Response of tomato growth to continuous elevated CO_2 concentration under controlled environment

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Abstract: CO_2 fumigation has been extensively used in greenhouses cultivation to enhance crop yield. The effects under the precise level of elevated CO_2 (e[CO_2]) on crop morphology, yield, and fruit quality remain largely elusive yet. To explore the response of plant growth to the continuous RCPs (Representative Concentration Pathways) projected CO_2 concentration [CO_2], tomato (Hezuo 908) plants were grown under ambient CO_2 (a[CO_2], 462 μmol/mol) and e[CO_2] (550, 700, 850 and 1000 μmol/mol): named as EC_{550}, EC_{700}, EC_{850}, and EC_{1000}, respectively, under uniform environmental condition for two planting seasons. Collective growth of tomato plants (plant height, stem diameter, and leaf area index) was significantly enhanced under EC_{700} and showed a slightly negative response under EC_{850}. The optimum yield was stimulated under EC_{700} by 74.05% and 55.91%, while maximum total dry weight (DW_t) was enhanced under EC_{1000} by 58.23% and 39.78% during autumn-winter and spring-summer planting seasons, respectively, as compared to a[CO_2]. The greatest yield and least DW_t stimulated under EC_{700} for both seasons indicated that EC_{700} improved the ability of the tomato plants to translocate carbohydrates to fruits. Optimum water use efficiency related to yield (WUE_y) was enhanced by 55.91-210.87% under EC_{700} compared to a[CO_2]. The titratable acid (TA) was improved by 19.94% (EC_{700}), 29.17% (EC_{850}), and 97.92% (EC_{1000}), and the lycopene (Lp) was increased by 2.22% (EC_{700}) and reduced by 2.28% (EC_{1000}). Thus, the overall optimum impact on tomato growth was explored under EC_{700}. Super e[CO_2] did not positively influence the tomato growth process and yield under adequate water and fertilizer conditions. The present study results are beneficial for greenhouse crop production and might be used as a reference to validate the climate change influence modeling.

Keywords: elevated CO_2, tomato plant, yield, water use efficiency, fruit quality
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1 Introduction

Agricultural scientists are facing a major challenge for crop production, which needs to be enhanced by +70% because of the growing population to sustain the food demand and supply chain[1-3]. Developing sustainable agricultural systems that produce more high-quality food in changing climate is also essential. The primary driver of climate change is the rapid increase in CO_2 concentration [CO_2] since the pre-industrial era[4]. The current [CO_2] is found at 410 μmol/mol[5]; according to Representative Concentration Pathways (RCPs), it was projected that [CO_2] would be reached about 1000 μmol/mol by the end of the 21st Century[6]. On the other hand, the elevation of CO_2 concentration (e[CO_2]) strategy has been used in commercial greenhouses to enhance yield and improve the quality of crop production[7]. Hence, quantifying the optimum e[CO_2] in greenhouses is not only important for improving crop yield but also meaningful for providing a scientific response to climate change.

Numerous studies have been conducted to explore the response of different crop growths under e[CO_2] in a controlled environment chamber (CEC) and free-air CO_2 enrichment (FACE), respectively, e.g., tomatoes[8,9], cucumber[10], rice[11], wheat[12] and maize[13,14]. Most studies documented that the influence on the growth of the crops under a single treatment of e[CO_2] is limited to finding the optimum crop yield. As reported, tomatoes production improved up to 38% under 1000-1500 μmol/mol of e[CO_2][15], while the yield of tomatoes was found 125% higher under 700 μmol/mol of e[CO_2][16] indicating the variation in the yield of tomatoes at two different levels of [CO_2]. Similarly, the e[CO_2] enhanced rice yield by 11.4%-19.7% under 60 μmol/mol elevated [CO_2] than ambient CO_2 (a[CO_2])[11]. The crop yield results of research studies varied at different levels of e[CO_2] creating a research gap to explore the precise level of e[CO_2] to get the optimum yield of crops. The wheat biomass was increased by 17%, and water use

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efficiency was enhanced by 52.33% under the e[CO_2] at 600 μmol/mol[17]. The biomass, branches, and seeds per plant of parthenium weed grown under 550 μmol/mol of [CO_2] were increased by 38%, 35%, and 37%, respectively[5]. *Senna reticulata* root and stem growth under e[CO_2] at 720 μmol/mol increased by 234.74% and 168.34%, respectively[18]. The results of previous studies reflected the impact of e[CO_2] considering only a single level of e[CO_2], which indicated that the response of plants growth, yield, biomass, water use efficiency, and fruit quality might be higher/lower under another e[CO_2] than selected e[CO_2] as it is reported that responses of plant growth, yield, biomass, water use efficiency and fruit quality under different e[CO_2] were found different. Considering the diversified results of research studies on plant growth and yield under different e[CO_2] levels, it is necessary to assess the precise level of e[CO_2] for adequate growth of crops.

Available scientific literature mainly focused on the response of crop growth and yield to the e[CO_2], the research on the influence of e[CO_2] on fruit quality was rarely reported. Furthermore, the interactive influence of e[CO_2] has been studied along with other variables, e.g., water stress, nitrogen, and temperature[11], which could not support the assessment of the mechanism for influence only by e[CO_2]. Therefore, investigation of the influence of only e[CO_2] is insufficient. Nevertheless, to date, no studies are available to our knowledge to investigate the impact against real-time experimental and continuous classified RCPs projected [CO_2] on the tomato for the whole growth season under controlled environmental conditions. Subsequently, it is hypothesized that the growth and yield of tomatoes may be enhanced at some limit of e[CO_2] and declined at super e[CO_2]. Consequently, it is essential to explore the response of tomatoes at RCPs projected [CO_2] to analyze the influence mechanism for only e[CO_2] during the whole growing season and discover suitable [CO_2] for tomato growth and yield under controlled environmental and field conditions.

