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Effects of Elevated CO_2 and Light Intensity on Growth, Yield, and Nutritional Quality of Tomato (*Solanum lycopersicum*) in Controlled Environment Agriculture Systems

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ABSTRACT

Controlled Environment Agriculture (CEA) is an improved cultivation system that promotes plant development by optimizing environmental factors such as carbon dioxide (CO_2) concentration and light intensity. This study considered the interactive effects of enhanced levels of CO_2 (400-1000 ppm) and varying light intensities (200-600 µmol/m²/s) on growth characters, yield, and nutritional composition of tomato (*Solanum lycopersicum*). Under hydroponics conditions, a factorial experiment was conducted in a climate-controlled greenhouse and plant physiological responses, productivity, and fruit quality were assessed. Higher level of CO_2 and light significantly increased plant height, leaf area, chlorophyll content, photosynthetic rate, and yield. The highest yield (6.86 kg/plant) was recorded at an 800 ppm CO_2 and 600 µmol/m²/s light intensity regime, while peak values for fruit weight and dry matter concentration impetuous at 1000 ppm CO_2. Nutrition content of fruit showed varied response for CO_2-light interaction. With increased CO_2 and light intensity, the highest lycopene content attained was 12.69 mg/100 g at 1000 ppm CO_2 and 600 µmol/m²/s light. Conversely, increasing CO_2 concentrations push vitamin C and protein content lower, probably due to nutrient dilution effects driven by biomass growth. These results highlight the need to pair CO_2 enrichment with light supplementation in optimizing the productivity-nutrition quality balance. An optimal combination of CO_2 and light intensity on the range of 800-1000 ppm CO_2 and 600 µmol/m²/s offers useful understandings for greenhouse and vertical farming systems. Future studies must investigate long term effects on post-harvest quality and economic feasibility to keep improving CO_2-light management strategies in CEA systems.

INTRODUCTION

Controlled Environment Agriculture (CEA) consists of fast-developing technologies that allow the maximization of plant growth by conscientiously manipulating environmental influences such as temperature, humidity, light intensity, and carbon dioxide concentration. Artificial Intelligence, Internet of Things, and robotics are being integrated with CEA in precision agriculture as scalable solutions for global food security and for sustainable agricultural methods (Polwaththa *et al.*, 2024). Medium temperature (21-25⁰C) available in the most growing areas are favorable for tomato growth and flowering. However, the production of better yield and yield traits require comparatively low temperature (10-20⁰C) during fruit setting in some areas (Nur *et al.*, 2022). Among all these factors, CO_2 enrichment and light supplementation take center stage in the improvement of plant productivity and resource-use efficiency. The cultivation of tomato (*Solanum lycopersicum*) in controlled environments has gained prominence due to its economic importance and sensitivity to environmental factors (Wang *et al.*, 2021). However, while CO_2 enrichment proves beneficial in photosynthesis and biomass accumulation, its combined effect along with light intensity on yield and the nutritional quality of fruits remains questionable and one big area of research (Zhao *et al.*, 2022). The interaction of these two factors is of great importance for optimizing CEA strategies to achieve high yield and high-quality production. Higher levels of CO_2 have been studied for their effects on photosynthesis, stomatal conductance, and carbon allocation in plants. Previous studies showed that CO_2 concentrations between 600-1000 ppm can hence promote 20-40% growth and fruit yield in tomatoes by enhancing the efficiency of carbon fixation and reducing photorespiration (Jin *et al.*, 2023). Conversely, while higher CO_2 induces increased fruit biomass, it may modify the compositions of essential elements due to the nutrient dilution effect in which higher carbohydrate accumulation translates into lower concentrations of minerals and proteins (Taub *et al.*, 2008).

