Technical Bulletin : 24

Impact of elevated CO_2, temperature and drought on crop-weed interaction and herbicide efficacy

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Foreword

In recent decades, the growing intensity of human activity has magnified climate change and its implications. Increasing temperatures and atmospheric CO_2 are the two major environmental factors associated with global climate change. These changes are likely affecting plant growth, function, and productivity, which will have an immediate impact on agriculture, food security around the world, and general human health.

Weeds are one of the major menaces to Indian agriculture and the environment. Their management continues to be a serious logistical, financial, and research challenge. Climate change will necessitate revisiting what we deem effectual for weed control to keep existing and future management strategies efficient and effective. Climate change will aggravate both the risk to biodiversity and the cost to agriculture of weeds. This is due to the fact that weed impacts on the environment will change and evolve, necessitating new or drastically altered adaptation responses to lessen harmful effects. Climate change certainly alter crop-weed interactions and herbicide efficacy as well as directly affecting crop performance and productivity.

This technical bulletin entitled 'Impact of elevated CO_2, temperature and drought on crop-weed interaction and herbicide efficacy highlights the information research progress at ICAR-DWR, Jabalpur. I appreciate the initiative of ICAR-DWR, Jabalpur for compiling such an important document and hope this will be useful for researchers, policy makers and other stake holders for formulating weed management strategies in future.

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Prologue

Future efforts to feed the growing global population will provide enormous problems for agriculture and the closely linked discipline of applied plant science research. The growth and yield of many crops are being hampered by heat, drought, salt, and changing light stress, which are all threats to agriculture globally. A recent research by United Nations estimates that the annual cost of reduced crop yield and soil degradation brought on by salinity, in particular, will exceed US$ 27.3 billion globally. It is predicted that climate change will upsurge the frequency of several stressful occurrences, including drought and heat stress. The impact of climate change is projected to boost weed competitiveness, resulting in a high yield drop by improper weed management practices. Total economic loss of about $ 11 billion was estimated due to weeds alone in 10 major field crops in 18 states of India. Actual economic losses were high in the case of rice ($ 4420 million) followed by wheat ($ 3376 million) and soybean ($ 1559 million).

Weed's genetic diversity and physiological flexibility seems to be superior to crops. Because of this, weeds are better able to survive and thrive in various situations and adapt quickly to resource accessibility fluctuations. Weeds are venomous plant species that are particularly well suited to invade and, in many instances, dominate an ecosystem by establishing a large population. The efficacy of many herbicides is affected by climatic factors such as CO_2, temperature, precipitation, wind and relative humidity. In addition to having large ecological amplitudes, weeds have unique biological traits that allow them to thrive in a plethora of challenging environmental conditions in disturbed habitats like crop fields. These traits include competitiveness, aggression, plasticity, and high fertility.

Research needs to be initiated on climate change studies using various other essential crops at multi-locations could enhance our knowledge and it will be certainly helpful in implementing appropriate weed management practices for increased production under adverse climatic conditions. Based on research methodologies adopted and results achieved in various projects, a bulletin has been prepared. It will be an important data resource book on the “Impact of elevated CO_2, temperature and drought on crop-weed interaction and herbicide efficacy”. We fervently hope that the report will be of immense use for the students, academicians, scientists, teachers, farmers and policymakers interested in weed management studies under climate change. This can also help orient research and development programs aiming to improve weed management to address the futuristic climate change issues.

We sincerely acknowledge all project team members Dr. V.S.G.R. Naidu, (Late) Dr. Bhumesh Kumar and Dr. Subhash Chander for their meticulous contribution to the comprehensive work on crop-weed interaction and herbicide efficacy. The contributions by the project staff engaged as research associates, senior research fellows and young professionals at different time periods are thankfully acknowledged.

Authors

Contents

1. Introduction

The cornerstone of life on Earth and the means by which 7.5 billion people are sustained is the growth and development of plants, including their processes for photosynthesis, transpiration, flowering, and fruiting (Pieruschka and Schurr, 2019). The agriculture that sustains humanity is now facing three stark challenges: climate change, resource depletion, and population growth (Kim, 2020). Worldwide agricultural productivity has been significantly impacted by global climate change. The severe repercussions of climate change include high and low temperatures, excessive sunlight, and rising CO_2 altering rainfall patterns geographically and making crops more susceptible to disease (Wang et al., 2018). Numerous studies have emphasized that climate change is now a major factor that significantly influences plant growth, development, and productivity by inducing biotic (weeds, pathogens, etc.) and abiotic stresses like salinity, drought and extreme temperature (Wang et al., 2018). On the other hand, a drop in agricultural production will threaten food security, resulting in chronic hunger and micronutrient deficiencies in the world's ever-expanding population (Hasegawa et al., 2018). Additionally, food security has further declined in the pandemic era as a result of diseases like severe acute respiratory syndrome coronavirus 2 (SARSCoV- 2), according to agricultural scientists, who predict that by 2020 the hunger index will have increased dramatically (Ukhurebor et al., 2021). The predicament becomes more complex as food security depends on economic growth, markedly influenced by global climate change (Ukhurebor et al., 2021).

The possibility that climate change could imperil agriculture is particularly intriguing in this context (Chauhan et al., 2014), as climatic conditions substantially impact the growth of all plant species, including crops and weeds. Variation in rainfall patterns and increased aridity consistent with a warming climate could alter weed distribution, herbicide efficacy and their impact on crop production. Most weeds have a high rate of evolutionary success or the continuation of a genetic line across duration due to their high reproduction rates and they can occupy wide range of environments. Therefore, weeds are the class of plants that have evolved the most successfully on our planet according to the Darwinian concept of "struggle for existence" (Auld, 2004).

Weeds appear to be more genetically diverse and physiologically flexible than crops. As a consequence, weeds adapt rapidly to alterations in the availability of resources and have a more substantial capacity to live and flourish in diverse environmental conditions. The effects of climate change are projected to enhance weed competitiveness, resulting in more considerable output losses if weeds are not properly controlled (Valerio et al., 2013). Climate change may alter crop-weed-pest interactions and livestock-agricultural systems, directly affecting crop performance and productivity. Instances of droughts, floods, heat stress, and freezing events will increase under climate change, which will have a detrimental influence on the agro-ecosystem output. Climate change particularly increased CO_2 levels, is likely to favor the yield and quality of several C_3 crops (such as wheat, rice, barley, and soybean). By 2050, higher CO_2 levels are anticipated to improve food yields by up to 13% (Jaggard et al., 2010). However, the beneficial effects of enhanced CO_2 concentrations on crop performance and production are negated by the adverse impacts of concomitant temperature rises for most food crops (Prasad et al., 2005). Elevated CO_2, on the contrary, causes partial stomatal closure, increasing plant tissue temperature, which has a detrimental impact on plant growth and production. Other directly related issues with climate change, such as irregular rainfall patterns and high temperatures, may impair agricultural output and quality (Singh et al., 2013). Hence, a second green revolution with more sustainable management of renewable resources and more efficient weed management practices is needed to sustain crop yields under current and future changing environments and ensure food security.

Generally, C_3 and C_4 plants react differently to CO_2 and temperature. At increased atmospheric CO_2 concentrations, carboxylation of ribulose biphosphate (RuBP; initial acceptor of CO_2) is promoted in C_3 plants. When temperatures rise beyond 25 °C, RuBP oxygenation is preferred, which results in increased photorespiration and inhibition of CO_2 assimilation (Jorden and Ogren, 1984). The temperature does not influence C_4 plants because decreased photorespiration rates are always maintained due to CO_2 pumps in mesophyll cells (Hatch, 1987). Because of these variations in the carbon fixation pathways, C_3 plants have a strong capacity to show a favorable response to elevated CO_2, whereas C_4 plants are adapted better to heat stress and drought (because of greater water use efficiency) (Morgan et al., 2001). Weeds will have an advantage over crops (mainly C_3 plants) under increasing temperatures and limited water availability since most of the weeds are C_4 weeds. Furthermore, the potential effects of climate change factors on weeds and crops–such as moisture regimes, CO_2, and temperature levels–allow weeds to compete successfully and thrive even in unpredictable environments (Hartfield et al., 2011). Consequently, enhanced CO_2 concentrations and temperature may have major consequences for crop–weed interactions, necessitating further attention.

Herbicides are the best tools to manage agricultural weeds and reduce agricultural output losses. The usage of herbicides has been gradually enhanced worldwide in traditionally low herbicide-using countries like China, India and some regions of Africa (Gianessi, 2007). It is already reported that elevated CO_2 and temperature can change herbicide efficacy (Varanasi et al., 2016). For instance, elevated CO_2-induced weed growth could lower the time at the seedling stage, which is the most critical and sensitive stage to herbicide action. Herbicide absorption also declined due to CO_2-induced stomatal conductance. However, elevated temperature enhance the herbicide efficacy by rapid absorption and translocation of foliar herbicides; but this leads to rapid metabolism, which ultimately reduces the herbicide efficacy in the target plants (Johnson and Young, 2002). It is suggested that enhanced atmospheric CO_2 concentrations and temperature may alter the leaf structure and morphology by enhancing leaf thickness or altering the cuticle wax, which results in a reduction in herbicide absorption (Ziska and Bunce, 2006).

Therefore, studies on climate scenario are imperative to look at crop-weed competition case by case to establish appropriate weed control measures for the emerging weed species. Climate Changes will bring changes in the weed population and their phenology. Many species of weeds can expand their range and spread into new areas. Apart from its impact on weeds, previous studies have reported that invasive species can become more of a threat due to their strong response to increased CO_2 concentrations and changes in climatic factors as opposed to other native species. Moreover, few weeds like as parthenium weed (*Parthenium hysterophorus* L.), directly impact human health through allergic reactions, skin irritations, or internal poisoning exhibited a positive growth to climate change, especially by producing increased plant biomass, poisonous compounds and pollen synthesis in response to increased atmospheric concentrations of CO_2. Climate change may profoundly impact weed management practices by lowering their effectiveness. Information about the effects of climate change on weeds is sparse. In this technical bulletin, we have made an attempt to cover the effects of climate change on crop-weed interaction and the efficacy of herbicides.

The major aim of this technical bulletin is to provide a comprehensive overview of hitherto progress made in crop-weed interaction and herbicide efficacy under climate change scenario. This review is expected to assist plant biologists in their endeavors by fetching greater harmonization of technological advances in weed management under climate change for better pragmatic approach having a practical perspective. Such information will be useful to plant biologists, agronomists and policymakers for developing strategies for increasing or sustaining crop yields under current and future changing environments and management practices to ensure food security.

2. Crop-weed interaction under climate change scenario

I. Maize

a. Effect of elevated CO_2 on the competitive interaction between maize and associated weeds (*Sorghum halepense* and *Euphorbia geniculata*)

A study was conducted in two Open Top Chambers (OTCs) to determine the effects of enhanced CO_2 (eCO_2) on maize (C_4) and related weeds [*S. halepense* (C_4) and *E. geniculata* (C3)] (DWR, 2008-09). The study revealed that the eCO_2 (550 ± 30 ppm) positively impacted the plant height, leaf area, biomass, seed filling, test weight and grain yield of maize compared to ambient (360± 20 ppm). However, *E. geniculata* competition had a considerable negative impact on seed filling, which decreased yields significantly. It was shown that the C_4 weed *S. halepense* was less competitive than the C_3 weed *E. geniculata* in the CO_2 condition (Ambient and eCO_2). However, when *S. halepense* was alone, the enrichment of CO_2 increased growth and biomass production. *E. geniculata* exhibited a comparable response to CO_2, although it impacted maize growth in the presence of eCO_2. As a result of climate change, this study predicts that *E. geniculata* will become a significant competitive weed for maize (Fig.1).

