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RESEARCH ARTICLE

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Impact of elevated CO_2 and Temperature on Nodulation and Crop Weed Competition in Groundnut (*Arachis hypogaea* L.)

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ABSTRACT

Background: Rising atmospheric CO_2 and temperature due to climate change pose significant threats to agricultural productivity, particularly in semi-arid tropics. These changes can alter weed distribution, population dynamics and crop-weed interactions. Assessing groundnut's adaptability to changing climates, weed competition and herbicide efficacy is crucial for developing resilient cultivars and effective herbicide management systems to mitigate yield and quality losses, thereby enhancing global food security.

Methods: A two-year (2022-23 and 2023-24) experiment was conducted in a Carbon Dioxide and Temperature Gradient Chamber (CTGC) at the Central Research Institute for Dryland Agriculture, Hyderabad. The study evaluated groundnut under four climate variables: ambient CO_2 + ambient temperature (aCO_2 + aT) (396-405ppm), elevated CO_2 (eCO_2, 550 ± 50 ppm), elevated temperature (eT, +2°C) and combined eCO_2 + eT (550 ± 50 ppm and +2°C) , three crop-weed combinations (groundnut + C_3 weeds, groundnut + C_4 weeds, groundnut + C_3 + C_4 weeds) and four herbicide rates (0X, 1X, 1.5X, 2X) using a completely randomized design. Growth parameters, soil rhizobium population and nodulation were assessed at 60 days after sowing (DAS).

Result: Pooled data revealed that eCO_2 significantly enhanced groundnut growth and nodulation, with increases in plant height (25%), leaf area (26%), chlorophyll content (12%), *Rhizobium* population (22%), nodulation (58%) and dry matter production (22%) compared to ambient conditions. Combination of elevated CO_2 and temperature also showed positive effects, though less pronounced, while *et al*one reduced all parameters. Herbicide application at various rates showed suppressive effect on *Rhizobium* population, nodulation and chlorophyll content compared to no application. However, plant height, leaf area and dry matter production were significantly higher at 1.5 X rate over no application under eCO_2 conditions in contrast to 1.0X rate under aCO_2 + aT, eCO_2 + eT and eT conditions. Groundnut exhibited better competitiveness against C_4 weeds compared to C_3 weeds or their combination. The findings revealed that groundnut growth and nodulation were significantly enhanced in treatments eCO_2 and eCO_2 + eT but reduced under eT. Herbicide efficacy declined under eCO_2, suggesting the need for higher application rate under future climate scenarios. These findings highlight the importance of adaptive strategies to sustain groundnut productivity under climate change scenario.

Key words: Climate change, Crop-weed competition, CTGC, Dry matter partitioning, Elevated CO_2 (eCO_2), Elevated temperature (eT), Herbicide efficacy, Nodulation.

INTRODUCTION

The global population is projected to reach 8.6 billion by 2030 and 9.6 billion by 2050, placing increasing pressure on agriculture to ensure food security, address climate change and improve soil health (Sharma *et al*., 2025). Groundnut (*Arachis hypogaea* L.), is an annual legume with high quality edible oil and easily digestible protein of its seeds (Vasanthi *et al.,* 2015). The crop is cultivated mainly for its seed and it comprises 40-50% oil, 20-30% protein (Naik *et al.,* 2022). It is cultivated on 7.74 million hectares in India, producing 7.8 million tonnes annually (FAO, 2023). It is vital for nutritional security and livestock fodder, especially as global demand for protein-rich diets grows. However, rising atmospheric CO_2 levels, driven by human activities, threaten agricultural productivity through climate change, altering weather patterns, increasing temperatures and intensifying pest and disease pressures. Since 1850, CO_2 concentrations have risen from 280 ppm to 407 ppm in 2017 (Asha *et al*., 2017), with projections reaching 421-936 ppm by 2100 (IPCC, Climate change, 2013).