In addition to CO_2, light intensity plays a big part in tomato yield and fruit quality. The photosynthetic efficiency and biomass accumulation dearly depend on the photosynthetically active radiation (PAR) available. Studies are showing light intensity of about 400-600 µmol m²/s significantly enhanced lycopene biosynthesis, vitamin C concentration, and sugar accumulation in tomatoes (Hao *et al.*, 2021). Also, higher light intensity might counteract some undesirable effects of CO_2 enrichment by enhancing the production of secondary metabolites and curtailing the nutrient dilution (Zhang *et al.*, 2023).

While there has been increasing interest in CEA-based CO_2 enrichment and light management, few researches have been conducted into their interaction

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affecting growth and nutrient composition of the crop, particularly tomato (Polwaththa & Amarasinghe, 2024). Thus, this study intends to address this knowledge gap through assessing the interactive effects of elevated CO_2 and light intensity on tomato plant physiology, yield performance, and fruit nutritional composition in order to provide understandings to greenhouse operators or vertical farm managers trying to optimize CO_2 and light supplementation strategies in sustainable tomato production. To achieve this, the study was conducted to study how the interaction between elevated CO_2 concentrations ranging from 400 to 1000 ppm and light intensities of 200 to 600 μmol/m²/s affect tomato growth, yield, and fruit nutritional composition.

MATERIALS AND METHODS

Pilot Study

A preliminary pilot experiment was performed in Sri Lanka to identify the range of most appropriate CO_2 and light intensity for the growth of tomatoes in advance of the main experiment. In this pilot trial, five CO_2 concentrations, 200, 600, 1000, 1400, and 1800 ppm, and four light intensities, 200, 400, 600 and 800 μmol/m²/s, were tested in controlled conditions to investigate plant growth responses, physiological parameters, and symptoms of possible stress. Under these conditions, the plants grew for six weeks, recording plant height, leaf area, chlorophyll content, photosynthesis rate, and stomatal conductance. It has been concluded from this experiment that levels above 1000 ppm of CO_2 do not contribute much to increasing photosynthesis, whereas at 1400 and 1800 ppm, some indications of stomatal closure and hence low transpiration use efficiency were evident. While higher light intensities of 600 μmol/m²/s increased photosynthetic efficiency, excessive CO_2 beyond 1000 ppm, under such a light level, resulted in chlorophyll degradation and reduced the stomatal conductance, indicating possible CO_2 saturation effects. Based on the results from the pilot experiment, CO_2 levels from 400 ppm up to 1000 ppm and light intensities from 200 μmol/m²/s up to 600 μmol/m²/s were chosen to narrow down the ranges for application in the main experiment, hence ensuring optimum physiological performance without causing stress to the tomato plants.

Main Experiment

Experimental Design

The effects of elevated CO_2 and different light intensities upon growth, yield, and nutritional composition of the tomato (*Solanum lycopersicum*) in a controlled environment agriculture (CEA) system were examined in this study. Since photosynthesis occurs under the direct influence of both CO_2 and light intensity, the effects of their interaction were focused on rather than individual responses. Therefore, a randomized complete block design (RCBD) in a factorial arrangement was carried out to express interaction effects of CO_2 and light intensity. The treatments consisted of four levels of CO_2 concentration (400 ppm, 600 ppm, 800 ppm, and 1000 ppm) and three levels of light intensity (200 μmol/m²/s, 400 μmol/m²/s, and 600 μmol/m²/s). Each design treatment was instantiated in this experiment for 10 replications thus making 120 experimental units. Each treatment consisted of an individual tomato plant grown in well-controlled environments.

Greenhouse Setup and Environmental Control

The setup was carried out in a climate-controlled greenhouse containing an automated CO_2 enrichment system and full-spectrum LED lighting to achieve the targeted levels of CO_2 and light. A hydroponic cultivation method was used to ensure a steady supply of nutrients for all experimental units. Infrared gas analysts (IRGA) monitored and regulated CO_2 concentrations every 2 hours to maintain continuous levels of CO_2, which were delivered by the automated diffusion system integrated into the greenhouse ventilation. The intensity of the light was controlled through programmable LED lamps, which were programmed to provide 16 hours of light and 8 hours of darkness a day. Quantum light sensors placed at the canopy level ensured that the target PAR intensity was met for each treatment.

