of some rare earth elements on pepper fruit yield and its quality during the two growing seasons of 2020 and 2021

Treatments	Ave. fruit weight (g)	Fruit diameter (cm)	Fruit length (cm)	Total yield (ton/fed.)	Ave. fruit weight (g)	Fruit diameter (cm)	Fruit length (cm)	Total yield (ton/fed.)
	1st Season				2nd Season			
T0	53.25	5.85	6.13	5.93	55.71	5.49	5.91	4.57
T1	63.94	6.18	7.21	6.04	66.91	5.92	7.06	5.98
T2	68.17	6.58	7.26	6.12	68.65	6.00	7.10	6.05
T3	71.82	6.60	7.37	6.17	71.72	6.56	7.38	6.30
T4	57.05	5.87	6.42	5.58	59.38	5.28	6.69	5.31
T5	60.28	5.94	6.70	5.82	63.79	5.57	6.98	5.65
T6	60.76	6.08	7.01	5.94	70.13	6.29	7.02	5.85
T7	73.72	6.67	7.67	6.45	74.16	6.74	7.40	6.34
T8	75.97	6.95	7.57	6.54	79.03	6.91	7.50	6.95
T9	80.91	7.03	7.86	6.86	87.02	7.00	7.73	7.13
L.S.D at 0.05	3.14	0.42	0.35	0.35	2.77	0.36	0.42	0.34

T0= tap water (control) **T1=** Pr (NO$_3$)$_3$ at 0.5 ppm **T2=** Pr (NO$_3$)$_3$ at 1.0 ppm **T3=** Pr (NO$_3$)$_3$ at 1.5 ppm **T4=** Ce (NO$_3$)$_3$ at 0.5 ppm , **T5=** Ce (NO$_3$)$_3$ at 1.0 ppm **T6=** Ce (NO$_3$)$_3$ at 1.5 ppm **T7=** Nd (NO$_3$)$_3$ at 0.5 ppm **T8=** Nd (NO$_3$)$_3$ at 1.0 ppm **T9=** Nd (NO$_3$)$_3$ at 1.5 ppm.

FD and FL and between 1.0 and 1.5 ppm for TY in both seasons. Also, no significant differences between 0.5 and 1.0 ppm Nd effects on AFW in 1st season. Generally, the effects of all treatments were T9>T8>T7>T3>T2 in all yield traits followed by T1>T6>T5>T4>T0 in descending order whereas no significant differences between T1, T2, and T6 in FL and TY. (1.5 ppm of Ce equal to 1.0 or 0.5 ppm of Pr). However, Ce in this study was not numerically efficient to reach maximize the results of neodymium or praseodymium as shown in Table 7.