The primary objective of this study was to investigate the response of tomato growth, yield, and water use efficiency at designed e[CO_2] as compared to a[CO_2], as well as among treatments to explore the adequate level of e[CO_2] for optimum tomato yield, water use efficiency and fruit quality under controlled environmental conditions. For this purpose, tomato plants were planted in CEC under five treatments with e[CO_2] (1000, 850, 700, 550 μmol/mol, and a[CO_2]) along with well-watered conditions. Treatments for [CO_2] were designed by considering the IPCC-2014 climatic scenarios (RCPs). The morphological parameters such as plant height, stem diameter, leaf area (LA), and total dry weight of each plant element were measured. Water use efficiency, fruit yield, and quality were assessed to explore the response of tomato plants under-designed e[CO_2]. The results of this study will project the complementary adaptation in terms of e[CO_2] for optimum production of tomatoes with good fruit quality and to choose the standard precise level e[CO_2] for research.

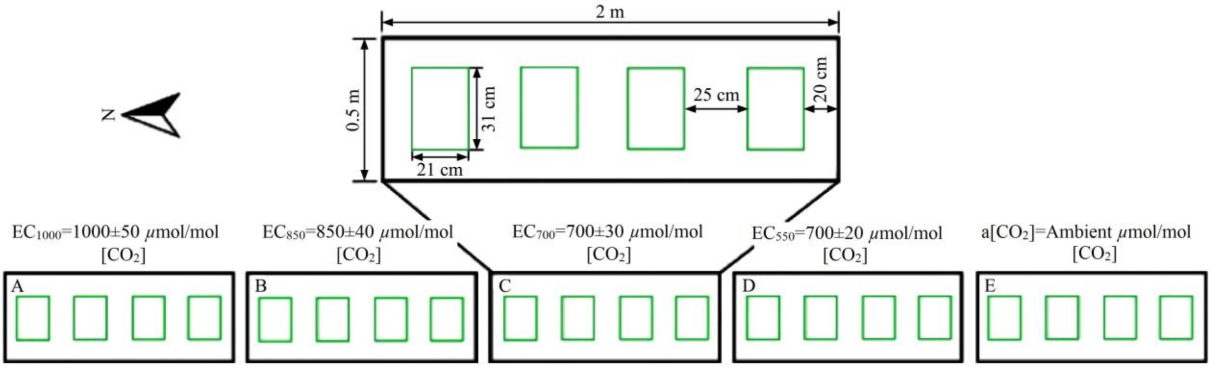
2 Materials and methods

2.1 Experiment site

The experiment was conducted in two planting seasons (autumn-winter: Sep. 7th, 2020-Jan. 7th, 2021 and spring-summer: Mar. 25th-Jul. 25th, 2021) in a greenhouse in Jiangsu University, Zhenjiang, Jiangsu, a Key Laboratory of Modern Agricultural Equipment and Technology (32.11°N, 119.31°E) under Ministry of Education, China. The mean ambient temperature, relative humidity, solar radiation, and CO_2 concentration inside the greenhouse were 22.8°C, 70 %, 39.9 W/m^2, and 429 μmol/mol during spring-summer, while 20.2°C, 77%, 35.8 W/m^2, and 462 μmol/mol during autumn-winter, respectively. The three-phase and porosity of soil were determined using the DIK-1150, Japan[19]. The original soil was classified with 59.5% clay, 39.5% silt, and 1.0% sand by sieve analysis. The bulk density and soil porosity were 1.45 g/cm^3 and 49.37%, respectively. The three-phase composition consisted of 50.63% solid phase, 24.07% liquid phase, and 25.31% gas phase. The soil was mixed uniformly and put into pots (12 L) to make uniform soil conditions.

2.2 Experimental setup

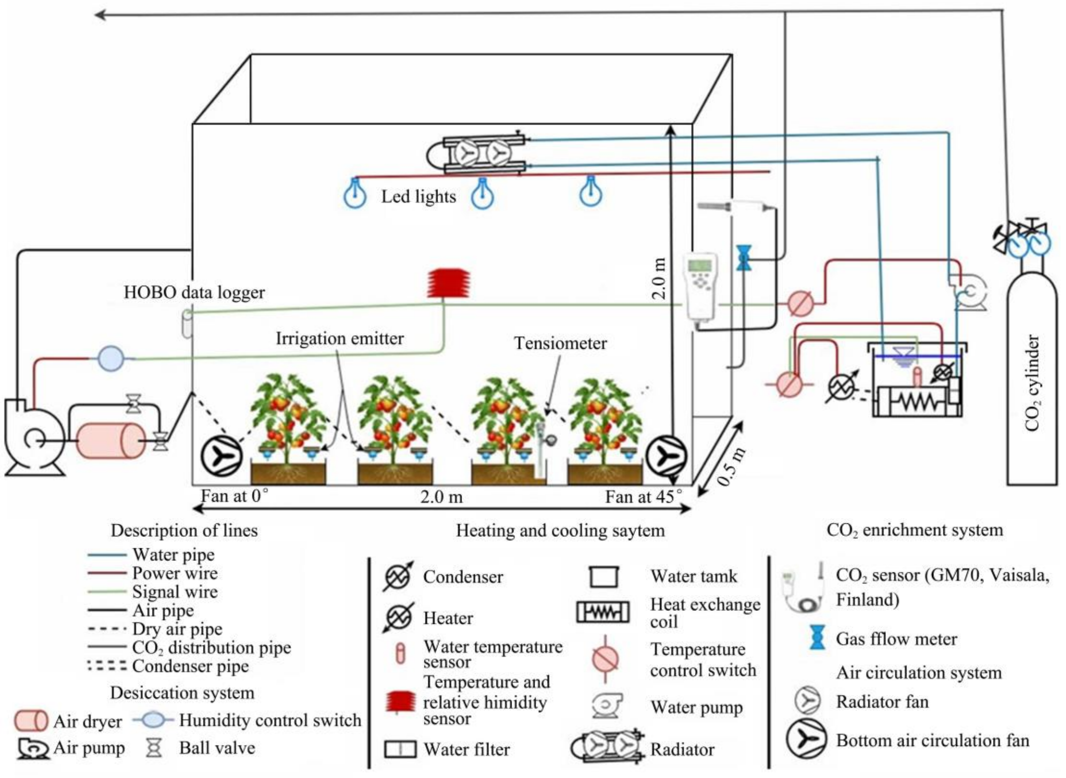
The experiment was designed with different e[CO_2] treatments: EC_{1000}, EC_{850}, EC_{700}, EC_{550}, and a[CO_2] were set at (1000±50) μmol/mol, (850±40) μmol/mol, (700±30) μmol/mol, (550±20) μmol/mol, and ambient [CO_2] in A, B, C, D, and E controlled environment chambers (CEC), respectively, with four replication completely randomized block, was adopted for each treatment as shown in Figure 1. Elevation of [CO_2] was classified into two classes, 700 μmol/mol (EC_{700}) and 550 μmol/mol (EC_{550}) declared as moderate e[CO_2], and 1000 μmol/mol (EC_{1000}) and 850 μmol/mol (EC_{850}) called super e[CO_2].