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Carbon dioxide in the C_3 pathway of photosynthesis promotes growth and productivity and is an example of a positive effect on C_3 plants (Pawar, 2025). C_3 plants like groundnut generally benefit from elevated CO_2, showing improved growth and CO_2 assimilation (Laza *et al*., 2021), but associated temperature rises can reduce yields (Vanaja *et al*., 2019). Weeds, with their diverse gene pools and physiological plasticity, may adapt better to changing climates, intensifying crop-weed competition (Ziska, 2001; Varanasi *et al*., 2016). Elevated CO_2 can also delay herbicide efficacy (Naidu *et al*., 2023), while higher temperatures may reduce herbicide effectiveness (Rudell *et al*., 2023). Understanding these interactions is crucial for optimizing weed control and ensuring food security under future climates. Hence, this study investigates the effects of climate change on groundnut growth, weed competition and herbicide efficacy.

MATERIALS AND METHODS

Location of the experimental site

The experiment was conducted in Carbon dioxide and Temperature Gradient Chamber (CTGC) facility located at ICAR-CRIDA, Hayathnagar Farm, Hyderabad (17°34′54.65″N latitude and 78°59′42.85″E longitude).

CTGC facility

The Carbon Dioxide and Temperature Gradient Chamber (CTGC) facility consists of four chambers, aT + aCO_2: Maintains ambient temperature and CO_2 levels (396-405 ppm), eT: Elevates temperature by 2°C above ambient using infrared heaters, eCO_2: Elevates CO_2 concentration to 550± 50 ppm) andeT + eCO_2: Combined elevated temperature (+2°C) and CO_2 (550±50 ppm).The facility uses solar radiation and heaters to regulate temperature, with cooling pads and exhaust fans maintaining airflow. A Programming Logical Controller (PLC) monitors and controls temperature and CO_2 levels, ensuring precise environmental conditions.

Treatment details

The experiment studied groundnut response under three factors:

Climate variables (4 levels)

- aT + aCO_2: Ambient temperature and CO_2 (396-405 ppm).
- eT: Elevated temperature (+2°C).
- eCO_2: Elevated CO_2 (550 ± 50 ppm).
- eT+eCO_2: Elevated temperature (+2°C) and CO_2 (550± 50 ppm).

Herbicide rates (4 levels)

- 0X: No herbicide.
- 1X: Recommended dose (75 g/ha Imazethapyr + 50 g/ha Propaquizafop).
- 1.5X: 150% recommended dose (112.5 g + 75 g/ha).
- 2X: 200% recommended dose (150 g + 100 g/ha).

Crop-weed combinations (3 levels)

- Groundnut + C_3 weeds (*Parthenium hysterophorus* and *Alternanthera sessilis*).
- Groundnut + C_4 weeds (*Cyperus rotundus* and *Cynodon dactylon*).
- Groundnut + C_3 + C_4 weeds.

The present experiment was taken under pot culture and popular groundnut cultivar in Telangana K6 was sown on 7-12-2022 and 6-12-2023 during both the years of study. Pot size of (12″ diameter, 14″ height) were filled with 18-19 kg red sandy loam soil. C_3 weed seeds and C_4 weed rhizomes were sown/transplanted alongside. Fertilizers (30 kg N + 40 kg P_2O_5 + 50 kg K_2O + 40 kg S/ha) and vermicompost (2 tons/ha) were applied. 75 g/ha Imazethapyr + 50 g/ha Propaquizafop herbicidew as sprayed post-emergence at 4 ml/L (1X), 6 ml/L (1.5X) and 8 ml/L (2X).

Sampling

At 60 DAS, parameters on crop growth and nodule number was recorded, Plant height was measured from the base to the top leaf tip. SPAD readings (chlorophyll content) were taken using a SPAD-502 meter. Rhizosphere soil samples were collected to assess Rhizobium population using Yeast Mannitol Agar Media (Al-Mujahidy *et al.,* 2013). Plants were carefully uprooted, washed, air-dried for 30 minutes and nodules counted. Leaves were separated and leaf area was measured using a LICOR 3100 leaf area meter. Stem, root and leaf dry weights were recorded after oven-drying at 60°C and total biomass was calculated by summing them.

