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RESEARCH ARTICLE

Impact of elevated carbon dioxide on plant growth, physiology and yield of vegetable cowpea cv. Arka Garima

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Abstract

The continuous rise in atmospheric carbon dioxide (CO_2) concentration due to global climate change necessitates research into its effects on important food crops. The experiment was conducted in 2023 at the Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad. This controlled environment open-top chamber (OTC) experiment evaluated the impact of elevated CO_2 (eCO_2) on the growth, physiology and yield of vegetable cowpea (*Vigna unguiculata* (L.) Walp. cv. Arka Garima). The study compared 2 CO_2 treatment levels: ambient CO_2 (aCO_2) maintained at 380 ± 25 ppm and an elevated concentration (eCO_2) of 550 ± 25 ppm. The results demonstrated that eCO_2 profoundly and positively altered cowpea plants, leading to an increase in vegetative growth and reproductive productivity. Morphological parameters exhibited substantial enhancements, including a dramatic increase in root volume (67.80 %, $p = 0.001$), plant height (41.29 %, $p<0.001$) and stem dry weight (37.52%, $p = 0.005$). Physiological responses indicated an improved plant status under CO_2 enrichment. The most notable finding was the accumulation of total soluble sugars (TSS), which increased by 15.58 % ($p<0.001$), reflecting enhanced photosynthesis. The leaf physiological status improved significantly, with the membrane stability index (MSI) increasing by 8.59 % ($p = 0.001$) and total chlorophyll content increasing by 6.88 % ($p = 0.007$). Elevated CO_2 levels significantly boosted crop yield and attributed traits. The number of pods per plant increased by 27.91 % ($p<0.001$), combined with an 18.75 % ($p<0.001$) increase in average pod weight and the total pod yield per plant showed a highly significant 30.89 % increase ($p<0.001$). These findings indicate that the cowpea cultivar Arka Garima is highly responsive to CO_2 enrichment, offering essential insights into effective crop management and adaptation strategies in the face of changing climatic conditions.

Keywords: climate change; CO_2 enrichment; open-top chamber; phenology

Introduction

Cowpea (*Vigna unguiculata* (L.) Walp.) is an important legume crop originating from Central Africa and serves as a vital and affordable source of protein. It is mainly grown in tropical and subtropical areas worldwide for its pods and seeds and to a lesser degree, it is also used as a fodder crop (1). It is the most versatile pulse crop because of its smothering nature, drought tolerance, soil-restoring properties and multiple uses. As a pulse crop, cowpea fits well into most cropping systems (2). In addition, cowpea forms excellent forage and it gives a heavy vegetative growth and covers the ground so well that it checks soil erosion (3). In agricultural ecosystems, nitrogen fixation plays a crucial role, particularly in cowpea, where it significantly enriches the soil with biologically fixed nitrogen, ranging from 32 to 67 kg N ha^{-1} (4).

In the context of studies investigating the impact of elevated carbon dioxide on plant growth, physiology and yield of vegetable cowpea is considered the cause, while the changes in plant growth, physiology and yield are the consequences. The concentration of CO_2 in the atmosphere rose to 421 ppm in 2022, marking an increase of nearly 50 % from the pre-industrial level of 280 ppm recorded in the 1700s (5). CO_2 fertilisation can boost photosynthetic rates, particularly in C_3 plant species, which constitute the bulk of the world's plant biomass (6). Under elevated carbon dioxide, cowpea and similar legumes undergo significant biochemical shifts that reflect both enhanced carbon assimilation and changes in the physio-biochemical assay (7). Enhanced photosynthetic carbon fixation under eCO_2 boosts the availability of triose phosphate, a central metabolic intermediate that is readily converted into soluble carbohydrates including sucrose, glucose and fructose (8).

The open-top chamber (OTC) facilitates the simulation of future climate change scenarios with the elevation of CO_2, which is one of the major dimensions of climate change (9). Crops can be grown without any etiolation, i.e., long, weak stems, smaller leaves due to longer internodes and a pale-yellow colour (chlorosis) (10). The data produced through the utilisation of this facility is genuine and comprehensively reflect the impact of CO_2 (11). In the context of climate change and rising atmospheric CO_2 levels, cowpea, similar many other crops, has been the focus of research on the effects of enhanced carbon dioxide (eCO_2) on growth, phenology, physiology and yield. However, the precise impacts can differ based on several parameters, including the type of cowpea, the adjacent environment and the concentration of CO_2. The study investigated the effect of elevated CO_2 concentrations on the growth and phenology of cowpea (*V. unguiculata*) cv. Arka Garima crop using OTC that allow the regulation of CO_2 concentration under chambers.