Note: EC_{1000}, EC_{850}, EC_{700}, EC_{550}, and a[CO_2] were set at 1000 μmol/mol, 850 μmol/mol, 700 μmol/mol, 550 μmol/mol, and ambient CO_2 concentration in A, B, C, D, and E controlled environment chambers.

Figure 1 Experimental layout: consisted of five CEC with four replicates in each CEC

The system consisted of five independent CEC (2.0 m×0.5 m×2.0 m) to control the [CO_2], air humidity, and temperature inside the chambers. The experimental structure of the CEC is shown in Figure 2. Each CEC was equipped with CO_2 sensors (GM70, Vaisala, Finland) at 1.6 m height and a CO_2 enrichment system, which controlled each CEC's set range of [CO_2]. The [CO_2] in each CEC was monitored daily for nine hours from 08:00 to 17:00 during all growth periods. A heating and cooling system, desiccating system, CO_2 enriching system, air circulating system, and LED lights were installed to sustain the required set range of temperature T (18℃<T<30℃), relative humidity RH (30%<RH<80%), and [CO_2] to reduce the [CO_2] gradient, temperature profile, and adequate radiation (during cloudy days) in each CEC, respectively. The psychrometers (Pro-V2, HOBO, USA) were installed in each chamber at 1.0 m height to collect continuous metrological data at 30 min intervals.



Note: LED: Light Emitting Diode.

Figure 2 Schematic diagram of Controlled Environment Chamber (CEC)

2.3 Field management

Tomato (*Solanum Lycopersicum* L.) variety Hezuo 908 seedlings with uniform height and diameter were transplanted into pots (31 cm in length, 21 cm in width, and 18 cm in depth) at 28 d after sowing, filled with 10 kg of soil and 10% compost. Tensiometers were installed in the pots to monitor soil moisture content and maintain the same moisture level. The range matric potential force (pF, pF=2.5-2.9) was maintained by drip irrigation with no water shortage to ensure the proper growth of the tomato plants. The first dose of 5 g urea was applied to each plant 30 days after transplanting (DAT), and the second same dose of urea was applied ten days after the 1st application. The flowing and fruiting stage commenced with one truss of flowers, and this first truss of flowers turned into fruits, respectively, for at least three replicates[20].

2.4 Measurements

2.4.1 Morphological parameters

Plant growth parameters were measured weekly in all replicates from each CEC for autumn-winter and spring-summer. Plant height and stem diameter were measured with measuring tape and a vernier caliper. The total leaf area of the plant and leaf area index was computed by Equation (1) and Equation (2), respectively[21].

$$LA=(0.348\times(L\cdot W)+33.85)\times N \tag{1}$$

$$LAI=LA/A_s \tag{2}$$

where, LA is the total leaf area of the plant, cm^2; L is the leaf length, cm; W is the leaf width, cm; N is the number of plant leaves; LAI is the leaf area index; A_s is the surface occupied by a plant, cm^2, in the test of this study A_s equals 50×40 cm^2.

2.4.2 Fruits yield, quality and water use efficiency

Total yield (Y_t) was quantified by pooling the fruit mass (g) after a regular interval. After the end of the growth period, all plant elements (leaf, stem, and root) were harvested and weighed the fresh mass. Plant samples of each treatment with four replications were oven-dried at 85℃ for 72 h to constant weight to quantify the leaf, stem, root, and total dry weight.

Plant water use (PWU) was accumulated during the whole growth period by adding up all measured water of irrigation based on the tensiometer reading installed in each CEC. The tensiometer's pF (2.50-2.90) range was maintained by applying measured water in the pots accordingly and recording the applied water. Water use efficiency in yield (WUE_y) was calculated by Equation (3).

$$WUE_y=Yt/PWU \tag{3}$$

where, PWU is the plant water use, m^3; Y_t is the total tomato yield, kg.

Five fruits with uniform size, maturity, and without any external defects were selected from each treatment to measure total soluble solids (TSS), titratable acidity (TA), pH, and lycopene (Lp). TSS was measured using a refractometer (RX-5000α, Atago, Japan)[22]. TA was calculated by Equation (4), with titration against 0.1 mol/L NaOH[22,23]. The pH of 5 uniform samples taken from each treatment was measured using a pH meter (HI 2214, Hanna Instrument, Romania). The Lp was measured using a colorimetric method by an ultraviolet-visible spectrophotometer (T6 new century, Beijing PGeneral, China)[24,25].

$$TA=(C\cdot V\cdot V_2\cdot A)/(m\cdot V_1) \tag{4}$$

where, C is the concentration of NaOH solution, 0.1 mol/l; V is the total volume of sample solution, 30 mL; V_1 is the volume of filtered sample, 10 ml; V_2 is the volume of NaOH consumed in titration, mL; A is the conversion factor of malic acid, 0.067; m is the mass of the sample, g.