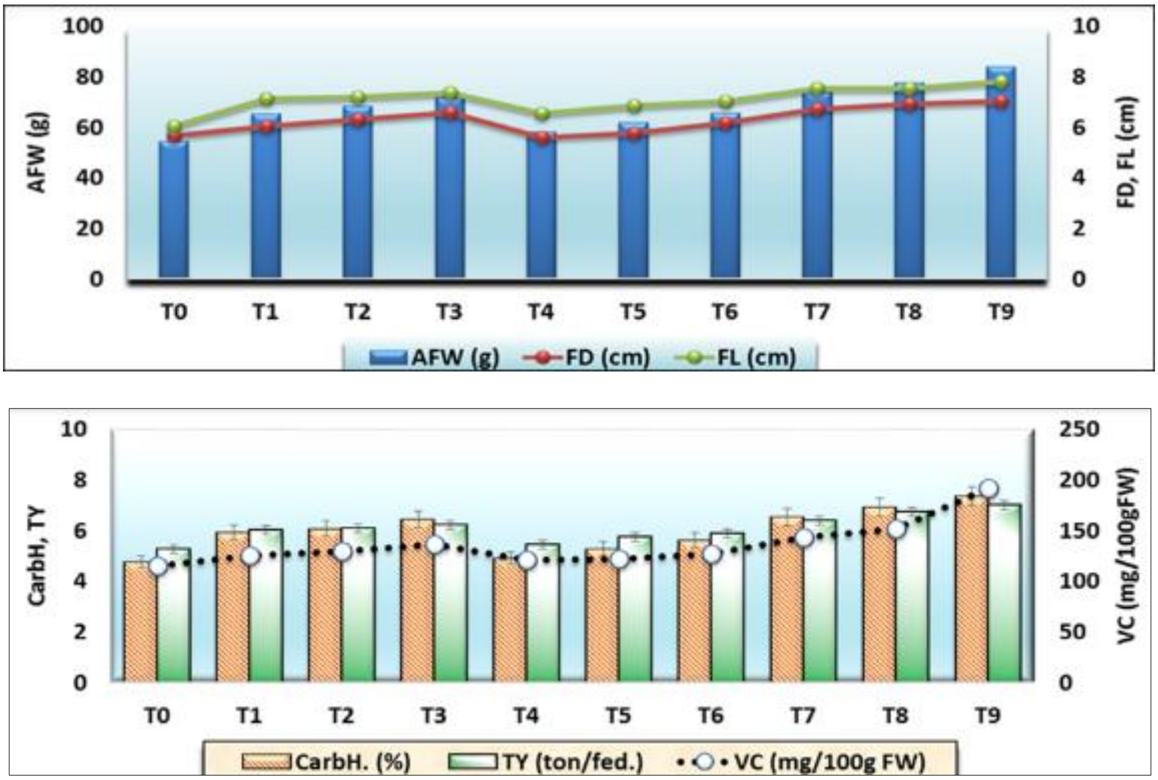

Figure 6 Pepper fruit (up), carbohydrate, V.C and yield (down) as affected by some rare earth elements as average of 2020 and 2021 seasons

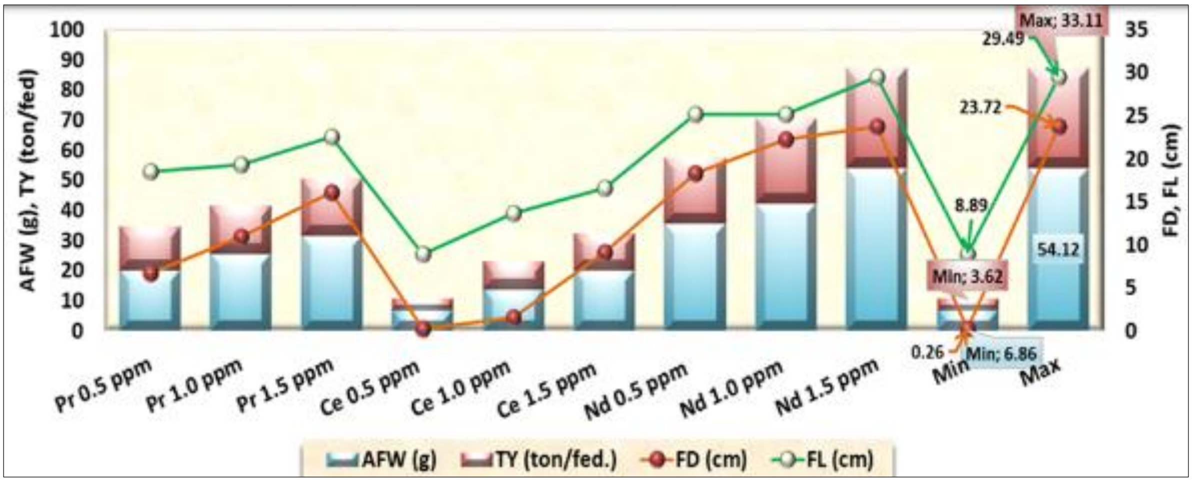

Figure 7 Changes percentage of fruit yield traits (average of 2020 and 2021 seasons) as affected by some rare earth elements over control