Materials and Methods

Two growth chambers were used: one for maintaining an elevated CO_2 (eCO_2) concentration (550 ± 25 ppm) and another for an ambient CO_2 (aCO_2) concentration (380 ± 25 ppm). The elevated concentration of CO_2 (eCO_2) was maintained throughout the 24 hr a day from sowing to final harvesting. The square-type OTC of 3 x 3 dimensions were constructed at the central research institute for dryland agriculture (CRIDA), Hyderabad (17.38 °N, 78.47 °E).

Five replications with 15 cowpea plants for each replication in each CO_2 concentration were harvested at 120 days. Carbon dioxide was introduced into the chambers and maintained at predetermined levels using manifold gas regulators, pressure pipelines, a CO_2 analyser and a system comprising program logic control (PLC) and supervisory control and data acquisition (SCADA) linked to a personal computer. The fully automated control and monitoring system, which comprises a CO_2 analyser, a PLC and SCADA program integrated with a personal computer, ensures the regulation of CO_2 levels within the OTCs. Additionally, this system incorporates sensors for temperature and relative humidity. The system is designed to continuously monitor the concentrations of CO_2, temperature and relative humidity within the OTCs. To ensure uniform CO_2 distribution, CO_2 gas is diluted with air and pumped using a compressor. Air samples are collected from the chamber's central point through a coiled copper tube, which can be adjusted in height to accommodate crop growth. The equipment responsible for monitoring and controlling CO_2 levels in the OTCs operates automatically, maintaining the desired CO_2 concentration consistently throughout the experimental period. (12).

The experiment was laid out on 7 September 2023 to assess the impacts of elevated CO_2 on growth, phenology and yield of cowpea. For the study with the vegetable cowpea cv. Arka Garima, seeds were obtained from the ICAR-Indian Institute of Horticultural Research, Bengaluru. Cowpea seeds (Arka Garima cultivars) were planted in pots. A total of 3 seeds per pot, containing soil + organic fertiliser in a 2:1 ratio, were sown. Thinning was carried out at 10 days after sowing, when the plants presented fully expanded primary leaves, leaving 2 plants per replicate, with nitrogen fertilisation carried out at 15 days after germination. The data for following growth, yield parameters viz., number of days to 50 % flowering, number of days to first fruiting, plant height (cm), number of leaves, root length (cm), root volume (mL $plant^{-1}$), leaf area (m^2), stem dry weight (g $plant^{-1}$), leaf dry weight (g $plant^{-1}$), root dry weight (g $plant^{-1}$), number of pods per plant, average pod weight (g), pod yield per plant (g) and biochemical parameters like malondialdehyde (MDA) (g FW), nitrate reductase (NR) (µM g^{-1} FW), total soluble sugars (TSS) (mg g^{-1} FW), relative water content (RWC) (%), membrane stability index (MSI) (%), total chlorophyll (mg g^{-1} FW) and carotenoids (mg g^{-1} FW) were recorded. The SPSS software 16.0 was used to analyse the data by using two-way ANOVA to test the significant difference ($p \leq 0.05$) in characteristics, CO_2 concentrations and interactions.

Bio-chemical parameters

Total soluble sugars estimation using phenol-sulphuric acid method (13)

In an acidic medium with elevated temperatures, glucose is dehydrated to yield hydroxymethyl furfural. This compound subsequently interacts with phenol, resulting in the formation of a green-coloured product that has an absorption peak at 490 nm.

Relative water content (RWC) as proposed previously (14)

$$RWC\,(\%) = \frac{(FW-DW)}{(TW-DW)} \times 100$$

Where, FW is the sample fresh weight, TW is the turgid weight and DW is the dry weight.