Statistical analysis

Data were analyzed using three-way ANOVA at 5% significance to assess variability among climate variables, herbicide rates, crop-weed combinations and their interactions using WINDOSTAT software.

RESULTS AND DISCUSSION

Plant height

Pooled data from two years (Fig 1) showed that groundnut height increased significantly by 25% under elevated CO_2 (eCO_2, 550±50 ppm) compared to ambient conditions, followed by eT + eCO_2 (12.4%) and eT (3.8%). The tallest plants (39.4 cm) were recorded with a 1.5X herbicide dose (Imazethapyr 3.75% + Propaquizafop 2.5% ME), similar to 1.0X but superior to 0X and 2X doses. Plants grew taller with C_4 weeds than with C_3 weeds or their combination. Naidu *et al*. (2023) noted that C_4 weeds like *Sorghum halepense* were less competitive than C_3 weeds like *Euphorbia geniculata* under eCO_2. The eCO_2 + 1.5X herbicide combination produced the tallest plants, outperforming other combinations except eCO_2 + 2.0X. Under ambient and eT conditions, plant height increased at 1X but declined at 1.5X and 2X, while under eCO, and eT + eCO_2, height increased up to 1.5X before declining at 2X. Other interactions were non-significant. Geethalakshmi *et al*. (2017) and Chander *et al*. (2023) also reported positive effects of elevated CO_2 and temperature on plant height, leaf area and nodulation in soybean.

Leaf area per plant

Leaf area was significantly influenced by all three factors independently, as well as by climate × herbicide and climate × crop-weed interactions (Fig 1). Maximum leaf area was observed under eCO_2, being 3%, 10% and 26% higher than eT, eT + eCO_2 and aT + aCO_2, respectively. Laza *et al.* (2021) found that long-term exposure to eCO_2 (650 ppm) enhanced CO_2 assimilation, transpiration efficiency, biomass and pod yield in peanuts. Leaf area was highest at the 1.5X herbicide rate, 10% greater than no application. C_4 weeds resulted in significantly higher leaf area compared to C_3 weeds or their combination. The interaction effect showed that leaf area with C_4 weeds was highest under eT + eCO_2. Climate × herbicide interactions revealed that the recommended dose increased leaf area over no application, but higher rates were ineffective under aT + aCO_2, eT and eT + eCO_2. Under eCO_2, 1X did not enhance leaf area, but 1.5X and 2X rates achieved maximum leaf area, suggesting higher herbicide rates may be needed for effective weed control und elevated CO_2 and temperature Varanasi *et al*. (2016) noted that herbicide efficacy is reduced under high temperature and CO conditions.

Leaf chlorophyll content (SPAD readings)

Chlorophyll content in groundnut leaves was significantly influenced by individual factors and climate × herbicide interactions (Table 1). eCO_2 resulted in the highest SPAD readings (43.3), significantly surpassing other climate variables, while eT recorded the lowest (35.9). Enriched CO_2 increased leaf area, photosynthetic rate and chlorophyll content, as reported by Dey *et al*. (2017). Similar trends were observed in maize, with eCO_2 showing the highest physiological parameters, comparable to eT + eCO_2. Herbicide application reduced chlorophyll content, with the highest SPAD (41.4) under no herbicide treatment, significantly higher than 1X, 1.5X and 2X rates. Makarian *et al*. (2016) also noted high concentrations of herbicide caused a significant decline in leaf chlorophyll content in maize and barley. Chlorophyll content was higher with C_4 weeds (41.1) in comparison to the C_3 weeds or their combination (40.2 and 39.1, respectively). weeds under elevated temperatures revealed that the C_3 weeds compete better in cooler conditions, while C_4 weeds adapt to higher temperatures (Upasani and Barla, 2018).