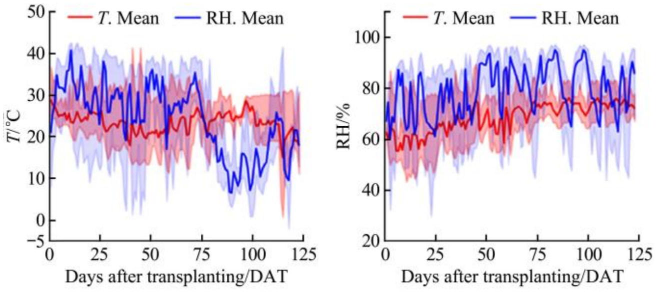
2.5 Statistical analyses

One-way factorial analysis of variance (ANOVA) was applied to reveal the response of the measured variables on e[CO_2] by the SPSS statistics software (version 18.0, IBM Electronics, USA), and the least significant difference (LSD) Post Hoc Test was used to find a significant difference among treatments.

3 Results

3.1 Controlled environmental condition

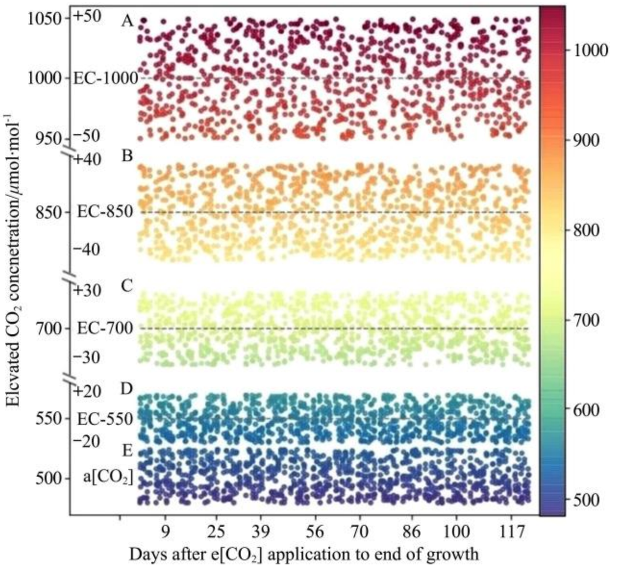
Air temperature and relative humidity were controlled by a heating/cooling system and a desiccation system. Daily mean-controlled *T* and RH within the CEC for autumn-winter and spring-summer are shown in Figures 3a and 3b, respectively. The average values of *T* and RH within the CEC were 23.3℃ and 67% for autumn-winter, and 24.5℃ and 79% for spring-summer, respectively. RH was observed as dependent on the *T*. The *T* values remained low up to almost 70 DAT, and RH responded with high values; after 70 DAT, RH responded reverse against *T* during autumn-winter and vice versa during spring-summer. The PAR values within the CEC were considered the same as outside of the CEC owing to a transparent sheet of chambers.



a. Autumn-winter b. Spring-summer

Figure 3 Meteorological data inside of the CECs in autumn-winter and spring-summer

Actual real-time data of [CO_2] for each treatment in CEC are shown in Figure 4. Mean values of [CO_2] are demonstrated according to designed treatments, and data points above and below the designed treatments are recorded. The range of designed treatments of EC_{1000}, EC_{850}, EC_{700}, and EC_{550} were maintained within ±50, ±40, ±30, and ±20, respectively. The designed treatments for autumn-winter and spring-summer for the growing season were set with the same pattern.



Note: The e[CO_2] treatment was designed at the same level of [CO_2] for the autumn-winter and spring-summer seasons.

Figure 4 Actual real-time data of elevated CO_2 concentration

3.2 Morphology

Growing stages were affected by e[CO_2], as listed in Table 1. The flowering stage commenced at 19, 17, 14, and 12 d early for autumn-winter and 11, 10, 8, and 5 d early for spring-summer owing to EC_{1000}, EC_{850}, EC_{700}, and EC_{550} as compared to a[CO_2], respectively. The fruiting stage commenced at 14, 10, 10, and 9 d early for autumn-winter, and 8, 5, 5, and 5 days early for spring-summer owing to EC_{1000}, EC_{850}, EC_{700}, and EC_{550} as compared to a[CO_2], respectively.

Table 1 Tomato early growth stages under e[CO_2]

Treatment	EC_{1000}		EC_{850}		EC_{700}		EC_{550}		a[CO_2]	
Season	AW	SS	AW	SS	AW	SS	AW	SS	AW	SS
Flowering stage (DAT)	27	31	29	32	32	34	34	37	46	42
Fruiting stage (DAT)	45	45	49	48	49	48	50	48	59	53

Note: DAT: Days after transplanting; AW: autumn-winter; SS: spring-summer seasons.