As for the average values of both seasons (Figs. 6&7), The extent of variation for the fruit yield and quality traits ranged from 6.86-54.12% (AFW), 0.26-23.72% (FD), 8.89-29.49% (FL) and 3.62-33.11% (TY) for all studied types of REEs over the control treatment. The foliar spray treatment of 1.5 ppm Nd exhibited the increment up to 54.12, 23.72, 29.49 and 33.11% over that observed in the control of AFW, FD, FL, and TY, respectively Fig. 7. Regarding the reported in several studies that REEs as plant applications lead to yield increases and improve fruit physical quality by influencing the enzyme activity [10], thus, rare earth application have been shown to improve potatoes tuber formation and increased total yield by 13.8 % [67]. Moreover, the yield responses were in the range of 8.5 to 18.5 % after rare earth application for corn, and 8.9% in soybean [15]. Also, enhancing crop yields have been reported in winter wheat treated with rare-earth-based fertilizer [68] and sunflower [69]. Corresponding mentioned above, the beneficial effects of REEs include several aspects improving plant nutrition, chlorophyll content, increased plant enzyme activity, and the photosynthetic rate which lead to healthy plant growth and thus produce great yield. In this concern, it was reported that Pr as plant application can improve plant yield, compared with Ce which obtained the lowest promotion [70].

3.2.3. Fruit chemical content

The beneficial effects of REEs on pepper fruit chemical content i. e., ascorbic acid, and carbohydrates percentage are demonstrated by both Nd and Pr concentrations as shown in Table 8 and Fig .6. The increment in previous parameters correlated positively with rising both Nd and Pr levels, it was clear that The highest positive values resulted from the different concentrations of neodymium, particularly the high-level solution 1.5 ppm where, the percentage increase of ascorbic acid in fruit produced from Nd-treated plant at level 1.5 ppm reached 63.76 and 69.57% up those obtained from the control treatment, while the raising in carbohydrates reached 70.54 and 42.99% in 1st and 2nd seasons, respectively. Cerium foliar spray exhibited the minimum influence concerning the above fruit's chemical content. Moreover, the extent of variation for the chemical traits ranged from 5.24-66.51 (V.C) and 3.48-55.22 (Carbohydrate) for all studied types of REEs Fig. 8 over the control treatment. The promoting role of REEs which appear in this study was explained based on the results demonstrating that the physiological aspects of rare earth in plants include increased plant enzyme activity, chlorophyll content, photosynthetic rate, and plant metabolite production as these helpful effects lead to enhances fruits chemical content [50] and [71]. These findings are consistent with previous research approved that REEs at suitable concentrate enhance fruit content of vitamin C [72] in grapes, accumulations of starch in potatoes [67], and sugar cane [66].

Table 8 Influence of some rare earth elements on ascorbic acid and carbohydrates percentage of pepper fruit during the two growing seasons of 2020 and 2021

Treatments	**Vitamin C mg/100g (fresh wt.)**	**Carbohydrates (%)**	**Vitamin C mg/100g (fresh wt.)**	**Carbohydrates (%)**
	1st Season		**2nd Season**	
T0	121.50	4.21	109.00	5.32
T1	133.33	5.93	117.33	5.95
T2	134.50	6.07	124.13	6.09
T3	144.33	6.38	129.07	6.49
T4	127.25	4.50	115.33	5.32
T5	127.43	4.95	116.33	5.65
T6	132.50	5.21	121.33	6.03
T7	151.60	6.45	135.50	6.61
T8	156.92	6.82	145.83	7.01
T9	198.97	7.18	184.83	7.55
L.S.D at 0.05	8.76	0.30	17.78	0.35

T0= tap water (control) **T1=** Pr $(NO_3)_3$ at 0.5 ppm **T2=** Pr $(NO_3)_3$ at 1.0 ppm **T3=** Pr $(NO_3)_3$ at 1.5 ppm **T4=** Ce $(NO_3)_3$ at 0.5 ppm, **T5=** Ce $(NO_3)_3$ at 1.0 ppm **T6=** Ce $(NO_3)_3$ at 1.5 ppm **T7=** Nd $(NO_3)_3$ at 0.5 ppm **T8=** Nd $(NO_3)_3$ at 1.0 ppm **T9=** Nd $(NO_3)_3$ at 1.5 ppm.