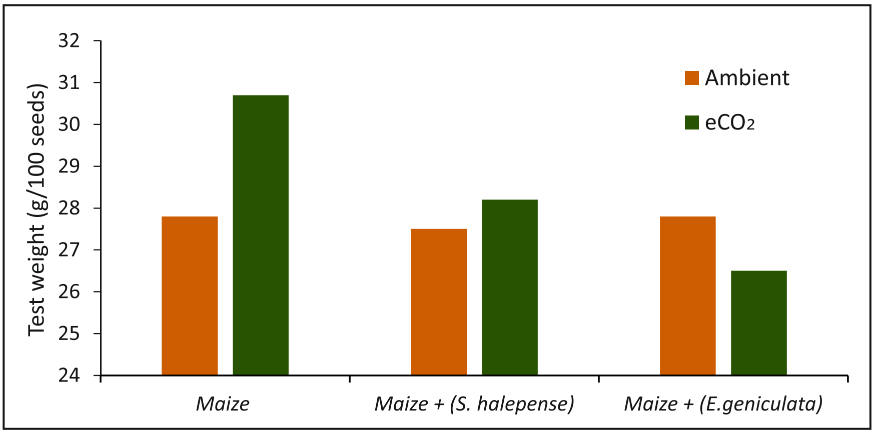
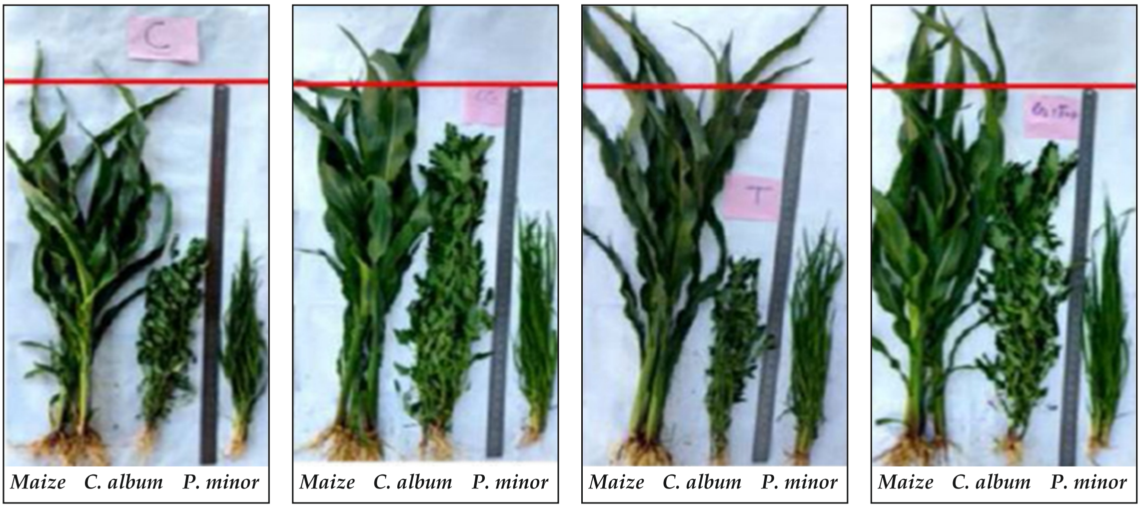


Figure 1. Interactive effect of elevated CO_2 and weeds on test weight of maize

b. Effect of elevated CO_2 and temperature on winter maize and weed species (*Chenopodium album* and *Phalaris minor*)

eCO_2 (550±50 ppm) alone and in combination with elevated temperature (eTem: ambient + 2^{o} C ± 0.5^{o} C) positively affected the growth and development of both crop and weeds (DWR, 2017-18). However, the response of *C. album* to eCO_2 was more visible, indicating that this weed species may be capable of adapting to climate change.

In comparison to ambient, eCO_2 increased plant height (Fig. 2.1), leaf area, and relative growth rate (RGR) in both maize and weed species at the 45 and 90 DAS growth stages (Fig. 2.2). Plant height and maize leaf area increased at eTem compared to ambient. However, not much difference was observed in the two weed species (*C. album* and *P. minor*). In comparison to ambient conditions, plant height and leaf area enhanced in both maize and *C. album* under eCO_2 and eTem alone and eCO_2+eTem. *P. minor*, on the other hand, showed only a slight rise. In contrast to ambient conditions, maize grain yield increased under eCO_2 (14.43%), eTem (17.53%), and a combination of these two factors (19.59%) (Fig. 2.3). The growth of the tropical crop maize is impaired by low temperatures. According to the study, a slight temperature difference of 2° C assisted in mitigating the adverse effects of the winter time low temperatures during the nights. Among the weed species, the *C. album* was most responsive to eCO_2; however, no difference was observed under eTem. Only a modest rise in *P. minor* was evident under eCO_2 alone and in combination with eTem.



Ambient **eCO_2** **eTem** **eCO_2+eTem**

Figure 2.1. Effect of elevated eCO_2 and eTem on growth and development of winter maize and weed species

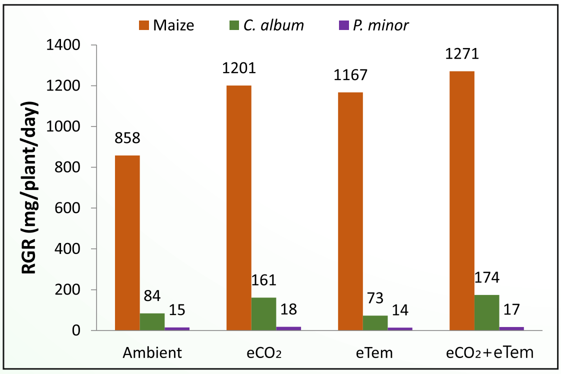


Figure 2.2. Effect of eCO_2 and eTem on relative growth rate of winter maize and weed species

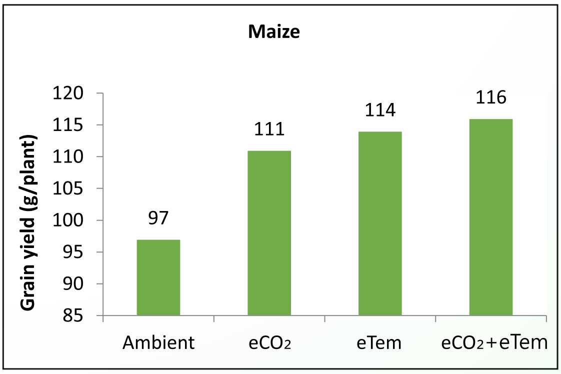


Figure 2.3. Effect of eCO_2 and eTem on grain yield of winter maize

II. Mungbean

a. Effect of elevated CO_2 on mungbean and associated weeds (*Euphorbia geniculata* and *Commelina diffusa*)

eCO_2 (550 ± 50 ppm) positively affected the overall growth of mungbean and weeds compared to ambient (385 ± 5 ppm) in FACE facility (DWR, 2011-12). The findings showed that mungbean nodule's biomass and size had increased (Fig. 3.1.A). Mungbean and weeds have increased carbonic anhydrase activity and photosynthetic rate (Fig. 3.1.B and 3.1.C). Nodule senescence was observed to be slower at eCO_2 than ambient (Fig. 3.F), indicating that exposure of plants to high CO_2 prolongs the functionality of nodules. Mungbean and *C. diffusa* were found to have decreased stomatal conductance and transpiration rates; however, *E. geniculata* showed an increase in these parameters at eCO_2, highlighting its distinct capacity for eCO_2 adaptation (Fig. 3.1.D) .

Ascorbate and glutathione in mungbean and *C. diffusa* switched from a reduced to an oxidised state due to CO_2 enrichment (Fig. 3.2.A and 3.2.B, respectively). *E. geniculata*, on the other hand, showed the ability to maintain redox homeostasis in its original state at enhanced CO_2 levels, which may have given it an advantage over other species in adapting to the effects of climate change. *In situ* staining of leaves indicated that reactive oxygen species (ROS) (hydrogen peroxide and superoxide radicals) accumulated only in mungbean, indicating the presence of a more potent antioxidant defense mechanism in weed species (Fig. 3.3.A). Isoenzymes activity profile (native PAGE) of antioxidant enzymes [superoxide dismutase (SOD), ascorbate peroxidase (APX), guaiacol peroxidase (GPOX), glutathione peroxidase (GPX) and glutathione reductase (GR)] shown differential regulation and the induction of novel isoforms in response to eCO_2 (Fig. 3B). *E. geniculata* was better able to adjust to climatic change than mungbean due to stronger antioxidant defense. At eCO_2, mungbean showed altered expression of antioxidant defence system genes (primer-specific) (Fig. 3.3.B&C).

Various crop and weed species responded differently to increasing atmospheric CO_2 concentration, which altered crop-weed competition in favor of weeds and reduced seed yield (Fig. 3.4.A). Additionally, increased levels of carbohydrates and decreased protein in mungbean seeds may indicate that the quality of the seed has been negatively impacted by atmospheric CO_2 enrichment (Fig. 3.4.B).

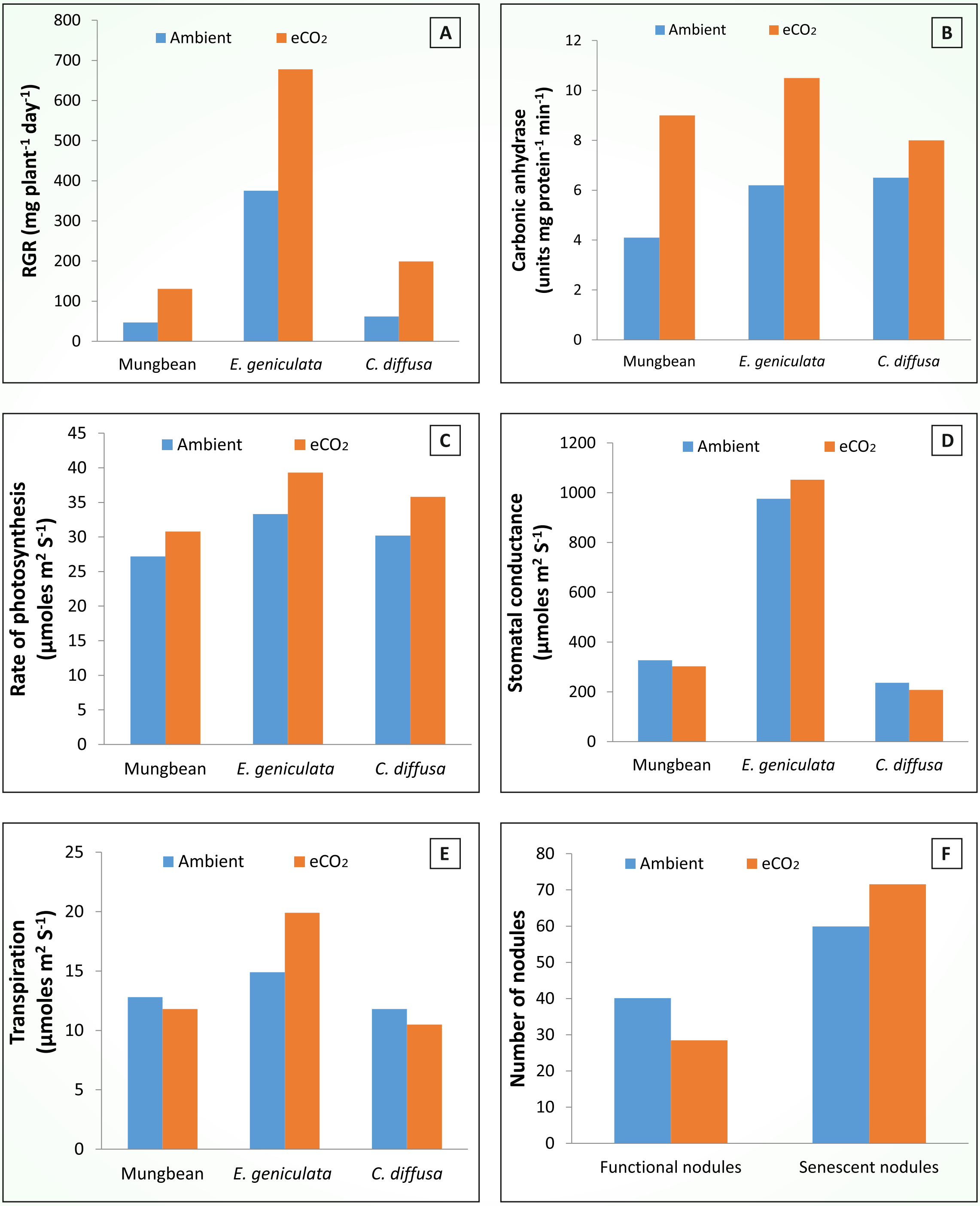


Figure 3.1. Effect of elevated CO_2 on growth and development of **(A)** RGR **(B)** Carbonic anhydrase **(C)** Rate of photosynthesis **(D)** Stomatal conductance **(E)** Transpiration **(F)** Number of root nodules