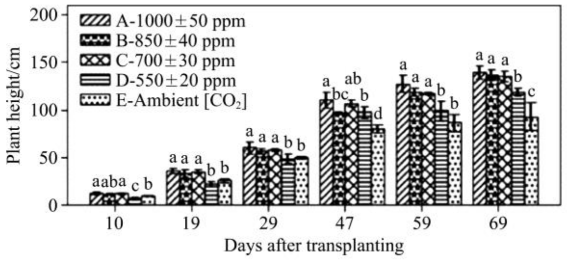
Plant height, stem diameter (SD), and leaf area index (LAI) were increased under all e[CO_2] treatments throughout the measuring period to a[CO_2] for both growing seasons, as shown in Figure 5. The accumulative effect of e[CO_2] on plant height, SD, and LAI to a[CO_2] are listed in Table 2. Plant height showed the highest and lowest values under EC_{1000} during autumn-winter and spring-summer, respectively, except 51 DAT during spring-summer. No significant difference under EC_{700} was found to be the highest plant height value during autumn-winter and showed the highest during spring-summer, indicating that the plant height responded under EC_{700} at the optimum level, as shown in Figures 5a and 5b. The highest LAI values were recorded on 15, 22, and 29 DAT under EC_{700}, and EC_{550} on 36 DAT and 43 DAT during spring-summer, as shown in Figure 5f. The SD maximum growth showed under EC_{1000} on 10, 19, and 29 DAT because of the buffer effect against high temperature, and under EC_{550} on 47, 59, and 69 DAT because of translocation of biomass from plant height during autumn-winter, as shown in Figure 5c.

Table 2 Percentage increment of parameters by e[CO_2] to a[CO_2]

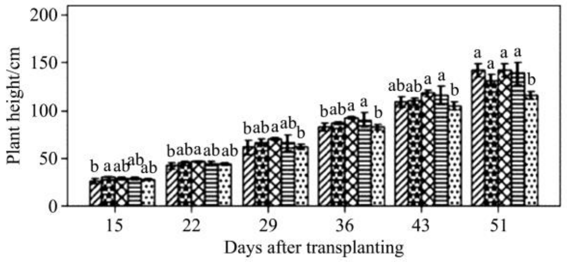
Treatment	EC_{1000}		EC_{850}		EC_{700}		EC_{550}	
Season	AW	SS	AW	SS	AW	SS	AW	SS
Plant height/%	37.2	2.8	27.8	6.4	31.6	13.1	31.6	8.5
SD/%	24.8	3.1	13.5	5.8	10.1	4.1	17.5	−3.0
LAI/%	172.4	2.0	57.8	18.4	53.7	20.8	44.5	15.9

Note: SD: Stem diameter; LAI: Leaf area index; AW: autumn-winter; SS: spring-summer season.

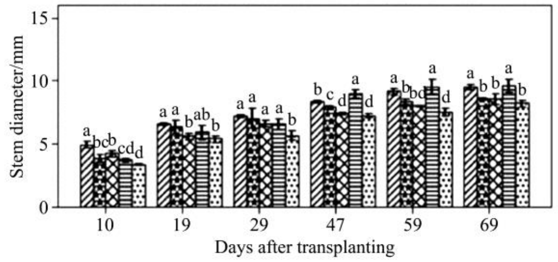
The plant height positive influence was detected at the autumn-winter beginning and spring-summer end at high temperatures, as shown in Figures 5a and 5b, indicating that super e[CO_2] showed resistance against the high-temperature negative impact on plant height. Super e[CO_2] impacted negatively under adequate temperature, as a declining trend of plant height was found on 19 DAT, 29 DAT, 47 DAT, and 59 DAT under EC_{850} during autumn-winter, and under EC_{1000} and EC_{850} during the whole spring-summer to EC_{700}. LAI responded to deaccelerated behavior under EC_{850} on 29, 47, and 59 DAT during autumn-winter, and EC_{1000} and EC_{850} during the entire spring-summer to EC_{700} except for 43 DAT under EC_{850}, as shown in Figures 5e and 5f. It implies that super e[CO_2] was not found suitable for the growth of plants under adequate temperature. LAI trend variation during autumn-winter occurred due to photosynthate translocation to plant height and SD.



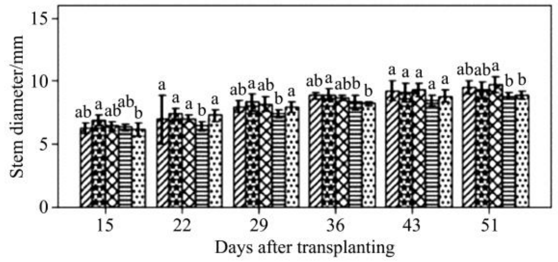
a. Plant height in autumn-winter



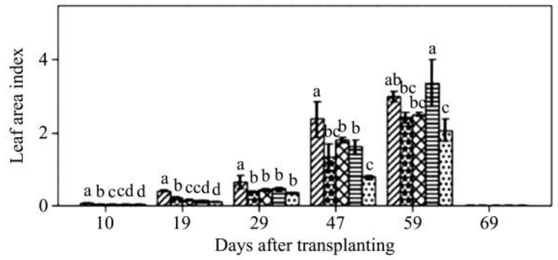
b. Plant height in spring-summer



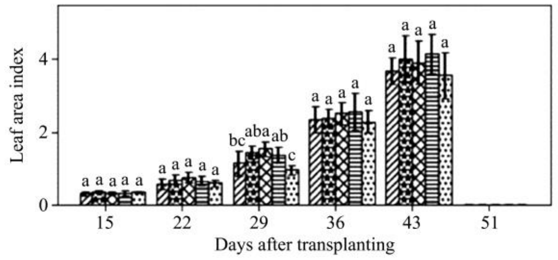
c. Stem diameter in autumn-winter



d. Stem diameter in spring-summer



e. Leaf area index in autumn-winter



f. Leaf area index in spring-summer

Note: Standard deviation is shown by bars, and significant differences (p<0.05) between treatments are shown by different alphabets, while similar alphabets show no significant differences. A: EC_{1000}; B: EC_{850}; C: EC_{700}; D: EC_{550}; E: a[CO_2].