Temperature and humidity were controlled by employing air conditioning and automated misting systems, keeping the range of 25 ± 20C and 65% ± 5% relative humidity. These environmental parameters mostly eliminated possible external environmental variations, permitting the differences in plant performances to be directly attributed to CO_2 and light intensity treatments.

Plant Materials and Growing Conditions

A hybrid tomato cultivar was selected for the present study because of its high yield potential, long fruiting period, and response to the modification of environmental conditions. Seeds were sown into peat-based seedlings trays under controlled conditions and were transplanted 21 days later into hydroponic system integrated with fertigation for supplying a nutrient solution at constant intervals. The nutrient solution supplied to the plants contained macronutrients like nitrogen, phosphorus, and potassium and essential micronutrients like magnesium, calcium, and iron. EC of 2.5 mS/cm and pH values ranging from 5.8 to 6.2 were maintained in the solution to encourage maximum uptake of nutrients.

Data Collection and Measurements

Growth and Physiological Parameters

To evaluate the effect of CO_2 and light intensity on plant growth, morphological and physiological traits were recorded at 30, 60, and 90 days after transplanting (DAT). Plant height (cm) was noted using measuring tape while leaf area (cm²) was determined using an automated leaf area meter. The chlorophyll content was measured using the SPAD chlorophyll meter, which gives a relative index of chlorophyll concentration. Photosynthetic rate (mol H_2O/m²/s) was measured with a handheld photosynthesis system (LI-6400XT, LI-COR Biosciences) by measuring net CO_2 assimilation under a standardized set of conditions. Stomatal conductance (mol $H_2O/m^2/s$) was measured with the same instrument to determine the plant's ability to limit water loss under different CO_2 levels.

Yield and Productivity Measurements

After harvest (90 DAT), total yield per plant (kg/plant) was recorded by weighing all fruits from each plant using a precision digital scale. Individual fruit weights (g) were determined by finding the average of ten randomly weighed fruits per plant. Dry Matter Content (%) was determined by drying an aliquot of tomato fruit at 700C for 48 hours and measuring the dry-to-fresh weight ratio. A digital refractometer (Atago PAL-1; Japan) was used to ascertain the sugar content (0Brix) by measuring the soluble solids concentration of fruit juices. These yield-related measurements gave understanding as to the impact of CO_2 and light intensity on total tomato production.

Nutritional Composition Analysis

In the present study, the quality of tomatoes was assessed in terms of vitamin C, lycopene, and protein contents by different determination methods. Vitamin C content was assayed by HPLC using a C18 column. The lycopene content was assayed by spectrophotometry at 502 nm after extraction with hexane and acetone. Protein content was analyzed by means of the Kjeldahl method, which quantifies total nitrogen as an indicator of protein concentration.

All these biochemical analyses were done in triplicate to ensure accuracy and repeatability. These nutritional analyses gave enough evidence on how enrichment with CO_2 and light intensity could affect the health-related properties of the tomatoes.

Statistical Analysis

Data were analyzed using two-way analysis of variance (ANOVA) in SAS with the objective of explaining the interaction effects of CO_2 enrichment and light intensity on growth, yield, and nutritional value of tomato. In the present study, the factorial ANOVA model was examined considering the interaction between the four CO_2 levels of 400, 600, 800, and 1000 ppm and three light intensities, i.e., 200, 400, and 600 μmol/m²/s.

Duncan's Multiple Range Test (DMRT) was applied at $p \leq 0.05$ to differentiate the means for statistical differences in treatments. Thus, it has been utilized to compare various treatment combinations in terms of identifying the optimal levels of CO_2 and light that would most enhance the growth of tomato and fruit quality. There were 10 replicates for each combination of treatments in order to achieve enough statistical power and ensure reliability of the outcome.