Membrane stability index (MSI) as proposed previously (15)

$$MSI = [1-(C1/C2)] \times 100$$

C1- The initial electrical conductivity of the solution containing the leaf samples after they have been subjected to a stress treatment

C2- The final electrical conductivity of the same solution after the leaf samples have been completely killed

Malondialdehyde content-lipid peroxidation method as described earlier (16)

The extent of lipid peroxidation in plant tissue was quantified by measuring malondialdehyde (MDA) levels, utilising the thiobarbituric acid (TBA) reaction. This method is predicated on the interaction between MDA, a terminal product of lipid peroxidation and TBA, resulting in the formation of a red chromogen.

a) Estimation of chlorophyll and carotenoid

Total chlorophyll content was calculated in mg g^1 FW using the following formula (17).

$$\text{Total chlorophyll} = \frac{(20.2\,(A645) + 8.02\,(A663)}{1000 \times W} \times V$$

Where, A645, A663 = Absorption at these wavelengths

V = Final extract volume (mL)

W = Weight of samples (g)

Carotenoid content: Calculated in mg g^{-1} FW using the formula given by previous researchers (18).

b) Estimation of nitrate reductase

When salicylic acid undergoes nitration in highly acidic conditions, the resulting complex exhibits maximum absorption at 410 nm in solutions with a pH greater than 12. The absorbance of this chromophore is directly linked to the concentration of nitrate-N present (19).

Results and Discussion

The research titled "Impact of eCO_2 on plant growth, physiology and yield of vegetable cowpea (*V. unguiculata*) cv. Arka Garima" was carried out in an open top chamber (OTC). The results of these experiments are presented below with the necessary tables and graphs under the following headings.

Physio-biochemical parameters

Data on various physio-biochemical parameters as detailed in Table 1 and graphical representation of *per se* values are given in

Fig 1. Elevated CO$_2$ concentrations induced a significant decline in lipid peroxidation, as indicated by a 7.05 % reduction in MDA content (p = 0.011). Plants, when exposed to an elevated CO$_2$ concentration (CE) of 1300 µmol mol^{-1} for 4 days, observed an increase in MDA content in French bean (20). In legume species, the reduction of oxidative stress parameters, such as lipid peroxidation (MDA levels), was more prominently observed with increased CO$_2$ concentrations. Elevated CO$_2$ significantly alleviates damage caused by peroxidation, with a more pronounced protective effect in legumes, potentially due to the contribution of molecular antioxidants in maintaining membrane stability (21).

The nitrate reductase (NR) activity was significantly suppressed under eCO$_2$, showing a 17.00 % decrease compared to the control (p = 0.008). French bean plants grown under eCO$_2$ conditions showed significantly lower NR activity compared to those grown under ambient CO$_2$ (22). The eCO$_2$ reduces photorespiration, a process that provides energy. This reduction in photorespiration limits the energy transferred to the process of NO$_3^-$ reduction, thereby inhibiting NR activity and overall nitrate assimilation (23).

The total chlorophyll content was significantly enhanced by 6.88 % in plants grown under eCO$_2$ (p = 0.007) in the experiment. Similarly, higher induction of chlorophyll molecules from precursors in plants grown under elevated CO$_2$ was reported by previous researchers (24) in mung bean. As reported another studies, elevated CO$_2$ concentrations were found to significantly enhance the total chlorophyll content in chickpea plants (25). Under conditions of increased atmospheric CO$_2$, plants may absorb nitrogen more rapidly. This enhanced nitrogen availability may lead to an increase in foliar nitrogen concentration and, consequently, an increase in leaf chlorophyll content (26).

A significant reduction of 4.99 % was also observed in carotenoid content (p = 0.048). In contrast to the increase in chlorophyll, the content of carotenoids, which are accessory photosynthetic pigments, decreased under elevated CO$_2$ in mung bean and the reduction of carotenoids offered more protection to its chlorophyll molecules against photo-oxidative damage (24).

Conversely, eCO$_2$ treatment had a pronounced positive effect on several key traits. The most notable increase was in total soluble sugars (TSS), which accumulated 15.58 % more under eCO$_2$ than under ambient conditions (p<0.001). The elevation in total soluble sugars (TSS) may be attributed to an enhanced stimulation of photosynthesis relative to conditions with ambient CO$_2$ levels (24). It had been reported that elevated CO$_2$ levels resulted in a significant 26.9 % increase in the soluble sugar content of soybean leaves (27). Soluble sugars are described as nutrient and metabolite signalling molecules that play a role in regulating physiological processes when plants respond to various stresses (28).