Soil *Rhizobial* population

The *Rhizobium* population (CFU/g soil) was significantly influenced by all three factors and due to their interactions (Table 2). eCO_2 increased *Rhizobium* colonies by 22%, while eT reduced them by 30% compared to ambient conditions. The combination (eT + eCO_2) partially offset this loss, showing an 11% increase. Herbicide application negatively impacted *Rhizobium* colonization, with higher rates causing greater declines. Groundnut with C_3 weeds had higher *Rhizobium* populations (19.7 CFU/g soil) than with C_4 weeds (16.4 CFU/g soil) or their combination (18.1 CFU/g soil). Vu *et al*. (2023) noted that soil microbial populations decreased with increased weed biomass. The highest *Rhizobium* population was observed under eCO, with C_3 weeds and in treatments with no herbicide application. Ruan *et al.* (2023) reported that CO_2 enrichment alone accelerated microbial growth, while combined temperature increases delayed it. Raghavendra *et al.* (2017) reported that herbicide application reduced Rhizobium populations in the soil, primarily because many herbicides are directly toxic to these beneficial microorganisms. In addition, herbicides can alter rhizosphere conditions by affecting root exudation, soil microbial balance and nutrient

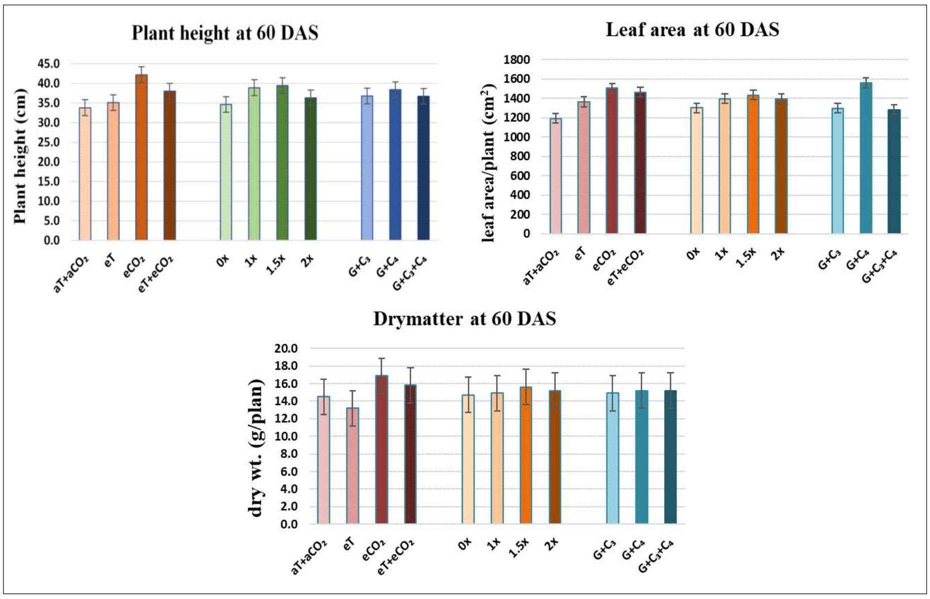

Fig 1: Growth parameters of groundnut as influenced by the climate variables, rates of herbicide application and crop weed interaction.

Table 1: Groundnut SPAD values as influenced by the climate variables, rates of herbicide application and crop weed interaction at 60 DAS.