RESULTS AND DISCUSSION

Growth and Physiological Responses

Table 1: Growth and Physiological Responses under different CO_2 and Light Levels

1	Light Intensity (μmol/ m²/s)	Plant Height (cm)	Leaf Area (cm²)	Chlorophyll Content (SPAD index)	Photosynthetic rate (μmol $CO_2/m^2/s$)	Stomatal Conductance (mol $H_2O/m^2/s$)
400	200	101.39 ± 13.07 g[1]	275.52 ± 51.92 g	44.26 ± 4.79 f	10.64 ± 1.87 f	0.30 ± 0.11 a
400	400	112.38 ± 11.78 f	293.98 ± 46.92 g	47.85 ± 3.98 ef	16.73 ± 2.31 e	0.21 ± 0.11 abc
400	600	121.69 ± 11.01 f	343.67 ± 49.20 f	50.35 ± 4.54 e	18.87 ± 1.87 d	0.14 ± 0.09 cd
600	200	116.45 ± 13.22 f	297.93 ± 38.72 g	49.97 ± 4.51 e	16.08 ± 1.49 e	0.26 ± 0.14 ab
600	400	137.03 ± 11.98 e	387.87 ± 26.68 de	54.53 ± 3.80 d	19.32 ± 2.64 d	0.15 ± 0.15 bcd
600	600	141.49 ± 10.67 de	370.13 ± 41.58 ef	56.47 ± 4.94 d	22.07 ± 2.17 bc	0.23 ± 0.06 abc
800	200	141.19 ± 13.30 de	364.51 ± 42.06 ef	55.98 ± 4.19 d	16.67 ± 2.29 e	0.23 ± 0.06 abc
800	400	150.03 ± 9.43 d	417.79 ± 40.98 cd	57.26 ± 5.13 cd	20.40 ± 2.32 cd	0.13 ± 0.12 cd
800	600	164.59 ± 13.33 c	431.45 ± 36.08 bc	63.67 ± 3.27 ab	26.52 ± 2.11 a	0.08 ± 0.15 d
1000	200	171.96 ± 10.38 bc	442.45 ± 53.71 bc	60.65 ± 5.67 bc	20.58 ± 1.93 cd	0.14 ± 0.11 cd
1000	400	179.89 ± 13.04 b	461.30 ± 37.08 b	63.78 ± 3.10 ab	23.30 ± 2.19 b	0.05 ± 0.14 d
1000	600	197.99 ± 11.96 a	488.52 ± 44.66 a	67.04 ± 5.11 a	26.22 ± 2.47 a	0.13 ± 0.10 cd

Means followed by the same small letters in the same column are not significantly different at 5% level in Duncan's Multiple Range Test.

The results in Table 1 shows that high CO_2 concentration and higher light intensity had a significant influence on plant height and leaf area. Tomato plants cultivated at 1000 ppm CO_2 and 600 μmol/m²/s light intensity yielded the highest plant height (197.99 ± 11.96 cm) and leaf area (488.52 ± 44.66 cm²), whereas the lowest was at 400 ppm CO_2 and 200 μmol/m²/s (101.39 ± 13.07 cm, 275.52 ± 51.92 cm²). The increased plant height development and leaf growth can be attributed to increased cellular enlargement and biomass accumulation, as high CO_2 enhances the carbon input into photosynthesis, thus enhancing plant development (Zhang *et al*., 2023). Additionally, the increased light intensity also enhances more carbon assimilation and light energy uptake, thus supporting more leaf growth and expansion.

Chlorophyll content also increased with rising CO_2 and light, maximally 67.04 ± 5.11 SPAD index at 1000 ppm CO_2 at 600 µmol/m²/s. Chlorophyll content was minimum at 400 ppm CO_2 at 200 µmol/m²/s light (44.26 ± 4.79 SPAD index). Increased content of chlorophyll under increased CO_2 concentration results from optimization of nitrogen use efficiency, promoting chlorophyll biosynthesis (Jin *et al*., 2023). High light intensity also triggers photoreceptors, causing expression of genes involved in chlorophyll biosynthesis, leading to increased accumulation of photosynthetic pigments (Huang *et al*., 2021). The same has been found in spinach (Spinacia oleracea), where increased CO_2 facilitated the preservation of chlorophyll, thereby increasing the efficiency of photosynthesis (Zhao *et al*., 2022). Excessive light in the absence of supplemental CO_2 at its optimal concentration induces photooxidative stress, however, which degrades chlorophyll, as seen in strawberry (Fragaria ananassa) (Jin *et al*., 2023).