Leaf physiological status improved significantly, with RWC increasing by 6.79 % and membrane stability index (MSI) by 8.59 % (p<0.001 and p = 0.001, respectively). Pea plants exhibited an enhancement in their RWC, indicating an increase in their water retention capacity (29). Evidence of improved membrane

Table 1. Effect of elevated CO$_2$ on physio-biochemical assay of vegetable cowpea cv. Arka Garima

Parameters	Treatment	Mean ± SE	% Change over Control	SD	p≤0.05
MDA (gFW)	aCO$_2$	41.692 ± 0.763	-7.05	1.706	0.011
	eCO$_2$	38.944 ± 0.371		0.830	
NR (µmol g^{-1} FW)	aCO$_2$	0.234 ±0.007	-17.00	0.015	0.008
	eCO$_2$	0.200 ± 0.007		0.016	
TSS (mg g^{-1} FW)	aCO$_2$	61.524 ± 1.461	15.58	3.267	0.000
	eCO$_2$	72.876 ± 0.998		2.231	
RWC (%)	aCO$_2$	84.706 ± 0.789	6.79	1.765	0.000
	eCO$_2$	90.872 ± 0.746		1.668	
MSI (%)	aCO$_2$	70.050 ± 0.976	8.59	2.182	0.001
	eCO$_2$	76.636 ± 1.085		2.427	
Total Chlorophyll (mg g^{-1} FW)	aCO$_2$	3.490 ± 0.038	6.88	0.085	0.007
	eCO$_2$	3.748 ± 0.062		0.139	
Carotenoids (mg g^{-1} FW)	aCO$_2$	1.388 ± 0.026	-4.99	0.059	0.048
	eCO$_2$	1.322 ± 0.011		0.024	

MDA: Malondialdehyde; NR: Nitrate reductase; TSS: Total soluble sugars; RWC: Relative water content; MSI: Membrane stability index.

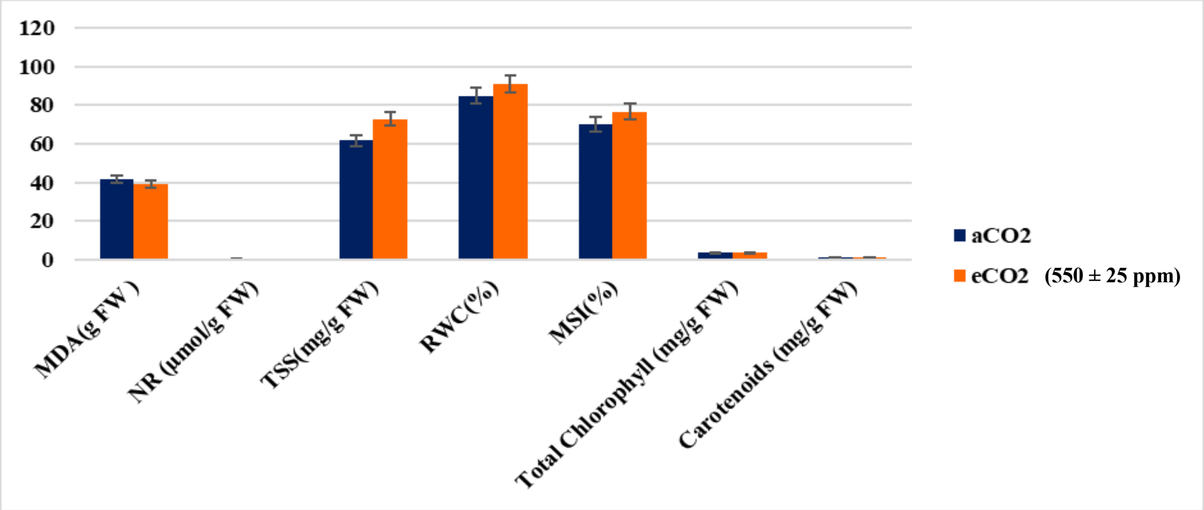

Fig. 1. *Per se* values of malondialdehyde (MDA), nitrate reductase (NR), total soluble sugars (TSS), relative water content (RWC), membrane stability index (MSI), total chlorophyll and carotenoids for cowpea at aCO$_2$ and eCO$_2$.

stability in potato plants grown under eCO_2 was found as solute leakage was decreased significantly (30). Elevated CO_2 helps maintain greater cell membrane stability or lower electrolyte leakage in plants under heat stress, thereby protecting cells from damage (31). The protective effects of elevated CO_2 on membrane stability are likely indirect, rather than a direct interaction between CO_2 and the membrane itself (32). Thus, elevated CO_2 levels markedly improved the carbohydrate status and membrane stability of vegetable cowpea plants while reducing oxidative stress, albeit at the cost of reduced nitrate reductase activity and carotenoid content.