Figure 5 Plant height in autumn-winter and spring-summer, stem diameter in autumn-winter and spring-summer, and leaf area index in autumn-winter and spring-summer under five treatments designed

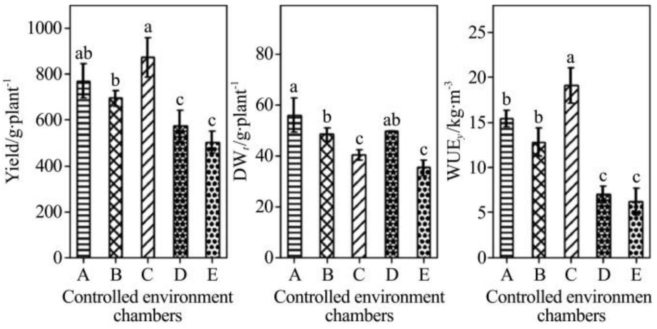
3.3 Yield, total dry weight, and water use efficiency

Total fruit yield (Y_t), total dry weight (DW_t), and water use efficiency (WUE_y) for two growing seasons are shown in Figure 6. The positive effect on Y_t, DW_t, and WUE_y by e[CO_2] to a[CO_2] are listed in Table 3. The Y_t responded maximum under EC_{700} to a[CO2], as shown in Figures 6a and 6d; in contrast, minimum DW_t was found under EC_{700} for both growing seasons compared to a[CO_2], as shown in Figures 6b and 6e. The results explored that the biomass translocation ability of plants to fruit was enhanced at the optimum level under EC_{700}. Under EC_{700}, WUE_y responded at the highest level compared to other treatments for both seasons, as shown in Figures 6c and 6f.

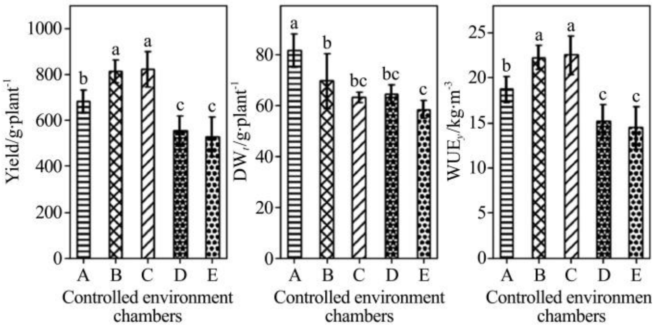
Table 3 Percentage increment of yield, total dry weight, and water use efficiency by e[CO_2] to a[CO_2]

Treatment	EC_{1000}		EC_{850}		EC_{700}		EC_{550}	
Season	AW	SS	AW	SS	AW	SS	AW	SS
Y_t/%	53.3	29.2	38.2	53.9	74.1	55.9	8.3	4.8
DW_t/%	58.2	39.8	36.7	19.2	13.7	8.3	40.1	10.6
WUE_y/%	150	29.3	109	54.0	211	55.9	14.6	4.9

Note: Y_t is the total fruit yield; WUE_y is the water use efficiency for two growing seasons; DW_t is the total dry weight; AW: autumn-winter; SS: spring-summer season.



a. Yield of autumn-winter b. Total dry weight of autumn-winter c. Water use efficiency of autumn-winter



d. Yield of spring-summer e. Total dry weight of spring-summer f. Water use efficiency of spring-summer

Note: Standard deviation is shown by bars, and significant differences between treatments are shown by different alphabets, while similar alphabets show no significance. A: EC_{1000}; B: EC_{850}; C: EC_{700}; D: EC_{550}; E: a[CO_2].

Figure 6 Yield of autumn-winter and spring-summer, total dry weight of autumn-winter and spring-summer, and water use efficiency of autumn-winter and spring-summer under five treatments designed

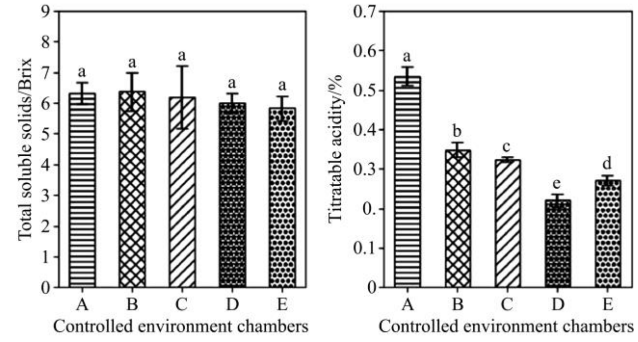
The deceleration trend of Y_t was found under super e[CO_2], as the significant difference (p<0.05) was recorded for Y_t under EC_{700} with respective to EC_{850} and EC_{1000} during autumn-winter and spring-summer, respectively. The declining trend of WUE_y was detected under the super e[CO_2], as significant differences (p<0.05) were detected under EC_{700} as compared to EC_{1000} and EC_{850} during autumn-winter and EC_{1000} during spring-summer. WUE_y

showed significant differences ($p<0.05$) under EC$_{1000}$, EC$_{850}$, and EC$_{700}$ to a[CO$_2$] for both seasons.

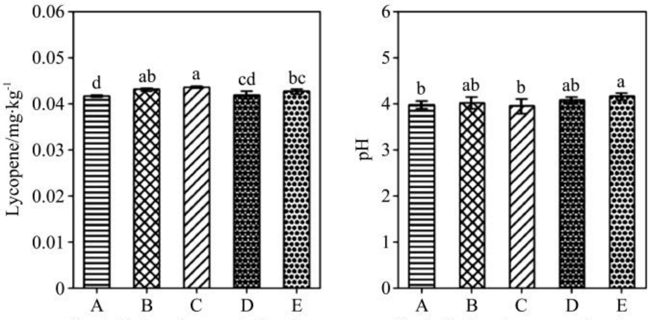
3.4 Fruit quality

Total soluble solids (TSS) were not significantly influenced by e[CO$_2$] as shown in Figure 7a. Significant differences were found in the titratable acidity (TA) of tomatoes produced under set treatments as shown in Figure 7b. The TA value for tomatoes grown under EC$_{1000}$ showed different values compared to EC$_{850}$ ($p<0.01$), EC$_{700}$ ($p<0.01$), EC$_{550}$ ($p<0.01$), and a[CO$_2$] ($p<0.01$) significantly. EC$_{850}$ affected TA with respect to EC$_{700}$ ($p<0.05$), EC$_{550}$ ($p<0.01$), and a[CO$_2$] ($p<0.01$) significantly. TA for EC$_{700}$ was observed differently as compared to EC$_{550}$ ($p<0.01$) and a[CO$_2$] ($p<0.01$), whereas, for EC$_{550}$ was also found different as compared to a[CO$_2$] ($p<0.01$) significantly. As compared to a[CO$_2$], TA was increased by 19.94% (EC$_{700}$), 29.17% (EC$_{850}$), and 97.92% (EC$_{1000}$), while TA was reduced by 18.15% (EC$_{550}$).