Photosynthetic rate was substantially enhanced by CO_2 enrichment and increased light intensities, with the maximum of 26.52 ± 2.11 µmol CO_2/m²/s at 800 ppm CO_2 and 600 µmol/m²/s light intensity. Photosynthetic activity plateaued at 1000 ppm CO_2 (26.22 ± 2.47 µmol CO_2/m²/s), indicating a CO_2 saturation point at which any additional increase in CO_2 does not augment photosynthesis. This is due to the fact that RuBisCO, the enzyme for carbon fixation, is saturated under high CO_2 levels, thus limiting further improvement in photosynthetic performance (Wang *et al*., 2021). Similar trends have also been reported in pepper (Capsicum annuum), where the photosynthesis rates increased with CO_2 enrichment up to an optimal level, beyond which photorespiration and stomatal limitations restricted further improvement (Wang *et al*., 2021). Correspondingly, studies of wheat (Triticum aestivum) have shown that CO_2 saturation effects reduce stomatal conductance and thereby limit CO_2 diffusion to the mesophyll cells (Taub *et al*., 2008).

There was a reduction in stomatal conductance with the increase in CO_2 levels, with the lowest values recorded at 1000 ppm CO_2 under 400 and 600 µmol/m²/s light intensity (0.05 ± 0.14 and 0.13 ± 0.10 mol H_2O/m²/s, respectively). The reduction in stomatal conductance can be attributed to CO_2 induced stomatal closure, lowering guard cell turgor pressure and resulting in partial stomatal closure and reduced water loss via transpiration (Zhang *et al*., 2023). While this can increase water-use efficiency, prolonged stomatal closure can prevent evaporative cooling, thus enhancing the likelihood of leaf overheating when high light is applied. Comparable findings have been reported in cabbage (Brassica oleracea) as well, where reduced stomatal conductance under high CO_2 helped in water conservation but at the same time increased its susceptibility to heat stress (Huang *et al*., 2021). Additionally, in soybean (Glycine max), stomatal conductance reduction at high CO_2 levels increased water-use efficiency and thus rendered the plants drought-tolerant (Zhao *et al*., 2022).

Yield and Productivity Responses

The data indicated (Table 2) that CO_2 concentration of higher levels and greater light intensity increased tomato yields. The highest yield (6.86 kg/plant) was achieved at 800 ppm CO_2 and 600 µmol/m²/s light intensity, while the lowest (4.59 kg/plant) was recorded at 400 ppm CO_2 and 200 µmol/m²/s light intensity. The enhanced production at elevated CO_2 can be due to increased photosynthesis and carbon assimilation, as usually reported in previous research on tomato and other crops (Hao *et al*., 2021; Jin *et al*., 2023). The similar results were obtained in wheat and rice, as elevated CO_2 concentration enhanced biomass accumulation and grain yield (Zhu *et al*., 2020). At 1000 ppm CO_2 concentration, yield did not rise above the 800 ppm level, and this could indicate a saturation effect. Some studies show that at very high levels of CO_2 concentration, there can be a process of photosynthetic down-regulation with declining returns in yield increase (Ainsworth & Rogers, 2007). Furthermore, although the CO_2 concentration is increased but with reduced light, photosynthetic efficiency could not be optimized (Zhang *et al*., 2023).