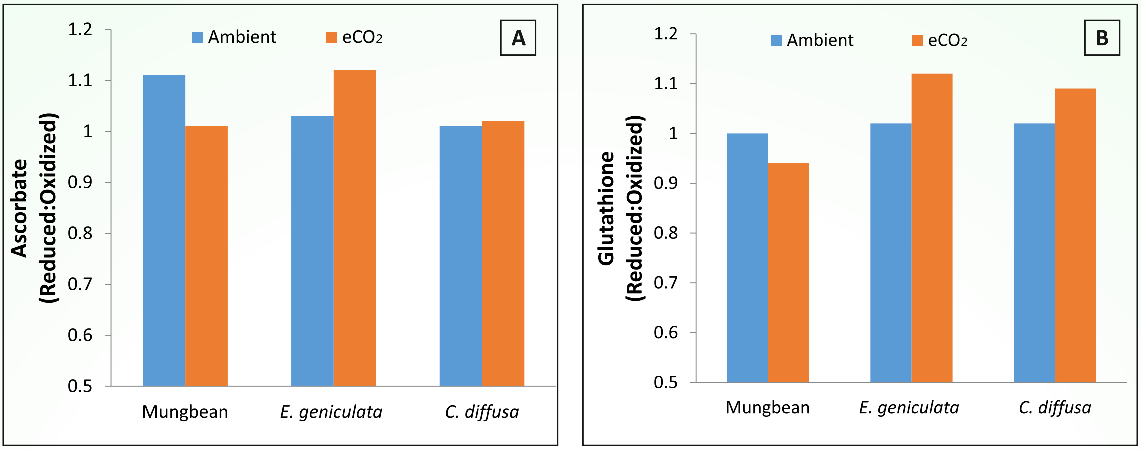


Figure 3.2. Effect of elevated CO_2 on ratio of reduced and oxidized ascorbate **(A)** glutathione **(B)** in mungbean and its associated weeds at 21 days after treatment (DAT)

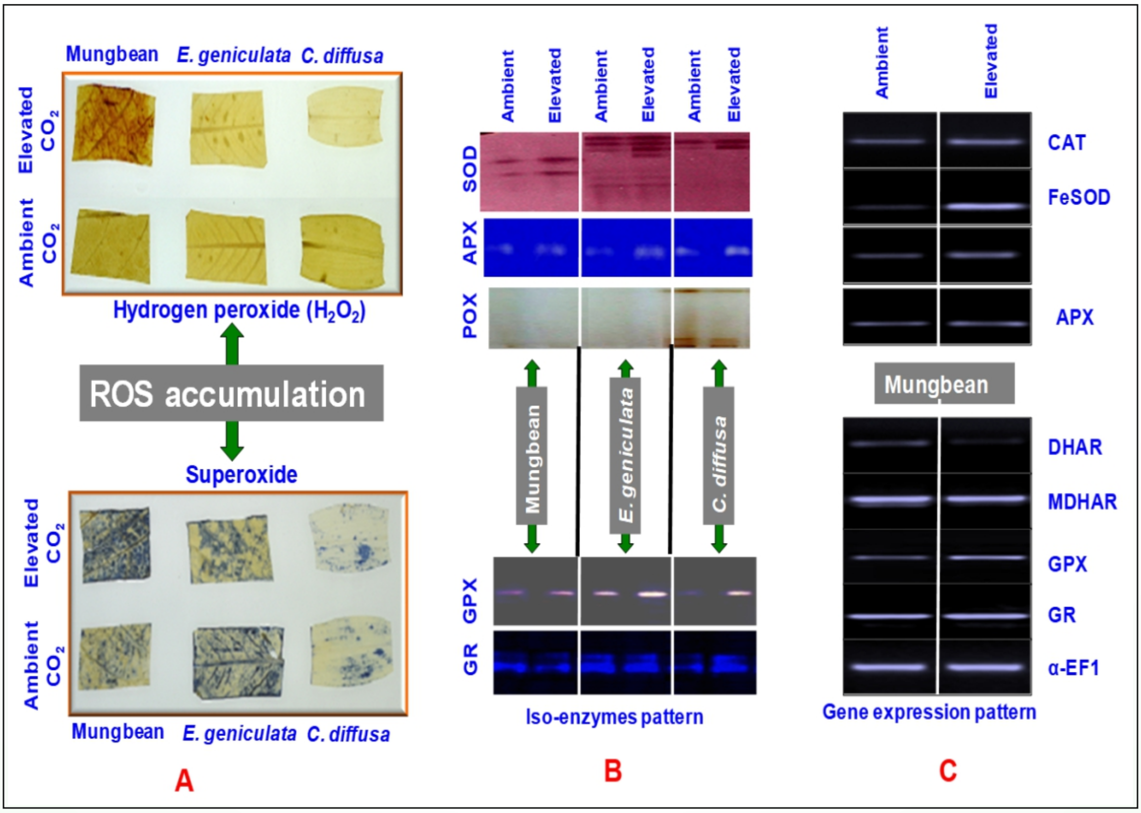


Figure 3.3. Effect of eCO_2 on the accumulation of reactive oxygen species **(A)**, profile of isoenzymes involved in antioxidant defense pathway in mungbean and associated weeds **(B)**, gene expression pattern of antioxidant defense pathway in mungbean **(C)** at 21 DAT

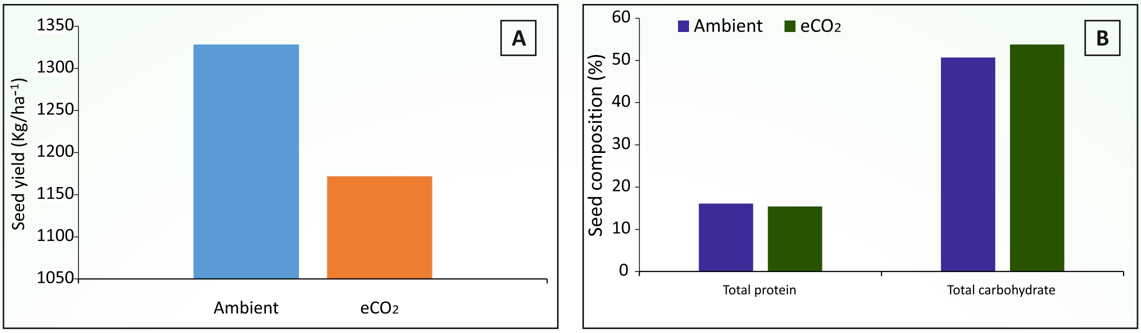


Figure. 3.4. Effect of elevated CO$_2$ on seed yield **(A)** and seed composition **(B)** of mungbean

b. Impact of elevated CO$_2$ on mungbean and associated weeds (*Brachiaria reptans* and *Eragrostis diarrhena*: Physiological and biochemical aspects

The effect of eCO$_2$ (550± 50 ppm) on summer mungbean and weed species (*B. reptans* and *E. diarrhena*) was studied in the FACE facility (DWR, 2012-13). The study found that eCO$_2$ significantly impacted the total growth of mungbean and weed species. The greater dry matter accumulation in above-ground components may be responsible for the growth promotion at eCO$_2$. Compared to ambient, mungbean showed a 19.5% increase in dry matter accumulation, *B. reptans* a 90.8% increase, and *E. diarrhena* a 75.6% increase (Fig. 4.1.A). Water use efficiency and photosynthetic rate both accelerated. However, in contrast to ambient CO$_2$, mungbean, *B. reptans*, and *E. diarrhena* showed a decrease in stomatal conductance and transpiration rate at eCO$_2$ (Fig. 4.1.A-E).

All three species responded favourably to eCO$_2$ exposure in terms of carbonic anhydrase activity (mungbean, *B. reptans* and *E. diarrhena*) (Fig. 4.1.F). However, compared to mungbean, two weed species had rise in carbonic anhydrase activity at eCO$_2$, which may be a factor in the improved photosynthesis at eCO$_2$. The CO$_2$ enrichment treatment led to a differential peptide pattern when resolved on 10% SDS-PAGE. Between the three species, it was determined that *E. diarrhena* had the fewest bands (peptides). A protein profile showed that a high molecular weight (200 kDa) peptide was up-regulated in mungbean while it was down-regulated in *B. reptans*. A 68 kDa peptide was also increased at eCO$_2$ in all three species, suggesting that it is unique to high CO$_2$. In response to eCO$_2$, different protein profiles for different species and stages were noticed (Fig. 4.2).

In comparison to ambient conditions, the activities of catalase, superoxide dismutase, ascorbate peroxidase, and glutathione reductase increased in *B. reptans* and *E. diarrhena* while reduced in mungbean. With a slight difference, *B. reptans* and *E. diarrhena* did not show a decrease in glutathione peroxidase activity at eCO$_2$ compared to ambient. However, regardless of the species, guaiacol peroxidase activity reduced at eCO$_2$ compared to ambient. An interesting finding from the study was that, in comparison to mungbean, weed species (*B. reptans* and *E. diarrhena*) had increased antioxidant enzyme activity both constitutively and at eCO$_2$ (Fig. 4.3.A-F).

Mungbean and two weed species showed an increased nitrate reductase activity at eCO_2 relative to ambient. In mungbean, *B. reptans*, and *E. diarrhena*, nitrate reductase activity enhanced by 14.1, 16.9%, and 18.6%, respectively, at eCO_2 (Fig. 4.4.A). The mungbean seed yield was significantly reduced (11.7%) by atmospheric CO_2 enrichment (Fig. 4.4.B). Seed protein concentration decreased at eCO_2 relative to ambient during the developing and mature stages (Fig. 4.4.C). A 0.7% decline in seed protein was observed 28 days after pod initiation. The total carbohydrate content of developing and mature seeds increased when mungbean plants were exposed to eCO_2. At 28 days after pod initiation, there was a 3.1% increase in the amount of seed carbohydrates. Findings showed that, in addition to reducing production, increasing atmospheric CO_2 could potentially degrade the quality of mungbean seed by increasing its carbohydrate content while decreasing its protein content (Fig. 4.4.D).

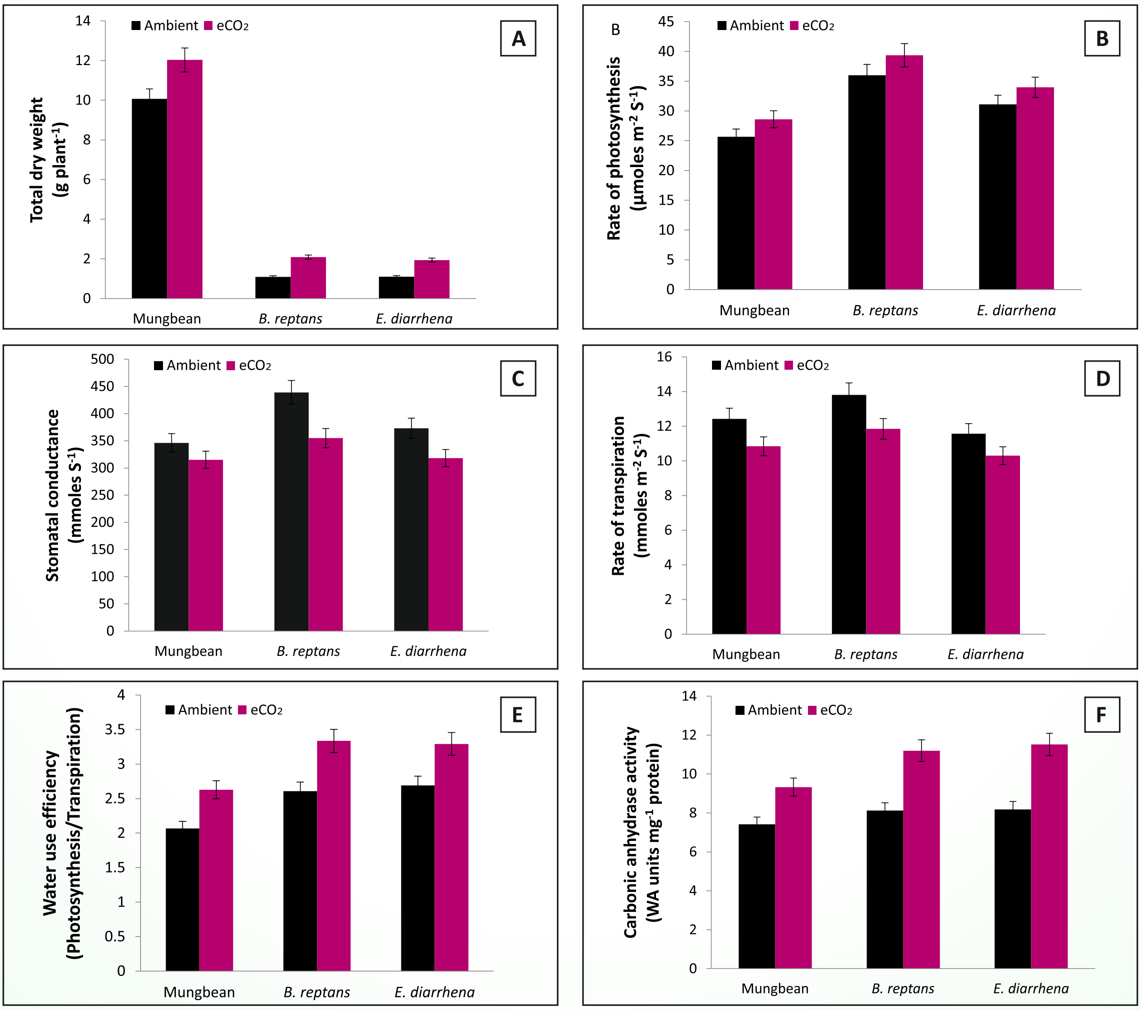


Figure. 4.1. Effect of elevated CO_2 on dry matter **(A)**, rate of photosynthesis **(B)**, Stomatal conductance **(C)**, transpiration **(D)**, water use efficiency **(E)** and carbonic anhydrase activity **(F)** in mungbean and its associated weeds (*B. raptans* and *E. diarrhena*) at 42 days after treatment.