Morphological parameters

The growth and developmental morphology of vegetable cowpea plants were profoundly and significantly altered by exposure to eCO_2 compared to aCO_2 conditions, as detailed in Table 2. Elevated CO_2 stimulated vigorous vegetative growth. Plant height exhibited a dramatic increase, being 41.29 % greater in eCO_2 grown plants compared to the control ($p<0.001$) (Fig. 2). Increased plant height was reported in black gram grown under elevated CO_2(550 ppm) (33) and in chickpea (600 ppm) (34).

This was accompanied by a 37.85 % enhancement in the number of leaves per plant ($p = 0.003$) and a significant 30.58 % expansion in total leaf area ($p = 0.017$) (Fig. 3). Physiological reasons were documented for the improved growth of the mung bean, which directly supports the increased leaf count (35). Carbon dioxide is the primary substrate for photosynthesis; increasing its availability facilitates plant functions and accelerates functional growth cycles (36). The increased leaf area under elevated CO_2 in this study aligns with previous studies, that reported significant enhancement in these growth parameters due to improved photosynthetic capacity and water use efficiency (37). These finding aligns with the results of earlier reports, which demonstrated that the influence of CO_2 was predominantly significant in determining the peak leaf area index (LAI) values, increasing compared to the control treatment (38). Compared to ambient conditions, the LAI under elevated CO_2 was found to be higher by 4.00 to 28.00 % in chickpea (39). Higher CO_2 levels activate RuBisCO, the key carboxylating enzyme, leading to the fixation of additional units of ribulose-1,5-bisphosphate (RuBP). This synthesis of extra triose phosphate, which shunts out to the cytosol, induces physiological changes. This rapid turnover of triose phosphate results in enhanced growth and leaf expansion rates (40).

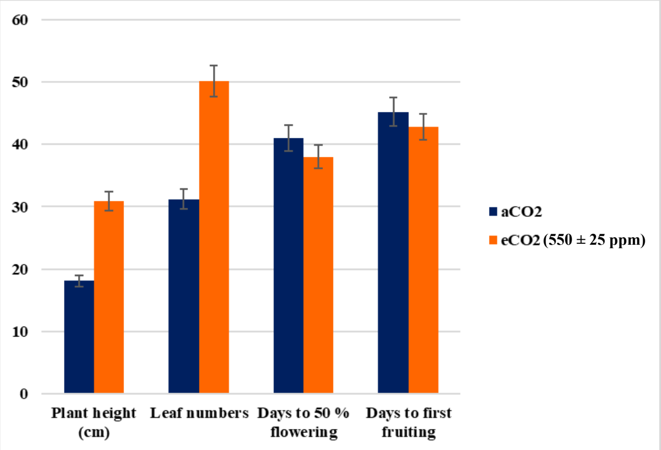

Fig. 2. *Per se* values of plant height, leaf number, days to 50 % flowering and days to first fruiting for cowpea at aCO_2 and eCO_2.

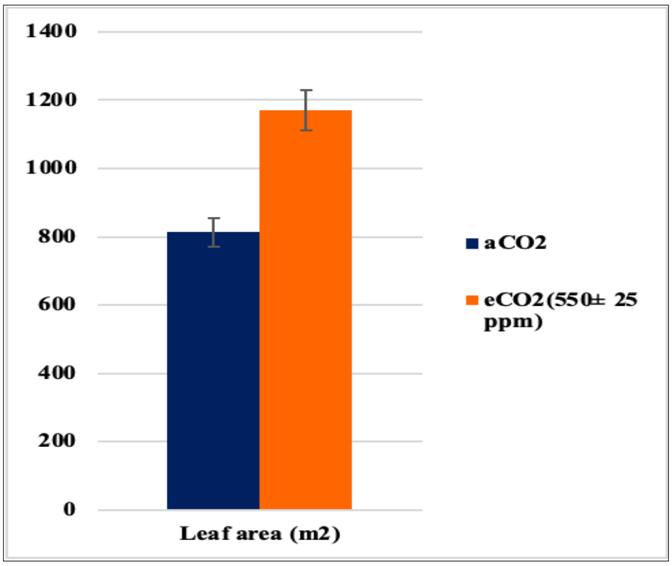

Fig. 3. *Per se* values of leaf area for cowpea at aCO_2 and eCO_2.