Table 2: Yield and Productivity under different CO_2 and Light Levels

CO_2 Level (ppm)	**Light Intensity (µmol/m²/s)**	**Yield (Kg/ plant)**	**Fruit weight (g)**	**Dry matter (% FW)**	**Sugar Content (oBrix)**
400	200	4.59 ± 0.87 c1	136.59 ± 12.80 e	7.41 ± 1.72 f	6.08 ± 0.95 g
400	400	5.30 ± 1.27 bc	148.03 ± 13.03 e	9.27 ± 1.65 de	6.69 ± 0.71 fg
400	600	6.01 ± 1.50 ab	155.26 ± 7.64 d	10.18 ± 1.32 d	8.49 ± 1.04 cd
600	200	5.68 ± 1.35 abc	155.68 ± 12.59 d	8.21 ± 1.40 ef	6.71 ± 1.00 fg
600	400	5.46 ± 1.14 bc	158.23 ± 11.73 cd	9.33 ± 1.24 de	7.71 ± 0.84 de
600	600	5.96 ± 1.11 ab	159.20 ± 10.19 cd	10.33 ± 1.06 cd	9.03 ± 0.95 bc
800	200	6.30 ± 0.82 ab	166.80 ± 8.43 bc	9.93 ± 1.41 d	7.12 ± 0.95 ef
800	400	5.74 ± 1.21 abc	167.97 ± 12.80 bc	10.42 ± 1.56 cd	7.89 ± 0.80 de
800	600	6.86 ± 1.21 a	166.65 ± 7.28 bc	12.47 ± 1.69 ab	9.97 ± 0.35 a

1000	200	6.75 ± 1.24 a	174.30 ± 12.01 ab	11.65 ± 1.28 bc	7.78 ± 0.97 de
1000	400	6.80 ± 1.19 a	179.29 ± 12.65 a	12.28 ± 1.38 ab	8.88 ± 0.94 c
1000	600	6.69 ± 1.23 a	182.47 ± 11.31 a	13.40 ± 1.42 a	9.80 ± 0.86 ab

1 Means followed by the same small letters in the same column are not significantly different at 5% level in Duncan's Multiple Range Test, FW- Fresh weight.

Both CO_2 and light intensity had a very significant impact on fruit weight, with the maximum fruit weight (182.47 g) at 1000 ppm CO_2 and 600 μmol/m²/s light intensity and minimum (136.59 g) at 400 ppm CO_2 and 200 μmol/m²/s light intensity. This is consistent with the work of Taub *et al.* (2008), who noted that CO_2 enrichment maximizes fruit size in crops because of the enhanced accumulation of carbohydrates. Dry matter content also followed the same pattern, with the highest (13.40% FW) being achieved at 1000 ppm CO_2 and light intensity of 600 μmol/m²/s. This indicates that high levels of CO_2 not only increased the fruit size but also allowed more dry matter to accumulate, which could be the consequence of greater storage of carbohydrates in the fruit tissues. The same was observed in strawberries and bell peppers wherein the firmness of fruit and dry matter was enhanced by CO_2 enrichment (Wang *et al.*, 2021).

Sugar content (0Brix) was significantly influenced by the two factors of CO_2 and light intensity; the highest value, 9.970 Brix, was recorded under the conditions of 800 ppm CO_2 combined with 600 μmol/m²/s. This result agreed with other works in proving that high CO_2 increases the sugar accumulation in tomato fruits through the increased fixation of carbon and synthesis of carbohydrates (Li *et al.*, 2019). However, sugar content at 1000 ppm CO_2 did not keep increasing, perhaps due to the CO_2-induced dilution effect in which too much carbohydrate accumulation may result in a relative decrease in soluble sugar concentration. Similar reports were given on lettuce and cucumber where sugar contents increased with CO_2 enrichment but did not keep increasing at very high levels (Zhao *et al.*, 2022). Meanwhile, light intensity significantly affected sugar accumulation: fruits developed under a higher light level-600 μmol/m_2/s-had significantly higher 0Brix values than fruits under low light. This agreed with reports that enhanced light intensity increases the activity of the enzymes in sugar metabolism, hence improving the sweet taste in fruit (Hao *et al.*, 2021).