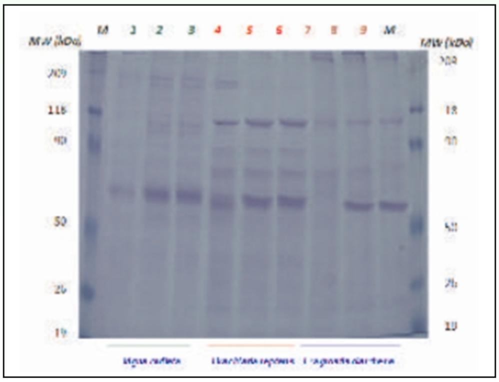


Figure 4.2. Effect of eCO_2 on SDS protein profile in mungbean and its associated weeds (*B. reptans* and *E. diarrhena*) at 42 DAT

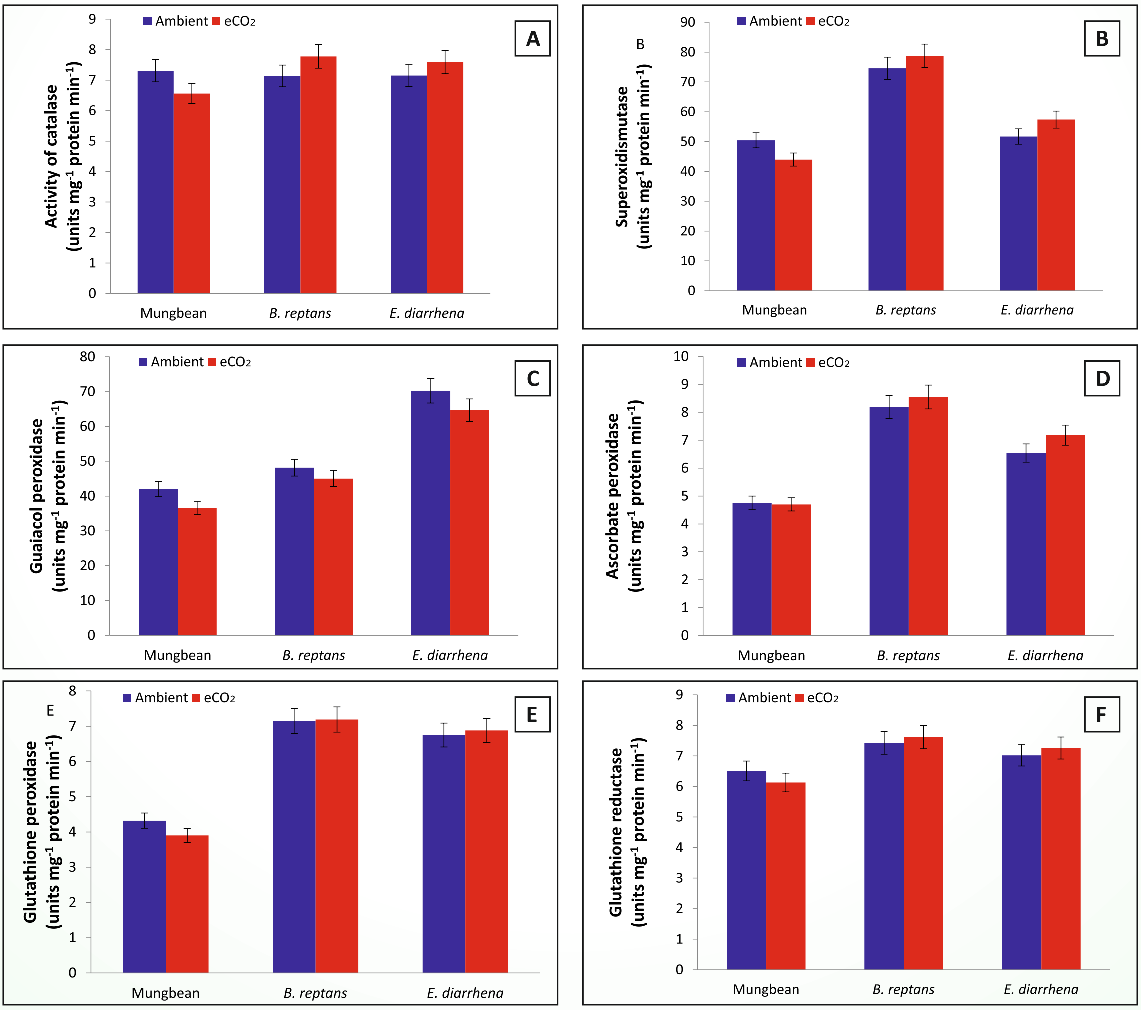


Figure. 4.3. Effect of elevated CO_2 on activity of catalase **(A)**, superoxide dismutase **(B)**, guaiacol peroxidase **(C)**, ascorbate peroxidase **(D)**, glutathione peroxidase **(E)** and glutathione reductase **(F)** in mungbean and its associated weeds (*B. reptans* and *E. diarrhena*) at 42 days after treatment.

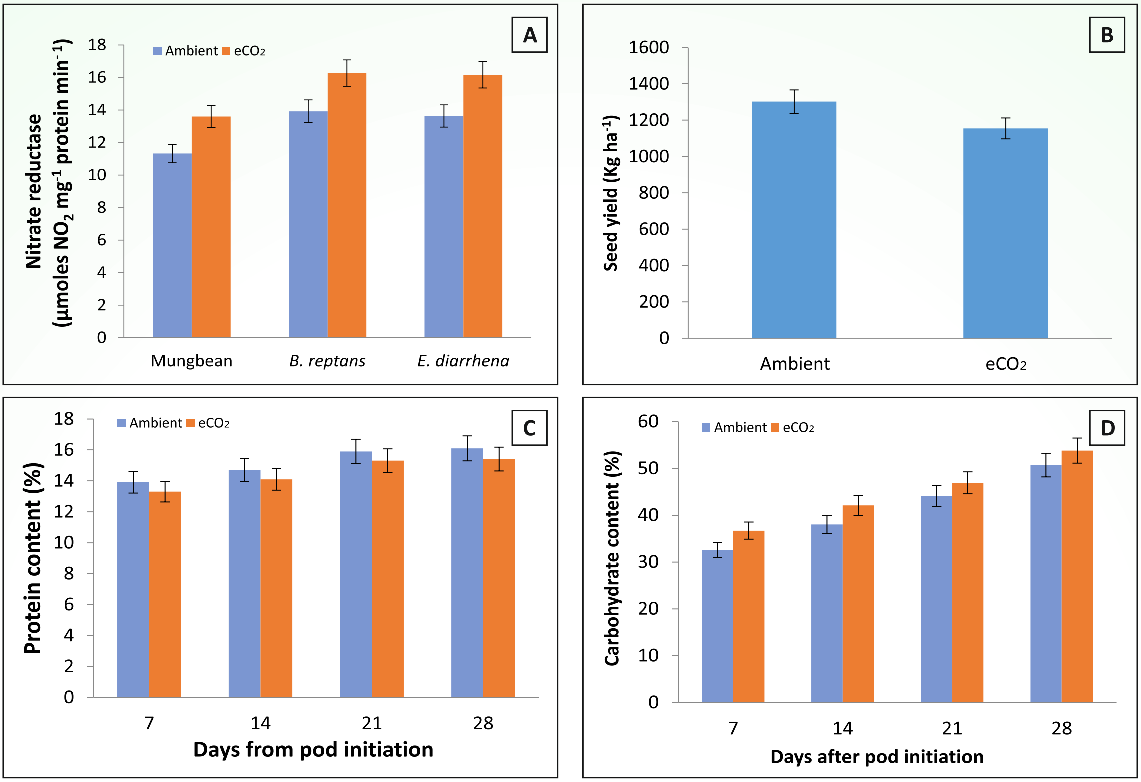


Figure 4.4. Effect of eCO_2 on the activity of nitrate reductase **(A)**, seed yield **(B)**, seed protein content **(C)** and carbohydrate content **(D)** in mungbean

c. Effect of elevated CO_2 and temperature on mungbean and asso Ciated weed species (*Euphorbia geniculata* and *Amaranthus viridis*)

The effect of eCO_2 (550 ± 50 ppm) and eTem (ambient + 2.0 ± 0.5° C) on summer mungbean and weed species (*E. geniculata* and *A. viridis*) were studied in OTCs (DWR, 2016-17). Both mungbean and weed species exhibited an increase in growth due to eCO_2. The increased dry matter accumulation in the above-ground components of all three species can be attributed to the promotion of growth at eCO_2. *E. geniculata* showed the highest increase in dry matter production, whereas *A. viridis* showed the negligible increase (C_4 weed). In mungbean, the photosynthesis rate increased while the transpiration rate dropped at eCO_2, but these effects were less pronounced in C_4 weed (*A. viridis*). *E. geniculata*, on the other hand, had a unique capacity for adaptation at eCO_2, increasing photosynthesis while maintaining the same level of transpiration (Fig. 5.1.A-F). The vegetative phase was shortened, leading to earlier maturity by eTem alone or in combination with eCO_2. Under the effects of climate change, species-specific expression of the antioxidant defense pathway's enzymes and genes was noticeable (Fig. 5.2.A-F). *E.geniculata* exhibited more vital antioxidant defense systems than mungbean and *A. viridis*. According to study results, *E. geniculata* might outcompete mungbean and C_4 weeds like *A. viridis* in different climate conditions (i.e., eCO_2, eTem, and eCO_2+eTem).