Climate	Ambient					Elev. Temp					Elev.CO_2					Elev. Temp + Elev.CO_2				
Crop-weed \ Herbicide	0X	1X	1.5X	2X	Mean (Climate × Crop-weed)	0X	1X	1.5X	2X	Mean (Climate × Crop-weed)	0X	1X	1.5X	2X	Mean (Climate × Crop-weed)	0X	1X	1.5X	2X	Mean (Climate × Crop-weed)
Groundnut + C_3	40.3	40.4	39.2	37.5	39.4	37.7	37.9	37.3	36.2	37.3	43.4	41.7	42.7	42.1	42.5	41.2	40.0	40.9	40.0	40.5
Groundnut + C_4	41.2	40.9	39.6	37.9	39.9	38.4	38.5	38.1	36.4	37.8	43.5	41.7	43.5	42.5	42.8	41.8	40.4	41.2	40.7	41.0
Groundnut + C_3 and C_4	40.0	40.2	38.7	36.5	38.8	37.6	37.6	36.9	35.8	37.0	42.6	41.1	42.1	41.1	41.7	41.1	39.4	40.9	39.7	40.3
Mean (Climate × Herbicide)	40.5	40.5	39.2	37.3		37.9	38.0	37.4	36.1		43.2	41.5	42.8	41.9		41.4	39.9	41.0	40.1	
Mean (Climate)		aT+aCO_2: 39.4					eT: 37.4						eCO_2:42.3					eT+eCO_2:40.6		
Mean (Herbicide)		0X: 40.7					1X: 40.0						1.5X: 40.1					2X: 38.9		
Mean (Crop-weed)		G+C_3:39.9								G+C_4:40.4								G+C_3+C_4:39.4		
		Factors								LSD (P=0.05)										
		Climate								0.421										
		Herbicide								0.421										
		Crop-weed								0.365										
		Climate × Herbicide								0.842										
		Climate × Crop-weed								NS										
		Herbicide × Crop-weed								NS										
		Climate × Herbicide × Crop-weed								NS										

Table 2: *Rhizobium* population (CFU/g soil) in soil rhizosphere as influenced by climate variables, rates of herbicide application and crop weed interaction at 60 DAS.

Climate	Ambient					Elev. Temp					Elev.CO_2					Elev. Temp + Elev.CO_2				
Herbicide / Crop-weed	0X	1X	1.5X	2X	Mean (Climate × Crop-weed)	0X	1X	1.5X	2X	Mean Climate × (Crop-weed)	0X	1X	1.5X	2X	Mean (Climate × Crop-weed)	0X	1X	1.5X	2X	Mean (Climate × Crop-weed)
Groundnut + C_3	23.3	21.0	16.2	18.7	19.8	16.2	13.3	11.5	10.0	12.8	30.5	18.7	21.8	23.3	23.6	27.0	24.7	19.3	20.3	22.8
Groundnut + C_4	18.6	16.3	17.5	12.5	16.2	14.0	11.2	12.3	11.3	12.2	24.8	22.5	13.6	16.6	19.4	21.8	14.0	20.2	14.7	17.7
Groundnut + C_3 and C_4	20.8	20.5	14.2	14.7	17.5	16.6	13.3	11.0	10.0	12.7	27.5	25.7	19.3	18.3	22.7	23.5	24.2	16.3	13.3	19.3
Mean (Climate × Herbicide)	20.9	19.3	15.9	15.3		15.6	12.6	11.6	10.4		27.6	22.3	18.3	19.4		24.1	20.9	18.6	16.1	
Mean (Climate)			aT+aCO_2: 17.9					eT: 12.6					eCO_2:21.9					eT+eCO_2:19.9		
Mean (Herbicide)			0X: 22.1					1X: 18.8					1.5X: 16.1					2X: 15.3		
Mean (Crop-weed)			G+C_3:19.7							G+C_4:16.4								G+C_3+C_4:18.1		

Factors	LSD (P=0.05)
Climate	1.415
Herbicide	1.415
Crop-weed	1.225
Climate × Herbicide	NS
Climate × Crop-weed	NS
Herbicide × Crop-weed	2.451
Climate × Herbicide × Crop-weed	4.902

Table 3: Nodulation (No. of nodules/plant) in groundnut as influenced by climate variables, rates of herbicide application and crop weed interaction at 60 DAS.

Climate	Ambient					Elev. Temp					Elev.CO_2					Elev. Temp + Elev.CO_2				
Herbicide / Crop-weed	0X	1X	1.5X	2X	Mean (Climate × Crop-weed)	0X	1X	1.5X	2X	Mean (Climate × Crop-weed)	0X	1X	1.5X	2X	Mean (Climate × Crop-weed)	0X	1X	1.5X	2X	Mean (Climate × Crop-weed)
Groundnut + C_3	249	242	224	203	229	199	179	187	138	176	422	388	320	305	358	364	324	299	287	318
Groundnut + C_4	258	247	227	216	237	210	192	187	153	185	440	402	339	325	377	367	345	316	292	330
Groundnut + C_3 and C_4	235	238	219	212	226	189	183	181	136	172	401	359	340	327	357	352	313	309	271	311
Mean (Climate × Herbicide)	247	242	223	210		199	184	185	142		421	383	333	319		361	327	308	283	
Mean (Climate)			aT+aCO_2: 231					eT: 178					eCO_2:364					eT+eCO_2:320		
Mean (Herbicide)			0X: 307					1X: 284					1.5X: 262					2X: 239		
Mean (Crop-weed)			G+C_3:271								G+C_4:282							G+C_3+C_4:266		