The findings indicate that CO_2 enrichment and light intensity significantly impact tomato yield and productivity and that the optimal combination is 800 -1000 ppm CO_2 and 600 μmol/m²/s light intensity. The results agree with findings in controlled environment agriculture (CEA) systems where the same CO_2 and light optimization led to enhanced crop productivity and improved fruit quality (Zhang *et al.*, 2023). However, supra-optimal CO_2 concentrations in excess of 1000 ppm did not generate further yield and quality enhancements and suggests that CEA systems have to strike a balance between CO_2 enrichment and the optimal amount of light concentration. Nevertheless, CO_2-induced carbohydrate storage also has to be closely regulated to avoid deleterious effects of nutrient dilution. These findings have excellent applicability to greenhouse and vertical farm operations since they demonstrate that CO_2 enrichment and supplemental light optimization can maximize tomato productivity and quality in closed systems. The long-term sustainable effects of CO_2 and light optimization on post-harvest quality and profitability of tomatoes in commercial CEA production systems can be further investigated.

Nutritional Composition and Fruit Quality

Table 3: Nutritional Composition and Fruit Quality under different CO_2 and Light Levels

CO_2 Level (ppm)	**Light Intensity (μmol/m²/s)**	**Vitamin C (mg/ 100g)**	**Lycopene (mg/ 100g)**	**Protein Content (% FW)**
400	200	19.50 ± 2.42 abc1	8.51 ± 2.53 cd	1.13 ± 0.20 ef
400	400	20.72 ± 2.95 ab	8.73 ± 1.74 cd	1.55 ± 0.16 b
400	600	21.96 ± 2.80 a	11.01 ± 2.01 abc	1.93 ± 0.21 a
600	200	19.58 ± 3.01 ab	8.38 ± 2.79 d	1.00 ± 0.22 f
600	400	19.97 ± 2.63 ab	9.60 ± 2.07 bcd	1.33 ± 0.22 cd
600	600	20.65 ± 2.94 ab	9.37 ± 1.94 bcd	1.63 ± 0.14 b
800	200	19.32 ± 2.31 abc	9.06 ± 2.26 bcd	0.73 ± 0.23 g
800	400	18.61 ± 2.70 bcd	9.54 ± 2.03 bcd	1.25 ± 0.18 de
800	600	19.27 ± 3.14 abc	11.53 ± 2.46 ab	1.48 ± 0.25 bc
1000	200	16.79 ± 2.40 cd	9.40 ± 2.63 bcd	0.55 ± 0.22 g
1000	400	16.20 ± 2.44 d	9.59 ± 2.54 bcd	1.00 ± 0.25 f
1000	600	18.36 ± 2.72 bcd	12.69 ± 1.98 a	1.31 ± 0.18cde

[1] Means followed by the same small letters in the same column are not significantly different at 5% level in Duncan's Multiple Range Test, FW- Fresh weight.

Table 3 shows that the nutritional composition and fruit quality of tomato with elevated CO_2 and light intensity. Vitamin C level in tomato fruit was significantly influenced by light intensity and CO_2 interaction. The highest vitamin C content (21.96 ± 2.80 mg/100g) was observed at 400 ppm CO_2 with 600 μmol/m^2/s light intensity, and the lowest (16.20 ± 2.44 mg/100g) was observed at 1000 ppm CO_2 with 400 μmol/m^2/s light intensity. Vitamin C or ascorbic acid is significantly impacted by light intensity since it takes part in antioxidant defense and photoprotective responses in plants (Shivashankara *et al*., 2013). Vitamin C biosynthesis is promoted with intense light by initiating metabolic processes involved in antioxidant biosynthesis and photosynthetic carbon fixation (Laxman *et al*., 2014). Nevertheless, CO_2 enhancement above 600 ppm reduced the concentration of vitamin C, in agreement with previous studies on lettuce (Lactuca sativa) that had increased CO_2 inducing reductions in ascorbic acid levels (Mattson *et al*., 2022). Similar was the trend in bell pepper (Capsicum annuum), where high levels of CO_2 lowered the content of vitamin C even though it augmented fruit yield (Dong *et al*., 2018). High CO_2 decline is due to dilution effects, which are the result of enhanced biomass gain, as well as modification in carbohydrate metabolism (Rajashekar, 2018).