Furthermore, eCO_2 treatment significantly accelerated reproductive development. The time taken to reach 50 % flowering was reduced by 7.89 % ($p<0.001$). Likewise, advanced timing of flowering in chickpea was observed under elevated CO_2 (25). The increased carbohydrate supply satisfies the demand of reproductive sinks (flowers, pods), avoiding energy limitation and accelerating development (41, 42). Carbohydrate over accumulation in leaves can sometimes lead to "photosynthetic acclimation" or down-regulation. However, when reproductive sinks (like flowers and pods) are strong, they utilise the extra carbohydrates quickly, preventing sugar buildup in the leaves and maintaining high photosynthetic capacity. The continuous production and growth of organs help minimise this acclimation (43, 44). Thus, elevated CO_2 concentration significantly enhanced vegetative growth metrics and promoted earlier reproductive transition in vegetable cowpea, indicating an overall positive morphological response to CO_2 enrichment.

Morphological parameters: Leaf and stem

The elevated CO_2 concentration had a significant positive impact on the biomass accumulation of vegetable cowpea plants, as evidenced by the analysis of leaf and stem dry weights (Table 3).

Table 2. Effect of elevated CO2 on the morphological parameters of vegetable cowpea cv. Arka Garima

Parameters	Treatment	Mean ± SE	% Change over Control	SD	$p \leq 0.05$
Plant height (cm)	aCO_2	18.106 ± 0.425	41.29	0.950	0.000
	eCO_2	30.840 ± 2.113		4.725	
Leaf numbers	aCO_2	31.200 ± 3.089	37.85	6.907	0.003
	eCO_2	50.200 ± 3.338		7.463	
Leaf area (m^2)	aCO_2	812.468 ± 22.422	30.58	50.138	0.017
	eCO_2	1170.284 ± 117.458		262.644	
Days to 50 % flowering	aCO_2	41.000 ± 0.374	-7.89	0.837	0.000
	eCO_2	38.000 ± 0.510		1.140	
Days to first fruiting	aCO_2	45.200 ± 0.374	-5.61	0.837	0.001
	eCO_2	42.800 ± 0.374		0.837	

aCO_2: Ambient carbon dioxide; eCO_2: Elevated carbon dioxide.

Plants grown under eCO_2 conditions exhibited a substantial increase in biomass production compared to those under ambient conditions. Leaf dry weight per plant increased significantly by 31.14 % ($p = 0.001$). An even more pronounced effect was observed in stem dry weight, which showed a 37.52 % enhancement under eCO_2 treatment ($p = 0.005$) (Fig. 4). Consistent with previous studies (45), the results show a significant increase in stem dry weight under elevated CO_2 levels. The authors reported that stem dry weight increased by approximately 4 to 23 % under 550 ppm CO_2 and a more substantial 7 to 80 % with 700 ppm CO_2. They also observed that while both 550 ppm and 700 ppm CO_2 levels generally led to higher leaf dry weights compared to ambient conditions, the response pattern varied over time and between the 2 elevated levels. These results demonstrate that elevated CO_2 significantly boosted the accumulation of dry matter in both the leaf and stem components of vegetable cowpea plants.

Root parameters

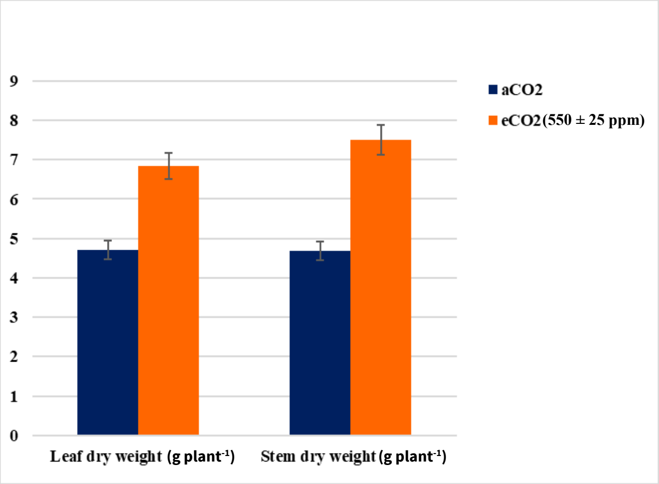

Fig. 4. *Per se* values of leaf dry weight and stem dry weight for cowpea at aCO_2 and eCO_2.