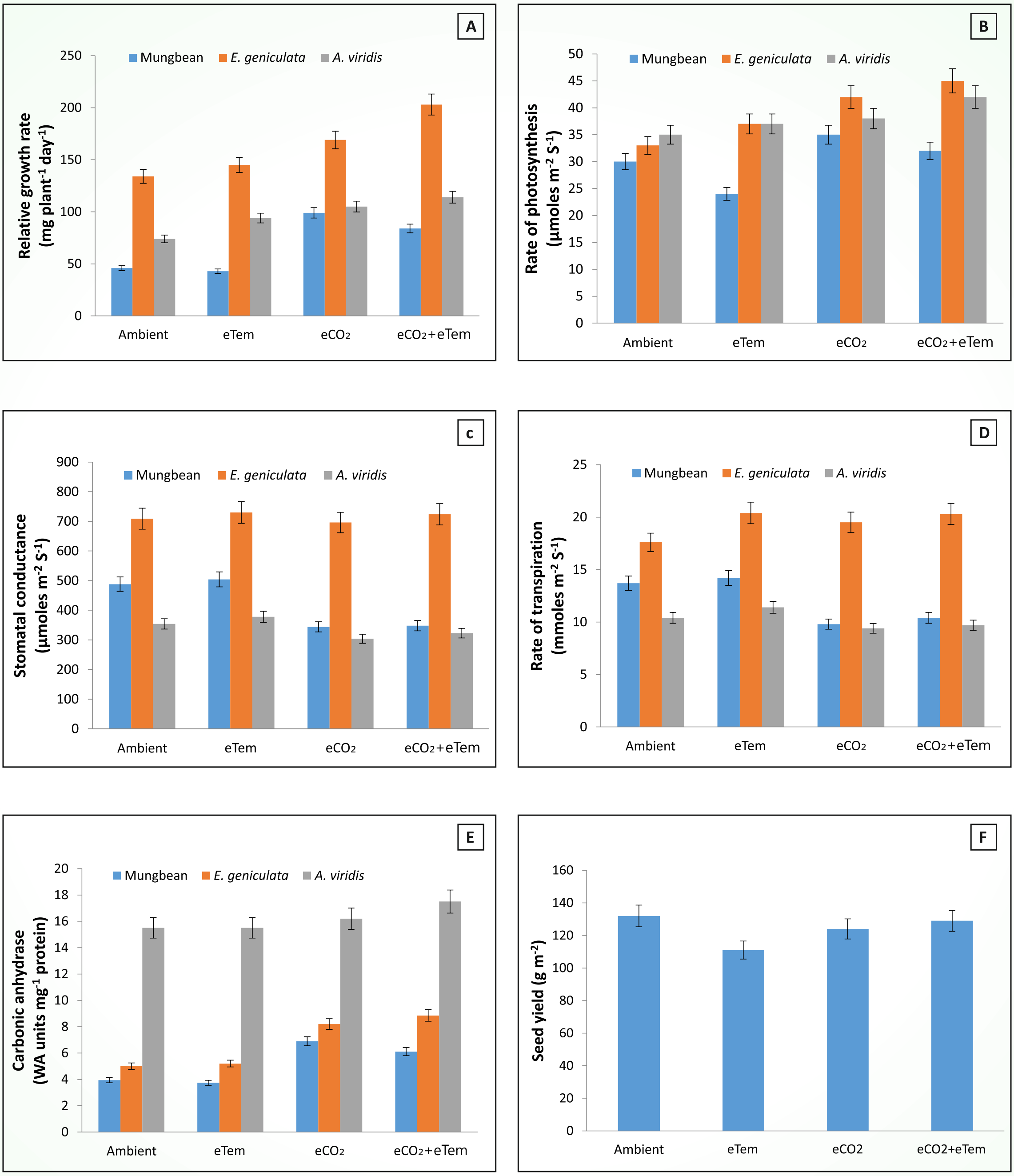


Figure 5.1. Effect of elevated CO_2 and temperature on RGR **(A)**, rate of photosynthesis **(B)**, stomatal conductance **(C)**, rate of transpiration **(D)**, carbonic anhydrase **(E)** and mungbean yield **(F)**

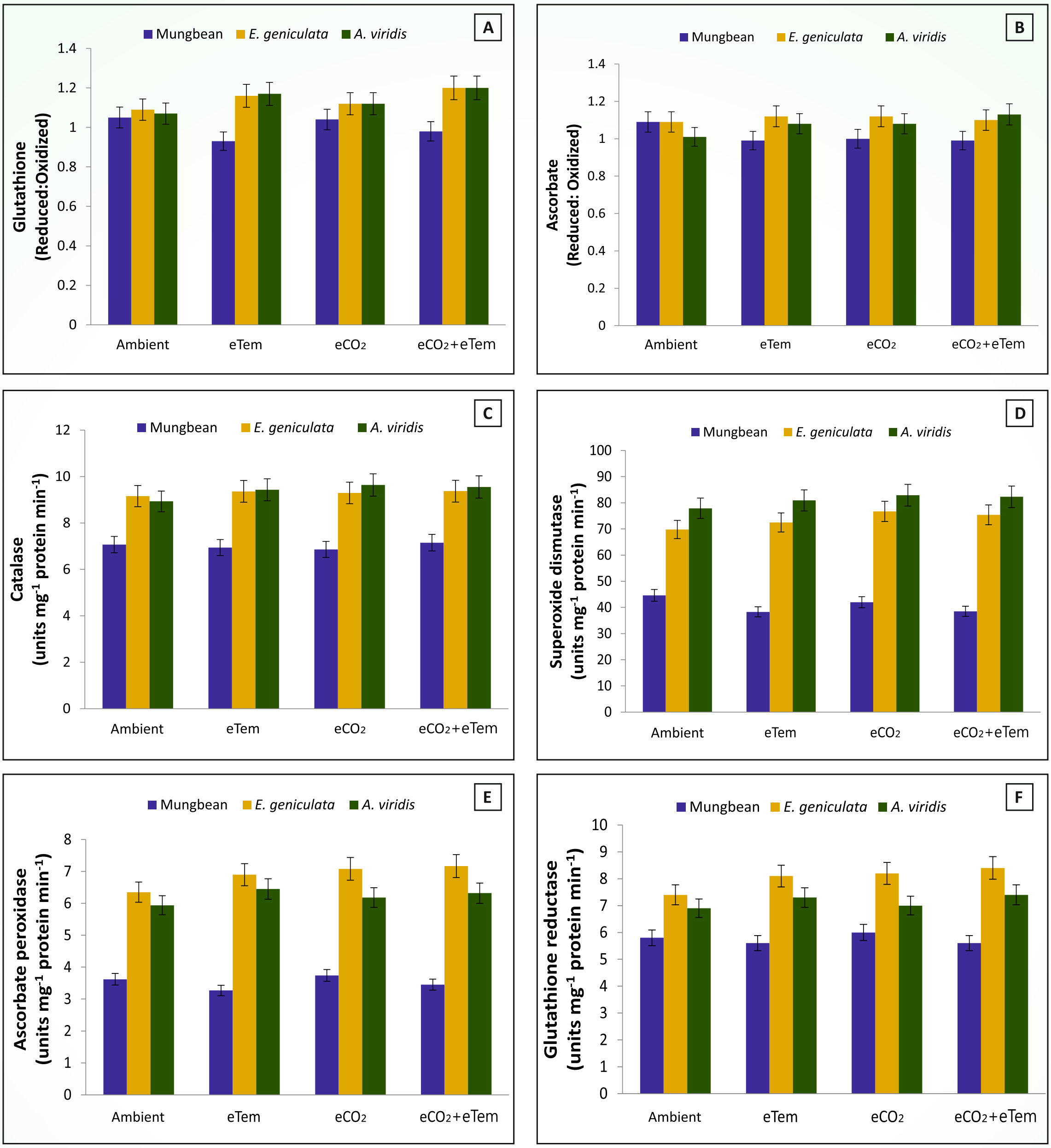


Figure 5.2. Effect of elevated CO_2 and temperature on redox homeostasis and enzymes involved in antioxidant defense pathway in mungbean.

d. Impact of drought stress on crop-weed interaction in mungbean *Trianthema portulacastrum* and *Echinochloa colona*

An experiment was conducted in the summer 2022 to study the impact of drought stress on crop-weed interaction using mungbean along with its major weeds, *Trianthema* *portulcastrum* L. and *Echinochloa colona* L. (Link). The findings of the study revealed that the rate of photosynthesis, stomatal conductance and rate of transpiration were adversely affected by drought stress (Table 1; Fig. 6.A-C). It was noticed that gaseous exchange parameters in mungbean was severely affected in the presence of *E. colona* in comparison to *T. portulacastrum*. The *E. colona* showed a detrimental impact on yield and yield attributes of mungbean in contrast to *T. portuclastrum*. Hence, it can be concluded that the *E. colona* will become a major problematic weed in the futuristic climate change scenario.

Table 1. Impact of drought and weeds on mungbean leaf gaseous exchange parameters

Treatment	**Photosynthetic rate (P_N-µmol CO_2 m^{-2} sec^{-1}) Mean± SE**	**Stomatal conductance (gs-mmol m^{-2} sec^{-1}) Mean± SE**	**Transpiration rate (E-mmol H_2O m^{-2} sec^{-1}) Mean± SE**
Weed free mungbean (Control)	33.56±1.10a	0.123±0.003a	7.25±0.13a
Weed free mungbean (Drought)	28.02±1.10b	0.016±0.003b	2.33±0.19c
Mungbean + *T. portulacastrum* (Control)	32.96±0.45a	0.120±0.005a	4.87±0.15b
Mungbean + *T. portulacastrum* (Drought)	24.48±0.73bc	0.008±0.001b	2.19±0.17c
Mungbean + *E. colona* (Control)	23.20±1.88bc	0.010±0.004b	1.56±0.15d
Mungbean + *E. colona* (Drought)	15.96±2.55d	0.006±0.002b	1.02±0.13e

Figure 6. (A) Weed free mungbean; (B) mungbean + *E. colona* (C) mungbean + *T. portulacastrum*

III. Chickpea

a. Effect of elevated CO_2 on physiological, biochemical and molecular aspects in chickpea and their associated weeds (*Phalaris minor*, *Medicago denticulata*, *Chenopodium album* L. and *Lathyrus aphaca*)

A study on the effect of eCO_2 (550 ± 50 ppm) on growth and development, physiological and biochemical aspects of chickpea and its associated weed species (*P. minor*, *M. denticulata*, *C. album* and *L. aphaca*) was conducted in FACE facility (DWR, 2010-11). The results showed that at both sampling stages, i.e., 21 and 42 DAT, the eCO_2 environment boosted the growth of chickpea plants and weed species. In chickpea and weed species, there was a general improvement in plant development at eCO_2, as seen by more branching and increased biomass output. Due to its propensity to spread out and impede the growth of nearby plants, *L. aphaca* appeared more vigorous at eCO_2 than other weed species. *L. aphaca* showed higher RGR at eCO_2 than chickpea and other weed species. *L. aphaca* can readily dominate the chickpea due to the high RGR at eCO_2 and may be detrimental to chickpea growth due to the greater growth rate at eCO_2 (Fig. 7.1).

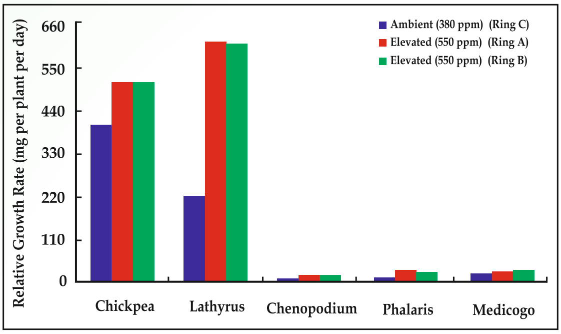


Figure 7.1. Effect of eCO_2 on RGR of chickpea and its associated weeds at 42 DAT

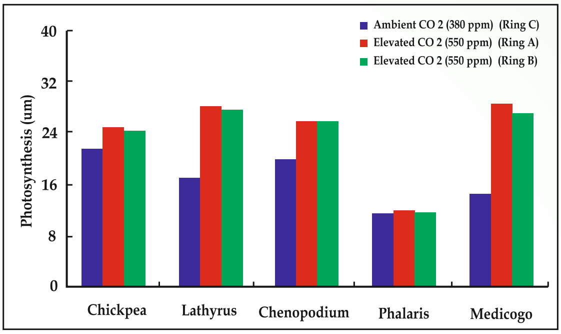


Figure 7.2. Effect of eCO_2 on the rate of photosynthesis in chickpea and its associated weeds at 21 DAT

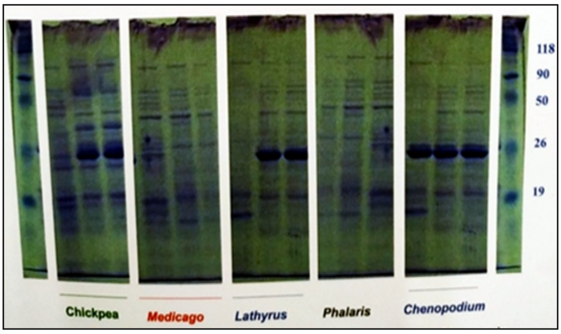


Figure 7.3. Effect of eCO_2 on protein profile (SDS-PAGE) of leaves in chickpea and associated weeds at 21 DAT

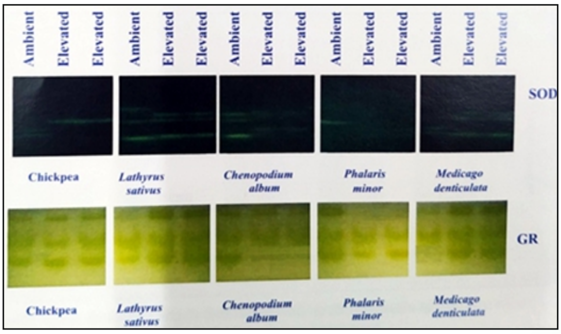


Figure 7.4. Effect of eCO_2 on isoenzyme pattern of GR in chickpea and its associated weeds at 21 DAT

Under eCO_2, chickpea and all weed species showed an increase in photosynthetic rate and water use efficiency (Fig. 7.2). In contrast, all of the species stomatal conductance and transpiration rate reduced at eCO_2 compared to ambient. The rapid growth of *L. aphaca* at eCO_2 can be attributed, "at least in part," to its capacity to sustain high transpiration and transpiration cooling compared to chickpea at eTem under eCO_2. However, because it depletes the available resources, this weed species capabilities could threaten agricultural species like chickpea. In this case, crop-weed interactions will be altered under a high CO_2 atmosphere in favor of weeds. *L. aphaca* had the highest carbonic anhydrase enzyme activity among all the species, suggesting that it can adapt to climate change.