Lycopene content was also affected by CO_2 level and light intensity, with the highest concentration at 1000 ppm CO_2 with 600 μmol/m^2/s light intensity at 12.69 ± 1.98 mg/100g. The lowest lycopene levels were at 400 ppm CO_2 with 200 μmol/m^2/s light intensity at 8.51 ± 2.53 mg/100g. Lycopene is a carotenoid pigment responsible for the red coloration in tomatoes and is highly dependent upon light exposure and CO_2 assimilation. Increased light intensity enhances lycopene biosynthesis by upregulating phytoene synthase and carotenoid biosynthetic genes (Verma *et al*., 2024). Previous studies in tomatoes and strawberries (Fragaria ananassa) have shown that high light intensity positively correlates with lycopene accumulation due to increased photosynthetic electron transport activity (Dannehl *et al*., 2021). The increase in lycopene content under high CO_2 levels (800-1000 ppm) agrees with previous reports in cucumber (Cucumis sativus) and watermelon (Citrullus lanatus), where high CO_2 enhanced carotenoid biosynthesis through increased carbon fixation (Ren *et al*., 2014). However, at very high CO_2 enrichment levels (>1000 ppm), lycopene content may be adversely affected by changes in phytoene desaturation processes (Talebi *et al*., 2024).

The protein content of tomato fruits is significantly different due to the interaction between CO_2 and light treatments. The highest protein content of 1.93 ± 0.21% FW was recorded at 400 ppm CO_2 with 600 μmol/m^2/s light intensity, while the lowest, 0.55 ± 0.22% FW, was recorded under 1000 ppm CO_2 combined with 200 μmol/m^2/s light intensity. In plants, protein biosynthesis is intimately associated with nitrogen assimilation, which shows a close interaction with CO_2 fertilization and light energy availability. Plants under high CO_2 enhance carbohydrate accumulation; however, this quite frequently causes the opposite effect, a decrease in nitrogen uptake and protein synthesis, by downregulating nitrate reductase activity (Loladze *et al*., 2019). Similar reductions in protein concentration have been reported in wheat and rice grown under elevated CO_2, which further supports the hypothesis that CO_2 induced carbohydrate accumulation dilutes protein levels in plant tissues (Pimenta *et al*., 2023). On the other hand, light intensity is one of the most important environmental factors affecting amino acid metabolism and protein synthesis. High light intensities enhance photosynthetic efficiency and nitrogen assimilation, which in turn increase protein content (Pan *et al*., 2019). There is an interactive effect of light and CO_2, in that the dual increase of both factors has indeed improved biomass production, probably linked to nutrient dilution effects mainly under extreme levels of CO_2.

CONCLUSIONS

This work has proved that high CO_2 levels and increased light intensity have a great effect on the growth, yield, and nutritional composition of tomatoes in CEA systems. Maximum plant height, leaf area, chlorophyll content, photosynthetic rate, and yield were observed under the optimum combination of 800-1000 ppm CO_2 and 600 μmol/m^2/s, while beyond 1000 ppm CO_2 saturation resulted in diminishing returns. Nutritional quality also varied; while lycopene was enhanced with increasing CO_2 and light, the vitamin C and protein contents declined under high CO_2 due to nutrient dilution effects. Such findings have drawn attention to a balanced use of CO_2 and light to assure optimum productivity without loss of quality in the produced fruits in tomato. These findings also have practical application for both greenhouse and vertical farming systems: the optimal level of CO_2 ranges from 800-1000 ppm with the light intensity of 600 μmol/m^2/s for their best performance. Long-term effects on post-harvest quality and economic viability for commercial tomato production should be further researched.

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