The influence of elevated CO_2 on the root system architecture of vegetable cowpea was complex, revealing a divergent response between root morphology and biomass accumulation (Table 4). A significant shift in root allocation was observed under eCO_2. While the primary root length decreased significantly by 17.69 % compared to the ambient control ($p = 0.009$), the root volume per plant exhibited a dramatic and significant increase of 67.80 % ($p = 0.001$) (Fig. 5). This suggests a transition from deeper rooting to a more prolific, shallower root system. Concomitantly, there was a trend of increased biomass investment in the roots, with root dry weight showing a 19.01 % increase under eCO_2. This increase in root volume and root dry weight was in line with the findings of (46). However, this increase was not statistically significant at the $p \leq 0.05$ level ($p = 0.070$). Thus, elevated CO_2 induced a significant alteration in root strategy, favouring a substantial increase in root volume over depth, accompanied by a non-significant trend towards greater root biomass.

A study on blackgram (cv. T-9) revealed a significant positive response of the root system to elevated CO_2 (45). They reported that root length, root volume and root dry weight increased under 700 ppm CO_2. This could be advantageous in drier climates by facilitating deeper soil penetration and spread. Elevated levels of atmospheric CO_2 have been demonstrated to considerably enhance the overall plant biomass, encompassing both leaf area and underground biomass (47).

Yield attributing traits

Exposure to elevated CO_2 significantly enhanced the yield and yield-attributing traits of vegetable cowpea, demonstrating a strong positive impact on reproductive output and harvestable biomass (Table 5). All measured yield parameters exhibited significant enhancement under elevated CO_2 conditions. The number of pods per plant increased substantially by 27.91 % compared to the ambient control ($p < 0.001$). Specifically, the number of pods per plant in cowpea increased from 10 under ambient conditions to 14 under elevated conditions. Furthermore, the individual average pod weight was also significantly greater,

Table 3. Effect of elevated CO2 on the morphological parameters of vegetable cowpea cv. Arka Garima

Parameters	Treatment	Mean ± SE	% Change over control	SD	$p \leq 0.05$
Leaf dry weight (g plant^{-1})	aCO_2 eCO_2	4.710 ± 0.215 6.840 ± 0.415	31.14	0.480 0.928	0.001
Stem dry weight (g plant^{-1})	aCO_2 eCO_2	4.692 ± 0.218 7.510 ± 0.704	37.52	0.487 1.575	0.005

aCO_2: Ambient carbon dioxide; eCO_2: Elevated carbon dioxide.

Table 4. Effect of elevated CO2 on the root parameters of vegetable cowpea cv. Arka Garima

Parameters	Treatment	Mean ± SE	% Change over control	SD	$p \leq 0.05$
Root length (cm)	aCO_2 eCO_2	8.768 ± 0.342 7.450 ± 0.185	-17.69	0.765 0.414	0.009
Root volume (mL plant^{-1})	aCO_2 eCO_2	0.152 ± 0.021 0.472 ± 0.062	67.80	0.047 0.140	0.001
Root dry weight (g plant^{-1})	aCO_2 eCO_2	1.994 ± 0.097 2.462 ± 0.203	19.01	0.216 0.454	0.070

aCO_2: Ambient carbon dioxide; eCO_2: Elevated carbon dioxide; SE: Standard error of the mean.

Table 5. Effect of elevated CO2 on the yield attributing parameters of vegetable cowpea cv. Arka Garima

Parameters	Treatment	Mean ± SE	% Change over control	SD	$p \leq 0.05$
Number of Pods per plant	aCO2 eCO2	11.266± 0.373 15.628 ± 0.496	27.91	0.833 1.109	0.000
Average Pod weight (g)	aCO2 eCO2	7.592 ± 0.184 9.344 ±0.184	18.75	0.412 0.412	0.000
Pod yield per plant (g)	aCO2 eCO2	88.858 ± 1.373 128.578 ± 1.696	30.89	3.069 3.793	0.000

aCO_2: Ambient carbon dioxide; eCO_2: Elevated carbon dioxide; SE: Standard error of the mean; SD: Standard deviation.