Differential regulation of a 26 kDa peptide (SDS-PAGE band) was seen depending on the kind of plant and the level of CO_2 (Fig. 7.3). eCO_2 concentration increased the amount of the peptide (26kDa) in chickpea and *L. aphaca* compared to ambient CO_2. Other weed species, however, did not exhibit such a response. Differential regulation of different isoenzymes (Native PAGE) of superoxide dismutase (SOD) and glutathione reductase (GR) was noticed among species at eCO_2. Among all the weed species, *L. aphaca* demonstrated a more potent antioxidant system in SOD and GR. In contrast, down-regulation of the isoenzymes of SOD and GR was observed in *C. album* and *P. minor*. According to the findings, the antioxidant defense system may be activated in response to eCO_2. The transcript profile of the antioxidant defense system's genes in chickpea showed that many genes were differentially regulated at eCO_2, suggesting that the antioxidant defense system may play a function in an environment with high CO_2 levels (Fig. 7.4).

b. Effect of elevated CO_2 on physiological, biochemical and molecular aspects in chickpea and dominant weed species (*Medicago denticulata* and *Lathyrus aphaca*)

The effect of eCO_2 (550± 50 ppm) on chickpea (*cv.* JG-16) and weed species (*L. aphaca* and *M. denticulata*) was studied in OTCs (DWR, 2013-14). eCO_2 positively affected the overall growth of chickpea plants and weed species (*L. aphaca* and *M. denticulata*). RGR for chickpea, *L. aphaca*, and *M. denticulata* at ambient was determined as 249, 448, and 126 mg dry weight/plant/day, respectively. When plants were exposed to eCO_2, the rate of photosynthesis increased in all three species. At 21 DAT, eCO_2 treatment boosted photosynthesis in chickpea, *L. aphaca*, and *M. denticulata* by 17.5, 15.0, and 18.2%, respectively; at 42 DAT, the increases were 8.3, 12.3, and 17.8%, respectively. On the other hand, regardless of the sample stages, a decrease in stomatal conductance was seen in all three species. Stomatal conductance was lowered by eCO_2 treatment in chickpea, *L. aphaca*, and *M. denticulata* at 21 DAT by 18.2, 19.4, and 18.9%, respectively, while by 42 DAT it was reduced by 16.5, 16.2, and 17.1%, respectively. Similarly, regardless of the sampling stage, the transpiration rate decreased in chickpea, *L. aphaca*, and *M. denticulata* at eCO_2 compared to that at ambient CO_2. At 21 DAT, eCO_2 exposure led a decrease in transpiration by 16.6, 13.8 and 12.0% in chickpea, *L. aphaca* and *M. denticulata*, respectively. In contrast, at 42 DAT, the reduction in chickpea, *L. aphaca*, and *M. denticulata*, respectively, was 8.8, 9.8, and 9.8% compared to ambient CO_2. In general, exposure to eCO_2 caused all three species' reproductive stages to accelerate by 10 days (Table 2).

In all three species, eCO_2 had a favorable impact on carbonic anhydrase activity. However, weed species showed a greater increase in carbonic anhydrase activity at eCO_2 than chickpea. It may contribute to the increased nitrate reductase rates in all three species when plants were exposed to eCO_2. At 21 DAT, exposure to eCO_2 increased the nitrate reductase activity in chickpea, *L. aphaca*, and *M. denticulata* by 6.6, 10.8, and 10.5%, respectively, while at 42 DAT, the increases were 5.3, 9.3, and 11.6%, respectively (Table 2).

Table 2. Effect of elevated CO_2 on net photosynthesis, stomatal conductance, transpiration, carbonic anhydrase and nitrate reductase of chickpea and its associated weeds (*L. aphaca* and *M. denticulata*) at 21 and 42 days after treatment.

Parameter	Crop/weed	Ambient		eCO_2	
		21 DAT	42 DAT	21 DAT	42 DAT
Photosynthetic rate (P_N-µmol CO_2 m^{-2} sec^{-1})	Chickpea	20.9	23.4	24.6	25.3
	L. aphaca	24.1	25.4	27.8	28.5
	M. denticulata	21.1	21.9	25.0	25.8
Stomatal conductance (gs-mmol m^{-2} sec^{-1})	Chickpea	335	356	274	298
	L. aphaca	367	377	296	316
	M. denticulata	366	352	297	295
Transpiration rate (E-mmol H_2O m^{-2} sec^{-1})	Chickpea	2.59	2.60	2.16	2.37
	L. aphaca	3.04	3.09	2.62	2.79
	M. denticulata	2.99	3.07	2.63	2.77
Carbonic anhydrase (WA units/mg protein)	Chickpea	6.48	6.40	7.33	7.75
	L. aphaca	7.22	7.25	8.66	9.23
	M. denticulata	6.85	6.83	8.03	8.05
Nitrate reductase (WA units/mg protein)	Chickpea	14.7	16.1	15.7	16.9
	L. aphaca	15.8	16.7	17.5	18.3
	M. denticulata	15.8	16.0	17.4	17.9

Isoenzymes activity profiles (native PAGE) of the antioxidant enzymes superoxide dismutase (SOD), guaiacol peroxidase (POX), and glutathione reductase (GR) show differential regulation as well as induction of novel isoforms in response to eCO_2 at 21 DAT (Fig. 8.1). Stronger antioxidant defense was seen in weed species, particularly *L. aphaca*, compared to chickpea, suggesting that an antioxidant defense system is involved in adaptation to climate change circumstances.

At eCO_2 the expression of genes involved in the antioxidant defense system was changed at 21 DAT, in chickpea (Fig. 8.2). DHAR showed down-regulation while *CAT2*, chloroplastic *CuZnSOD*, *APX1* and *APX2* and showed up-regulation at eCO_2. Cytoplasmic *CuZnSOD* transcript levels were markedly elevated, but GR remained unaltered. Differential regulation of antioxidant defense pathway genes suggested that these genes were engaged in CO_2 environment adaptability.

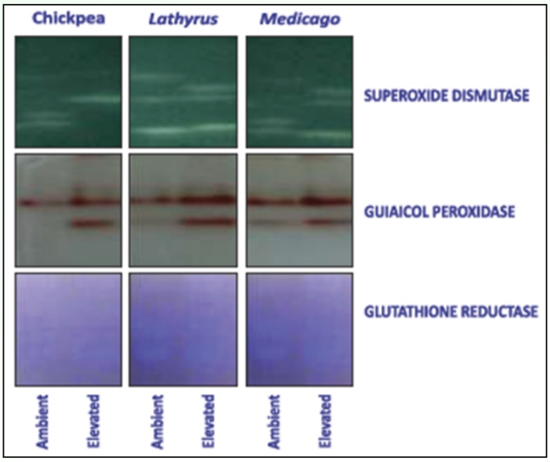


Figure 8.1. Effect of eCO_2 on isoenzymes of SOD, POX and GR in chickpea and its associated weeds (*L. aphaca* and *M. denticulata denticulata*) at 21 days after treatment.

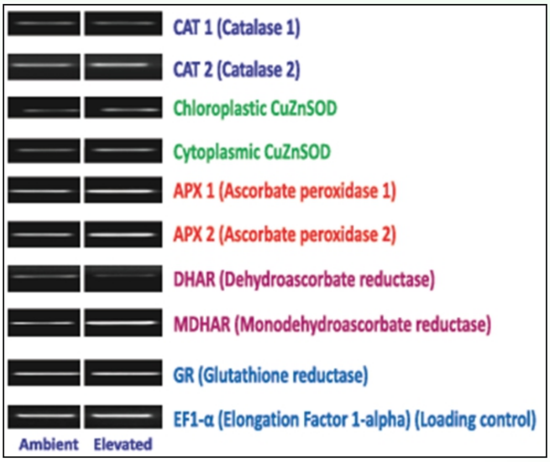


Figure 8.2. Effect of eCO_2 on transcript level of genes involved in antioxidant defence pathway in chickpea at 21 DAT.

IV. Wheat

a. Effect of elevated CO_2 and temperature on physiological, biochemical and molecular aspects in wheat and *Phalaris minor*

The effect of eCO_2 (550 ± 50 ppm) and eTem (ambient + 3.0 ±0.5° C) on wheat (GW-273) and weed (*P. minor*) was studied in OTCs (DWR, 2015-16). eTem alone or in combination with eCO_2 had a negative impact on the growth and development of wheat, but no such adverse effect was observed in the case of *P. minor* plants. The phenology (emergence of panicles) of wheat and *P. minor* was significantly influenced by high temperature, either alone or in combination with eCO_2. At both sampling stages, *P. minor* naturally show a higher rate of photosynthesis than wheat (30 and 60 DAT). Regardless of the growth stage or species, an increase in the rate of photosynthesis was noticed at eCO_2. However, at eTem, the rate of photosynthesis in wheat reduced; in contrast, no such decline was seen in *P. minor*. The detrimental effect on photosynthesis at eTem was confirmed by eCO_2 in combination with eTem. Regardless of the growth stage, eCO_2 reduced the stomatal conductance and rate of transpiration in wheat and *P. minor*. However, at eTem, the opposite was true in both species (Fig. 9).

Wheat grain yield was significantly lower (19.9%) than expected at eTem. However, at eCO_2, wheat grain yield increased by 18.6%. Only a 9.34% decrease in eCO_2 was enough to partially counter the negative impact of eTem on wheat grain production. Likely contributing to the observed grain yield reduction at eTem, test weight (1000-grain weight) was similarly lower when plants were exposed to either high temperature alone or in combination with eCO_2.

Wheat **_P. minor_**

Figure 9. Effect of eCO_2 and eTem on growth and development of wheat and *P. minor*

b. Effect of drought stress on crop-weed interaction in wheat, *Phalaris minor* and *Medicago denticulata*

An experiment on effect of drought stress on crop-weed interaction was conducted in *Rabi* 2021-22. Results indicated that *M. denticulata* interference reduced the RWC by 24.91% in wheat under drought compared to weed-free control. The MSI was significantly decreased by 30.02% with *M. denticulata* interference under drought compared to weed-free control. *M. denticulata* interference increased the proline content by 2-fold in wheat under drought compared to weed-free control (Fig. 10.A-D).

Compared to weed-free control, the total phenolic content was significantly increased by 2.85-fold with *M. denticulata* interference under drought. In wheat, protein content was significantly decreased by 53.74% with *M. denticulata* interference under drought compared to weed-free control. *M. denticulata* interference increased the total chlorophyll content by 56.55% in wheat under drought compared to weed-free control. *M. denticulata* severely impaired yield and yield attributes under drought stress (Table 4).

Table 4. Effect of drought stress and weeds on yield and yield attributes of wheat

Parameter	Plant height (cm)	Spike length (cm)	No. of seeds/spike	Yield/plant (g)	Plant dry weight (g)
WFC	79±1.05a	8.4±0.51a	30.40±0.51a	1.29±0.11a	1.29±0.11a
WFD	74.2±0.86b	6.9±1.10ab	27.16±0.75b	1.07±0.07ab	1.07±0.07ab
WPC	71.4±0.51c	5.4±0.40bc	24.20±0.58c	0.92±0.07bc	0.92±0.07bc
WPD	68.2±0.37d	4.9±0.10cd	21.00±1.14d	0.72±0.15cd	0.72±0.15cd
WMC	67.2±0.66d	4.4±0.24cd	18.20±0.97e	0.81±0.06bcd	0.81±0.06d
WMD	62.8±1.16e	3.5±0.16d	15.80±0.97e	0.55±0.04d	0.55±0.04e

WFC Weed free control; ***WFD*** Weed free drought; ***WPC*** Wheat, *P. minor*, control; **WPD** Wheat,*P. minor*, drought; ***WMC*** Wheat, *M. denticulata*, control; WMD Wheat, *M. denticulata*, drought.