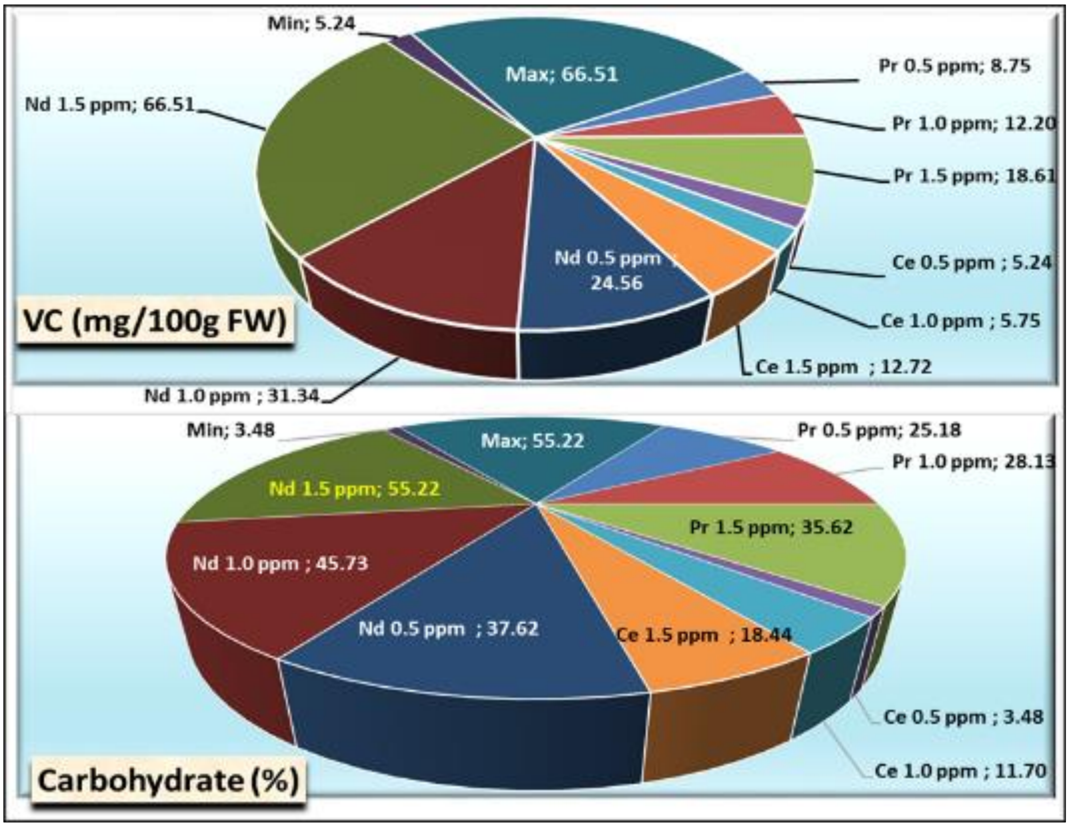

Figure 8 Changes percentage of V.C and carbohydrates (average of 2020 and 2021 seasons) as affected by some rare earth elements over control

4. Conclusion

The application of adequate REEs can promote the germination of pepper seeds and plant development, increase plant biomass, and improve the quality of fruiting, and these elements can improve the growth and development of pepper plants when supplied at a suitable concentration. From this study, it can conclude that cerium could enhance pepper seeds germination rate particularly at concentrations of 1.0 and 1.5 ppm as irrigation in the seedling. Both cerium and neodymium at all levels encourage the coefficient of germination velocity. Cerium at a high level of 1.5 ppm maximized seedlings' parameters compared with the control treatment. Neodymium at various concentrates significantly produced vigorous plant growth, stimulating total yield and fruit physical quality and increasing fruit chemical content of ascorbic acid and carbohydrates.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest.

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