Impact on Lycopene (Lp) was found significant due to e[CO$_2$] as shown in Figure 7c. Lycopene of fruits produced under EC$_{1000}$ was observed differently with respect to EC$_{850}$ ($p<0.01$), EC$_{700}$ ($p<0.01$), and a[CO$_2$] ($p<0.01$) significantly, whereas no difference for Lp was found between EC$_{1000}$ and EC$_{550}$ significantly. EC$_{850}$ was not found effective as compared to EC$_{700}$ and a[CO$_2$] significantly, while a significant difference was found between EC$_{850}$ and EC$_{550}$ ($p<0.05$). The effect of EC$_{700}$ was recorded significantly to EC$_{550}$ ($p<0.05$) and a[CO$_2$] ($p<0.05$), whereas no difference was noted between EC$_{550}$ and a[CO$_2$]. As compared to a[CO$_2$], Lp was increased by 1.06% (EC$_{850}$) and 2.22% (EC$_{700}$) and reduced by 2.28% (EC$_{1000}$).



a. Total soluble solids b. Titratable acidity



c. Lycopene d. pH

Note: A: EC$_{1000}$; B: EC$_{850}$ (B); C. EC$_{700}$; D: EC$_{550}$; E: a[CO$_2$]. Standard deviation is shown by bars, and significant differences between treatments are shown by different alphabets, while similar alphabets show no significance.

Figure 7 Total soluble solids, titratable acidity, lycopene, and pH of the tomato fruit under five treatments designed

The pH of tomatoes was significantly different among the experimental treatments, as shown in Figure 7d. No significant difference was found among EC$_{1000}$, EC$_{850}$, EC$_{700}$, and EC$_{550}$, whereas the impact of EC$_{1000}$ on pH was showed significant to a[CO$_2$] ($p<0.05$), No influence of EC$_{850}$ on pH was observed in EC$_{700}$, EC$_{550}$, and a[CO$_2$]. EC$_{700}$ showed a significant effect on pH with relation to a[CO$_2$] ($p<0.05$), while no impact of EC$_{700}$ on pH was recorded as compared to EC$_{550}$. The pH of fruit produced under EC$_{550}$ was not significantly different from a[CO$_2$]. The pH was reduced by 5.04 (EC$_{700}$) and 4.61 (EC$_{1000}$) as compared to a[CO$_2$].

4 Discussion

4.1 Effects of elevated CO$_2$ on the morphology of plants

The purpose of the present study was to assess the effect of e[CO$_2$] levels on the morphology of tomato plants under controlled environmental and field conditions. The results obtained over two growing seasons showed that the plant height, SD, and LAI were enhanced by e[CO$_2$] under a controlled environment (Figure 5). Consistently, Li et al.[26] claimed that maize plant height, SD, and LAI under e[CO$_2$] at 550 μmol/mol, 700 μmol/mol, and 900 μmol/mol were increased significantly. The plant height, SD, and leaf width of tomatoes were enhanced significantly under 1000-1500 μmol/mol of [CO$_2$][15]. Leaf area also was improved under e[CO$_2$] at 800 μmol/mol[27-29]. It is indicated that e[CO$_2$] improved the growth elements (plant height, stem diameter, and LAI) of plants; nevertheless, the limitation of a single treatment of [CO$_2$] might not identify an adequate level of the [CO$_2$] to get optimum growth of plants.

The growth elements variation was observed in the present study due to the allocation of photosynthates (carbohydrate) into other respective growth elements. As claimed by Mamatha et al.[16], tomato plant height was observed higher under 550 μmol/mol than 700 μmol/mol of [CO$_2$], but the leaf area showed lesser under 550 μmol/mol than 700 μmol/mol. On other aspects, Kadam et al.[30] presented that the maximum gladiolus plant height was observed under EC$_{700}$ compared to EC$_{900}$, which indicated that e[CO$_2$] enhanced the plant height up to some limit; beyond that limit, the plant height tends to decrease. A similar phenomenon was observed during the spring-summer season in the present study, where a declining trend was observed for plant height, SD, and LAI under EC$_{1000}$ and EC$_{850}$. It implies that growth was deaccelerated under super e[CO$_2$]. It was reported that LAI was not always enhanced under e[CO$_2$] significantly as compared to a[CO$_2$][31-33].

The present study results in the autumn-winter season showed that the plant height and LAI decreased at EC$_{850}$ compared to EC$_{700}$, but increased at EC$_{1000}$. The cause for such kind phenomenon was reported by Fitzgerald et al.[34] that e[CO$_2$] acted as a buffer against heat stress which stimulated the most significant wheat growth. In the present study, a high temperature was also observed during the initial growth stage of the autumn-winter season; the plant's growth was accelerated under EC$_{1000}$ and EC$_{850}$ compared to EC$_{700}$ and EC$_{550}$ owed to the buffer effect of super e[CO$_2$] against heat stress. The same phenomenon was observed during the spring-summer season, as the growth rate was observed higher at the end of the growth stage than at the initial growth of the planting season.