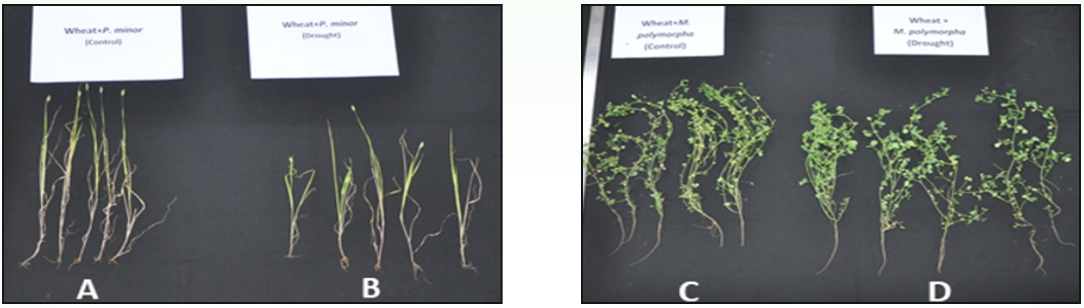


Figure 10. Impact of drought stress on **(A)** *P. minor* (Control); **(B)** *P. minor* (Drought); **(C)** *M. denticulata* (Control); *M. denticulata* (Drought) **(D)**

V. Rice and Weedy rice

Effect of elevated CO_2 and temperature on rice and weedy rice

a. Impact of elevated CO_2 on rice and weedy rice biotypes

The effect of eCO_2 (550 ± 50 ppm) on the growth of weedy rice was studied using OTCs (DWR, 2013-14). Two weedy rice accessions and cultivated rice were grown in the OTCs maintained at elevated and ambient CO_2 concentrations. Germination percent and germination index did not significantly differ amongst the lines tested (Fig. 11.1).

Total leaf area, the number of tillers per plant, net photosynthesis, and transpiration in the experiment's cultivated and weedy rice biotypes were all significantly impacted by eCO_2. Real-time PCR of ascorbate peroxidase reveals variations in expression levels amongst weedy rice and cultivated rice (Fig. 11.2). In weedy rice biotypes, the expression of APX is reduced. However, compared to ambient CO_2, they were higher in rice grown under eCO_2, indicating that this enzyme may be involved in adaptation to the eCO_2 environment.

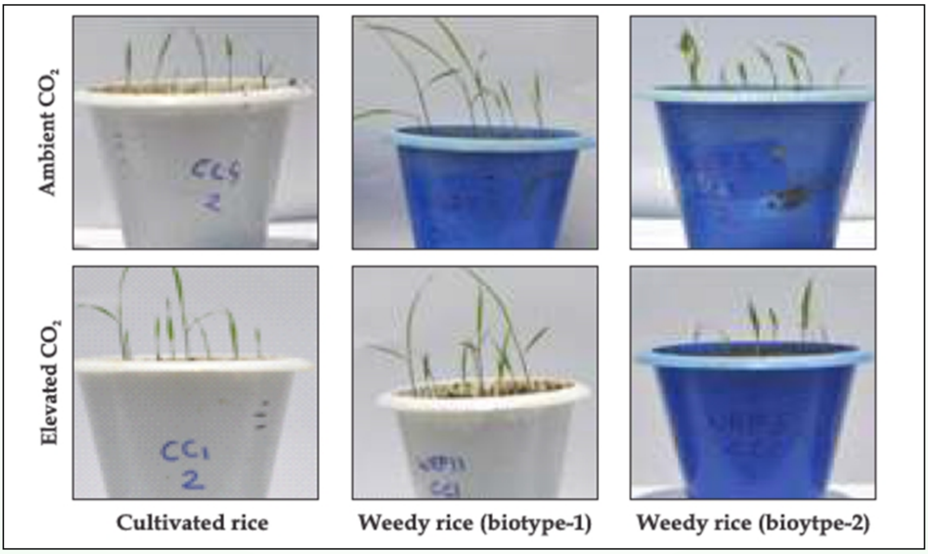


Figure 11.1. Effect of eCO_2 on germination of cultivated and weedy rice

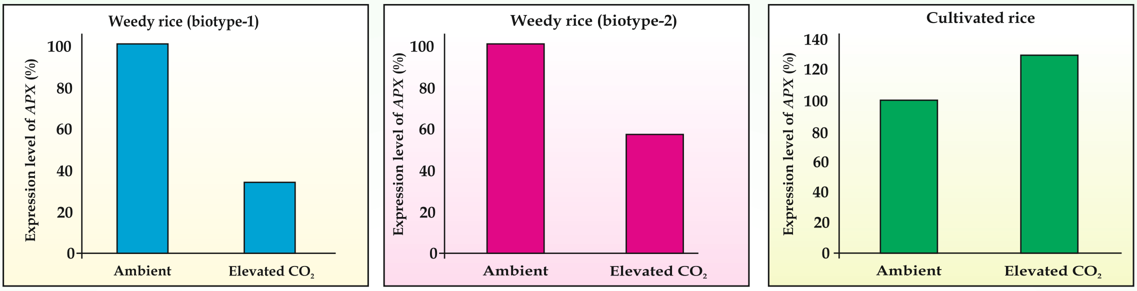


Figure 11.2. Variation in expression levels of ascorbate peroxidase (APX) in cultivated and weedy rice biotypes at eCO$_2$

b. Effect of elevated CO$_2$ and temperature on activity of soil enzymes in rhizosphere of rice, wild rice, weedy rice and *Echinochloa crusgalli*

A study on the influence of eCO$_2$ and temperature on soil enzyme activity was conducted in OTCs (DWR, 2014-15). The study revealed that whereas eTem caused a decrease in enzyme activity, exposure to eCO$_2$ boosted the activity of all three soil enzymes. *E. crusgalli* had a positive response towards eCO$_2$ and eTem among the examined plant species. *Echinochloa crus-galli* was found to have a greater Fluorescein diacetate (FDA) hydrolysis rate at eCO$_2$ alone and when combined with eTem, which is a sign of overall microbial activity. In *E. crus-galli*, eCO$_2$ had the highest dehydrogenase activity, which was followed by eCO$_2$ and eTem. eCO$_2$ induced significantly higher activity of urease in soil collected from the rhizosphere of *E. crus-galli*, followed by cultivated rice. Overall, it can be concluded that when exposed to eCO$_2$ alone or in combination with eTem, *E. crus-galli* responded well to all three soil enzymes (Table 5).

Table 5. Effect of elevated CO$_2$ and temperature on the activity of soil enzymes

Activity of soil enzymes	**Crop/weed**	**Treatments**			
		Ambient	**Elevated CO$_2$**	**Elevated temperature**	**Elevated CO$_2$+ Elevated temperature**
Fluorescein diacetate (FDA) hydrolysis rate (µg fluorescein/ g soil/ h)	Weedy rice	9.6^{ef}	12.3^{d}	6.5^{g}	12.8^{d}
	Wild rice	8.9^{efg}	15.6^{c}	9.6^{ef}	18.2^{ab}
	Cultivated rice	7.6^{fg}	11.2^{de}	8.7^{efg}	16.4^{bc}
	E. crus-galli	8.7^{efg}	18.5^{ab}	6.9^{g}	19.7^{a}
Dehydrogenase (µg TPF/g soil/24 h)	Weedy rice	26.5^{be}	28.6^{bc}	25.8^{ef}	22.3^{dg}
	Wild rice	27.6^{bcd}	29.8^{bc}	20.6^{efg}	18.9^{g}
	Cultivated rice	18.9^{g}	19.5^{g}	22.3^{dg}	16.9^{g}
	E. crus-galli	32.4^{b}	39.8^{a}	18.9^{g}	34.8^{b}
Urease (µg NH_4/g soil/24 h)	Weedy rice	39.1^{abc}	39.8^{abc}	23.6^{e}	34.6^{bcd}
	Wild rice	33.9^{bcd}	36.9^{ad}	29.8^{de}	29.5^{de}
	Cultivated rice	36.5^{bcd}	42.9^{ab}	32.8^{cd}	28.9^{de}
	E. crus-galli	36.5^{bcd}	45.6^{a}	33.6^{cd}	35.5^{bcd}

Values represent mean of three replications, values followed by same letter in a row are not significantly different from each other as analyzed by DMRT (p=0.05)

c. Effect of elevated CO$_2$ and temperature on rice, wild rice and weedy rice

eCO$_2$ (550 ± 50 ppm) and eTem (ambient + 3.0 ±0.5^{o} C) on rice, wild rice, and weedy rice were studied in OTCs (DWR, 2015-16). The findings showed that, at 75 DAS, cultivated rice and weedy rice roots were shorter under eCO$_2$, eTem, and a combination of eCO$_2$ and eTem than ambient. On the other hand, wild rice showed an increase in root length at both eCO$_2$ alone and in combination with eTem. Similarly, sufficient tillers at 120 DAS reduced rice under both eCO$_2$ and eTem combined conditions. In contrast to ambient and other treatments, the number of tillers in wild rice declined at eTem. Results indicated that, wild rice may outcompete both cultivated and weedy rice under changing climatic conditions (eCO$_2$+ eTem), as shown by its numerous effective tillers and long roots.

d. Effect of elevated CO$_2$ and temperature on rice and its associated weeds (*Alternanthera paronychioides* and *Leptochloa chinensis*)

A study was conducted using rice and its major weeds *A. paronychioides* and *L. chinensis* in OTCs to assess the impact of eCO$_2$ (550±50), eTem (Ambient + 2^{o} C) and eCO$_2$+eTem on crop weed interaction (DWR, 2020). The response of rice and two weed species was different to eCO$_2$ and eTem in terms of growth and yield response. In *L. chinensis*, increased plant height, i.e., 11.46%, 20.39% and 25.82%, was recorded at both eCO$_2$, eTem and eCO$_2$+ eTem, respectively, as compared with ambient. eCO$_2$ levels significantly improved the plant height (27.08%) of *A. paronychioides* compared to ambient and eTem. However, an increase in plant height (16.27%) was noticed in rice under eCO$_2$ compared to ambient (Fig. 12.1). Compared with the ambient condition, the leaf area (30.97%, 61.81%) of *A. paronychioides* was significantly enhanced under eCO$_2$ and eCO$_2$+ eTem, respectively. eTem remarkably enhanced the leaf area (108.23%) of *L. chinensis* compared with ambient. eCO$_2$ levels slightly improved the leaf area of rice (Fig. 12.2).

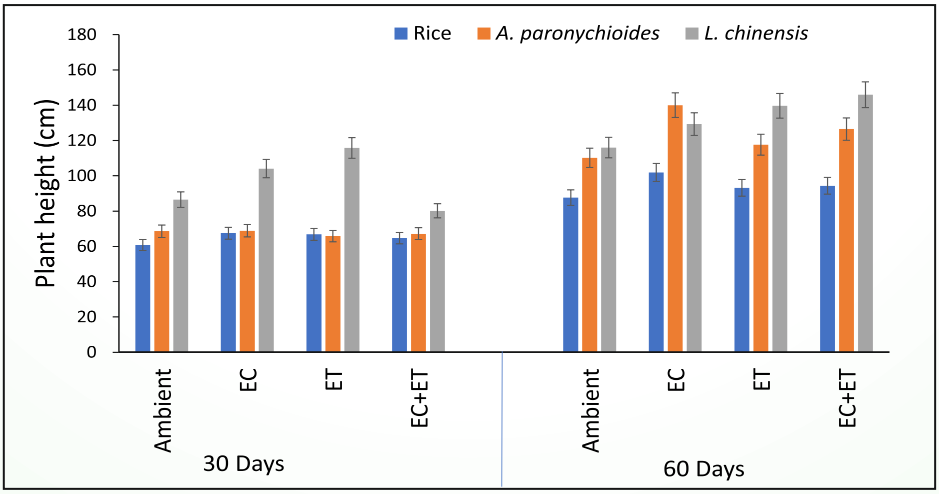


Figure 12.1: Effect of elevated CO$_2$ and temperature on plant height of rice, *Alternanthera paronychioides* and *Leptochloa chinensis;* EC: Elevated CO$_2$, ET: Elevated Temperature

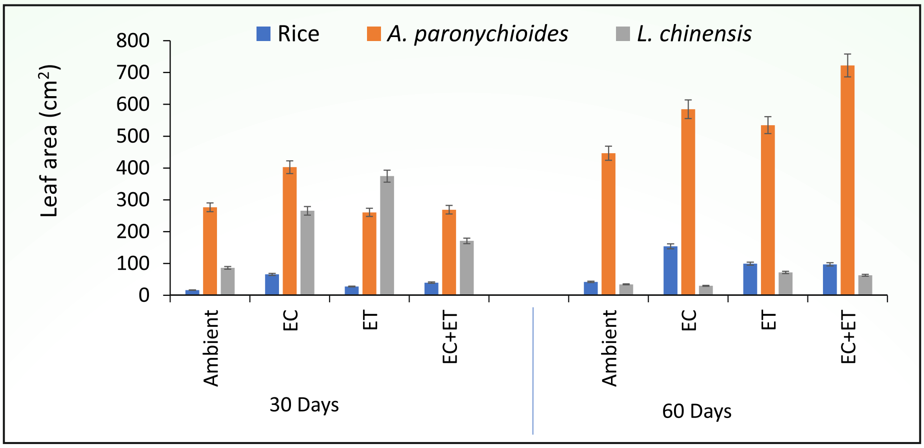


Figure 12.2: Effect of eCO_2 and eTem on leaf area of rice, *A. paronychioides* and *L. chinensis;* EC: Elevated CO_2, ET: Elevated Temperature

Impact of drought stress crop-weed interaction on rice and its major weeds *Alternanthera paronychioides* and *Echinochloa colona*

An experiment on the effect of drought stress on crop-weed interaction using rice along with its major weeds *A. paronychioides* and *E. colona* was conducted in *Kharif*-2022. To examine the impact of drought and weed species on rice leaf gaseous exchange parameters were analyzed at the crop anthesis stage. Results from the study revealed that *A. paronychioides* interference had an adverse effect on leaf gaseous exchange indices. The rate of photosynthesis was significantly reduced by 54.08% compared to weed-free control (Table 6). In summary, the effect of weeds under more in comparison to control. The findings revealed that the effect of *A. paronychioides* is more compared to *E. colona*. The impact of drought on weeds and the rate of photosynthesis was non-significant (Table 7).