Factors	LSD (P=0.05)
Climate	4.653
Herbicide	4.653
Crop-weed	4.030
Climate × Herbicide	9.307
Climate × Crop-weed	NS
Herbicide × Crop-weed	8.060
Climate × Herbicide × Crop-weed	16.12

availability, creating a toxic or unfavorable environment for Rhizobium survival and activity.

Nodule number

Nodulation, a key indicator of groundnut's nitrogen-fixing ability, was significantly influenced by climate variables, herbicide doses, crop-weed competition and their interactions (Table 3). Nodulation increased by 58% under eCO_2 and 39% under eT + eCO_2 compared to ambient conditions but decreased by 23% under eT. Libault (2014) noted similar trends, with eCO_2 enhancing nodulation and eT reducing it due to soil moisture changes. Growth, nodule dry weight and nitrogenase activity are inversely related to temperature (Day *et al*., 1978). Herbicide application reduced nodulation by 7%, 15% and 22% at 1.0X, 1.5X and 2.0X rates, respectively, consistent with Zaidi *et al*. (2005). The highest nodulation (440 nodules/plant) was observed under eCO_2 with C_4 weeds and no herbicide application while the lowest was under ambient conditions with 2X herbicide and C_3 weeds. Elevated CO_2 may boost plant growth, but weed competition for resources can affect nodulation outcomes. Climate change modifies plant–herbicide interactions by altering crop physiology, herbicide uptake and effectiveness and weed competitiveness. These changes can either suppress or stimulate nodulation, depending on crop species, environmental conditions and the intensity and type of weed competition (Burul *et al*., 2022).

Dry matter production

Dry matter accumulation in groundnut was significantly influenced by climate variables, herbicide doses and their interactions (Fig 1). The highest dry matter (16.9 g/plant) was recorded under eCO_2 (550±50 ppm), followed by eT + eCO_2 (15.8 g/plant), while eT resulted in the lowest (13.2 g/plant). Similar increases in biomass under eCO_2 were reported by Saha *et al*. (2012) in pigeon pea and by Vanaja *et al*. (2019) and Guna *et al*. (2024) in groundnut and black gram, respectively. Dey *et al*. (2017) noted a 20.7% and 17.3% increase in photosynthetic rate at 25 and 45 DAS in mung bean under eCO_2, enhancing biomass production. Among herbicide doses, the highest dry matter (15.6 g/plant) was observed at 0X, significantly higher than 1.0X and 2.0X but similar to 1.5X. Interaction effects were non-significant. While herbicides improve growth by reducing weed competition, excessive doses can cause phytotoxicity, reducing productivity (Galon *et al*., 2015).

CONCLUSION

Elevated CO_2 (eCO_2) significantly enhanced groundnut growth, increasing plant height, leaf area, chlorophyll content, nodulation and dry matter production, while elevated temperature (eT) reduced these parameters. The combination of eCO_2 + eT partially offset the negative effects of eT. Herbicide application improved growth at moderate rates but suppressed *Rhizobium* populations and nodulation at higher doses. Groundnut competed better with C_4 weeds than with C_3 weeds. Under future climate scenarios, higher herbicide rates may be needed for effective weed control, as herbicide efficacy is reduced under elevated CO_2 and temperature. These findings highlight the need for adaptive management strategies to sustain groundnut productivity under changing climatic conditions.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

All animal procedures for experiments were approved by the Committee of Experimental Animal care and handling techniques were approved by the University of Animal Care Committee.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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