4.2 Effects of elevated CO$_2$ on yield, total dry weight, and water use efficiency

The response of plants' yields and quality to a single e[CO$_2$] has been intensively investigated[35,36]. In general, e[CO$_2$] enhanced crop yield and growth[37-39] by promoting leaf photosynthesis (Pn), which was accelerated by inhibition of oxygenation and carboxylation reaction through the positive reactive activity of Rubisco at chloroplast[40]; furthermore, promotion of sink strength as compared to source strength and more carbohydrate might be contributed under e[CO_2][15]; therefore, development of fruits and production of DW_t were enhanced more because of motivating translocation of photosynthates[41-43].

The results of our study showed the highest yield under EC_{700}. In contrast, the highest DW_t was recorded under EC_{1000} and the lowest at EC_{700} for both seasons. It is reported by literature that the e[CO_2] promoted the product by increasing total biomass and translocating biomass to fruits[44,45]. It is claimed that the total biomass of tomatoes was enhanced by 9.56% under 800 μmol/mol compared to a[CO_2][8], and the biomass of tomato plants was also increased by 67% under 720 μmol/mol compared with a[CO_2][46], elevated [CO_2] increased leaf dry weight in two tomatoes cultivars (24% and 11%), while stem dry weight of the first cultivar increased by 48% and the second cultivar only by 1% under 590 μmol/mol[39]. The current study results showed that biomass increased under all e[CO_2] treatments and the highest biomass allocation to fruit was observed under EC_{700} for both seasons, respectively (in Figures 6a and 6b). Therefore, results indicated that the EC_{700} is suitable to get optimum crop production under standard water and fertilizer management conditions. Similarly, a previous study reported that the highest yield was recorded at EC_{700} which was 125% higher than a[CO_2], however, super e[CO_2] was not considered to investigate the negative impact on crop production[16].

The plants conserved water and enhanced the water productivity by decreasing stomatal conductance[47], and increasing the photosynthesis activities under e[CO_2] significantly[4, 48-50]. Consequently, yield and fresh biomass were motivated by the translocation of photosynthates; which improved the WUEy[16,51]. The results of this study showed that WUE_y was enhanced by e[CO_2] for both seasons (Figures 6c and 6f). Earlier studies have reported that tomato plants grown under e[CO_2] (800 μmol/mol) responded 18.3% higher WUE to a[CO_2][4], the remarkable significance of leaf WUE was observed in tomato plants grown under e[CO_2] 800 μmol/mol: leaf WUE was directly linked with promotion WUE_y[9], it is reported that e[CO_2] (550 and 700 μmol/mol) enhanced WUE synergistically[16]. It was claimed that a reduction in transpiration rate is achieved under e[CO_2] 800 μmol/mol, which improved plant water balance because of the promotion of WUE in maize[48]. Moreover, compared with a[CO_2], WUE for maize leaf was increased by 52%, 91%, and 185% under 550, 700, and 900 μmol/mol, respectively[26]. Considering the above discussion, e[CO_2] would be beneficial under water scarcity, which occurred due to changing climate.

4.3 Effects of elevated CO_2 on fruit quality

In this study, TSS increased under e[CO_2] but not significantly (Figure 7a), and titratable acidity also increased at e[CO_2] except for 550 μmol/mol treatment (Figure 7b) as compared to a[CO_2]. Lycopene showed positive and negative responses under different e[CO_2] (Figure 7c) and pH was reduced under e[CO_2] (Figure 7d) with respect to a[CO_2]. The results of our study are similar to other studies, as lycopene contents were increased by 53% under e[CO_2] at 800 μmol/mol[52]. In contrast, fruit quality was characterized by the lower lycopene at e[CO_2] (800-900 μmol/mol)[53]. Furthermore, lycopene content was reduced by 9.3% at EC_{700} e[CO_2], and increased by 1.9% at EC_{550}, respectively, compared to a[CO_2][16]. Helyes et al.[54] reported a 52% higher value of lycopene at e[CO_2] 700 μmol/mol compared to a[CO_2], which confirms the results of this study. Furthermore, TSS and titration acid in cherry tomato was increased up to 7.2% and 0.4%, respectively, at e[CO_2] (1000-1500 μmol/mol) as compared to a[CO_2][15]. A cause to improve TSS was reported as soluble sugar was found in leaves, which might be translocated into fruit, enhancing fruits TSS[55]. Moreover, a recent study explored that e[CO_2] enhances the tomato plant's ability to uptake the K and P for fruits[9], which might have improved the lycopene content, high temperature might affect the fruit quality[56]. The response of fruit quality to e[CO2] is complex and merits further investigations.

5 Conclusions

Summary of what research was conducted in this study. The accumulative growth: including plant height, stem diameter, and leaf area, of tomato was improved significantly under elevated CO2(e[CO_2]) and were translocated among each other. Growth declined under super e[CO_2]. The highest yield and the lowest total dry weight (DW_t) were recorded under e[CO_2] 700 μmol/mol (EC_{700}) indicating that EC_{700} may stimulate carbohydrates to translocate from biomass to fruits. The Water use efficiency in yield (WUE_y) was enhanced by e[CO_2] and achieved at the maximum level under EC_{700}. The total soluble solids (TSS) increased under e[CO_2] but not significantly. The optimum level of lycopene (Lp) was obtained under $EC_{700,}$ and lower values were observed under e[CO_2] 1000 μmol/mol (EC_{1000}) and e[CO_2] 550 μmol/mol (EC_{550}). Titratable acidity also increased at e[CO_2] except for 550 μmol/mol treatment compared to ambient CO_2 (a[CO_2]). Hence, the precise level of e[CO_2] was recommended at 700 μmol/mol for proper growth, optimum yield, quality, and water use efficiency for greenhouse tomato production under standard water and fertilizer management conditions.

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