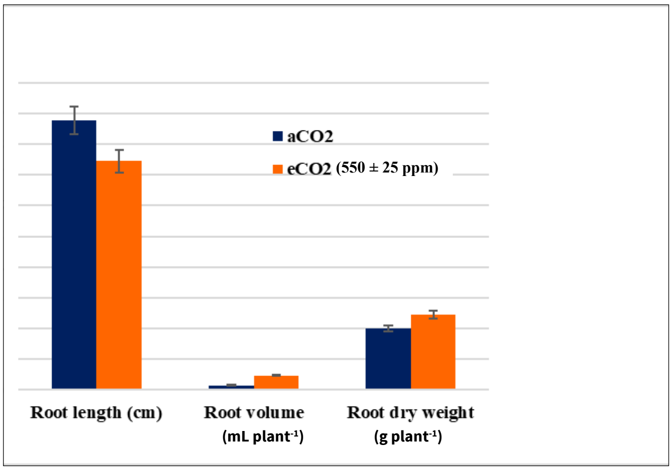

Fig. 5. *Per se* values of root length, root volume and root dry weight for cowpea at aCO_2 and eCO_2.

showing an 18.75 % increase (p<0.001) (Fig. 6). Pod weights (g) for cowpea rose significantly from 1.98 g in ambient conditions to 2.66 g under elevated temperature and CO_2. In blackgram (48), greengram (49) and in cowpea (50, 51) reported a significant increase in the number of pods and average pod weight under elevated CO_2 conditions.

The combined effect of a higher pod number and heavier individual pods resulted in a highly significant 30.89 % boost in the total pod yield per plant (p<0.001). The elevated CO_2 concentration markedly improved the yield potential of vegetable cowpea by enhancing both the number of pods produced and the weight of each pod, culminating in a greater than 30 % increase in overall yield. Elevated carbon dioxide dramatically increased chickpea yield, affirming its significant positive response as a C_3 legume under future atmospheric conditions (39).

Conclusion

A controlled OTC experiment demonstrated that elevated carbon dioxide acts as a potent carbon fertiliser, profoundly enhancing the growth and yield of vegetable cowpea (cv. Arka Garima). The core finding is that eCO_2 significantly boosted photosynthetic efficiency, leading to greater biomass accumulation, improved plant water status and reduced oxidative stress. These physiological improvements translated directly into superior agronomic performance, including accelerated flowering and a remarkable 30.89 % increase in pod yield per plant due to more and heavier pods. While minor trade-offs like suppressed nitrate reductase activity were observed, the cultivar's overall response was overwhelmingly positive. This study confirms that the Arka Garima cowpea is highly responsive to eCO_2, highlighting its potential for sustaining productivity under future climate scenarios.

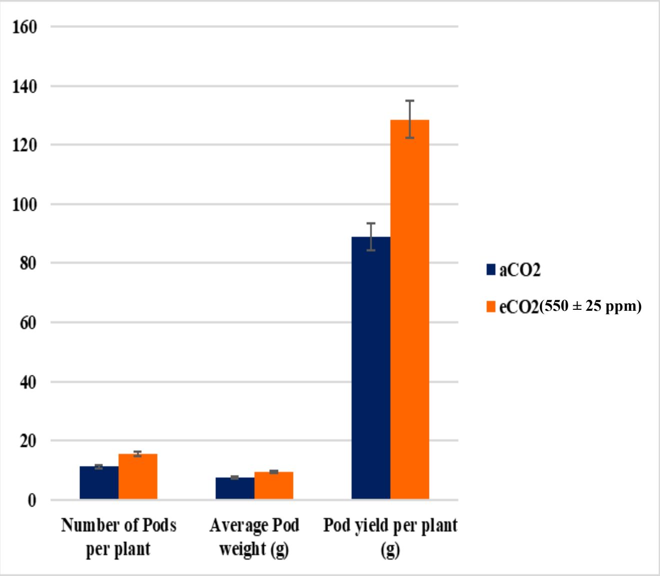

Fig. 6. *Per se* values of the number of pods per plant, average pod weight and pod yield per plant for cowpea at aCO_2 and eCO_2.

Authors' contributions

RRB carried out the experiment in the open-top chambers (OTC) and drafted the manuscript. SPGS participated in the design of the study and performed the statistical analysis. AGKR conceived the study and participated in its design and coordination. KDS drafted the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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