Table 6. Impact of drought, *A. paronychioides*, *E. colona* on leaf gaseous exchange parameters of rice

Treatment	Photosynthetic rate (P_N-µmol CO_2 m^{-2} sec^{-1}) Mean± SE	Stomatal conductance (gs-mmol m^{-2} sec^{-1}) Mean± SE	Transpiration rate (E-mmol H_2O m^{-2} sec^{-1}) Mean± SE
Weed-free rice (Control)	21.30±0.89a	0.63±0.01a	9.37±0.19a
Weed-free rice (Drought)	14.60±0.44c	0.35±0.01b	5.60±0.58b
Rice+*A. paronychioides* (Control)	12.17±0.22ed	0.56±0.01c	7.83±0.28de
Rice+*A. paronychioides* (Drought)	9.78±0.53b	0.32±0.01d	4.13±0.06c
Rice+*E. colona* (Control)	9.01±0.36d	0.51±0.01ed	3.14±0.12d
Rice+*E. colona* (Drought)	7.35±0.33e	0.28±0.01e	2.25±0.14e

Table 7. Impact of drought, *A. paronychioides*, *E. colona* on leaf gaseous exchange parameters of rice

Treatment	**Photosynthetic rate (P_N-µmol CO_2 m^{-2} sec^{-1}) Mean± SE**	**Stomatal conductance (gs-mmol m^{-2} sec^{-1}) Mean± SE**	**Transpiration rate (E-mmol H_2O m^{-2} sec^{-1}) Mean± SE**
A. paronychioides **(Control)**	17.30±0.60a	0.063±0.01a	4.21±0.28b
A. paronychioides **(Drought)**	14.80±1.02a	0.019±0.01b	1.37±0.07b
E. colona **(Control)**	16.70±0.97a	0.019±0.01b	1.31±0.09b
E. colona **(Drought)**	15.97±1.23a	0.016±0.01b	1.20±0.04a

VI. Soybean

a. Effect of elevated CO_2 and temperature on soybean and associated weed species

Echinochloa colona* and *Ischaemum rugosum

The effect of eCO_2 (550±50 ppm), eTem (ambient + 2° C) and eCO_2+eTem on soybean crop and its major dominating two grassy weeds (*E. colona, I. rugosum*) were studied in OTCs (DWR, 2018-19). Plant height, dry matter accumulation, and soybean seed yield were all positively impacted by eCO_2 and eTem (Fig. 13.1 & 13.2). Similar to eCO_2, eTem positively impacted growth compared to ambient conditions. At eTem, soybean plant height was higher than at the ambient but at par with eCO_2. However, compared to ambient, its dry weight was 29% greater in eCO_2+eTem. At 90 DAS, the plants growth was comparable in eCO_2 and eCO_2+eTem. In contrast, greater growth was observed with eCO_2 than eCO_2+eTem. Soybean seed yield was 21, 18, and 15% greater in eCO_2+eTem, eCO_2, and eTem conditions, respectively, than in ambient (Fig. 13.3.)

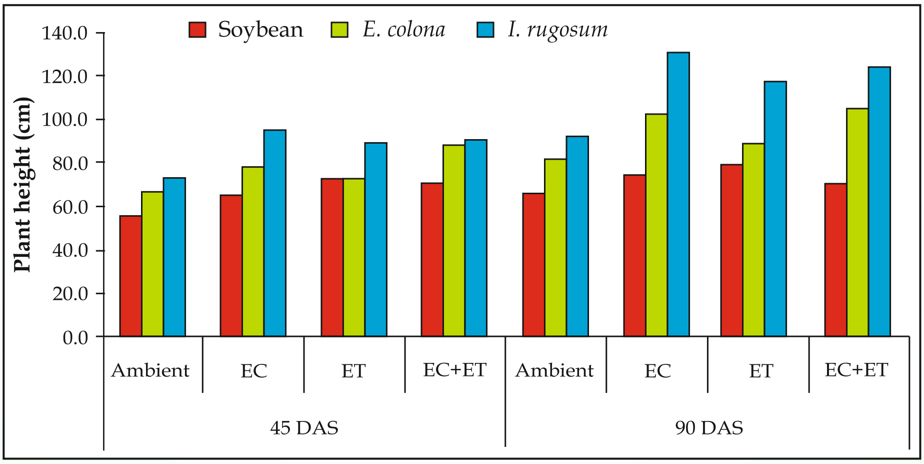
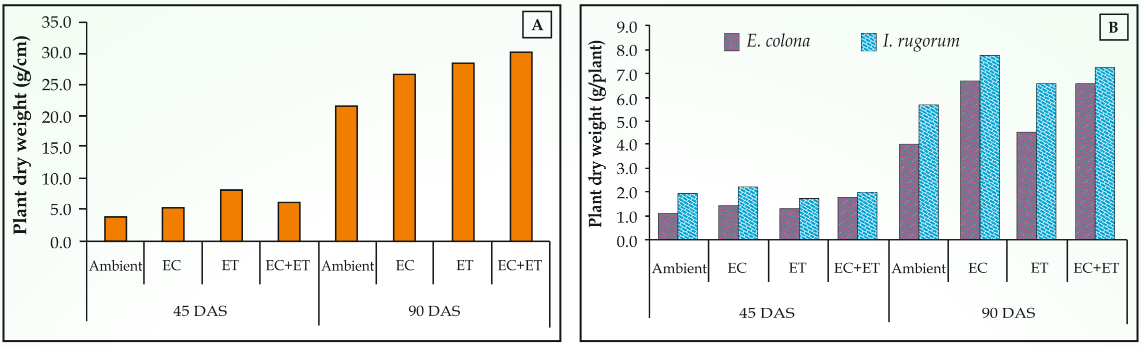


Figure 13.1. Effect of eCO_2 and temperature on plant height of soybean, *E. colona* and *I. rugosum*. EC-Elevated CO_2, ET-Elevated temperature



(EC-Elevated CO_2, ET-Elevated temperature)

Figure 13.2. Effect of eCO_2 and temperature on plant dry weight of soybean **(A)**, *E. colona* and *I. rugosum* **(B)**

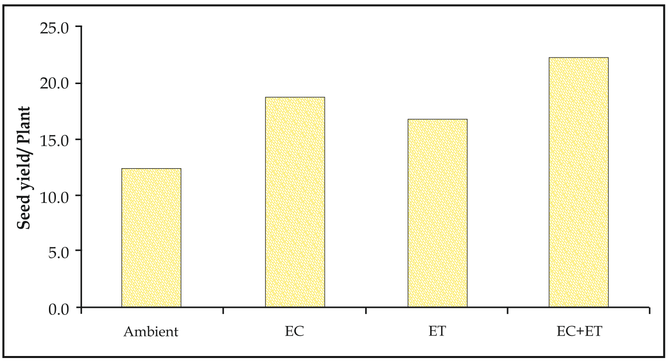


Figure 13.3. Effect of eCO_2 and temperature on seed yield of soybean.
EC-Elevated CO_2, ET-Elevated temperature

VII. *Parthenium hysterophorus* and *Amaranthus viridis*

Growth and Biomass partitioning in two weed species, *Parthenium hysterophorus* L. and *Amaranthus viridis* L. under elevated CO_2

An experiment on the growth response of *P. hysterophorus* and *A. viridis* to eCO_2 (550 ppm) an experiment was conducted in OTCs (DWR, 2006-07). The eCO_2 enhanced the growth and biomass production of both weed species. In *P. hysterophorus*, the plant height increased by more than 100% at eCO_2, and there were more primary branches and leaves. The leaf area increased by 49% even though the number of leaves was 291% more than that of ambient (360 ppm). This resulted from the branches under eCO_2 producing smaller leaves (Fig.14.1 & 14.2). In addition, it was observed that the abundant branching at the top portion and the robust growth of the taproot caused the root length to expand by 56% and the root biomass to by 700%. Under conditions of ambient CO_2, almost 87% of the biomass was divided between the stem (44%) and leaves (43%), while the remaining 13% was nearly equally divided between the root and flowers. Contrarily, under eCO_2, 71% of the biomass accumulated in the stem, with the remaining amounts found in the leaves (12%), flowers (9.4%), and roots (7.6%).

In the case of *A. viridis*, the growth acceleration under eCO_2 started after 60 DAS and persisted until the end. This results from increased biomass output under eCO_2, mainly attributable to abundant branching and the development of numerous leaves and flower heads. Under eCO_2, most of the biomass (93%) accumulated in the stem and inflorescence. The tremendous growth response of *A. viridis* is in contrast to the generalized opinion that C_4 plants show little response to CO_2 enrichment (14.3 & 14.4).

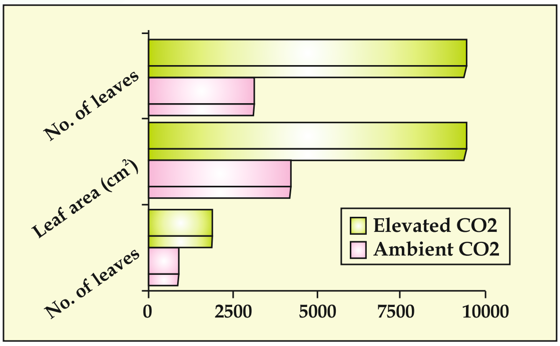


Figure 14.1. Leaf and flower production in *P. hysterophorus* under ambient and eCO_2

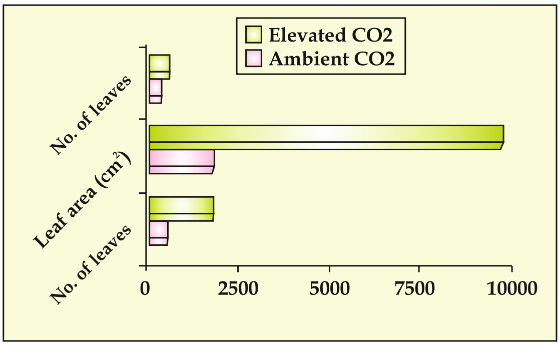


Figure 14. 2. Leaf and flower production in *A. viridis* under ambient and eCO_2

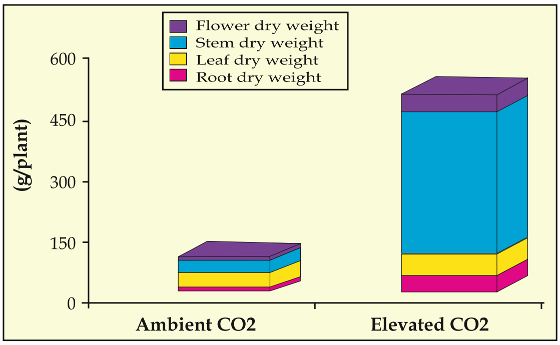


Figure 14. 3. Biomass partition in *P. hysterophorus* under ambient and eCO_2

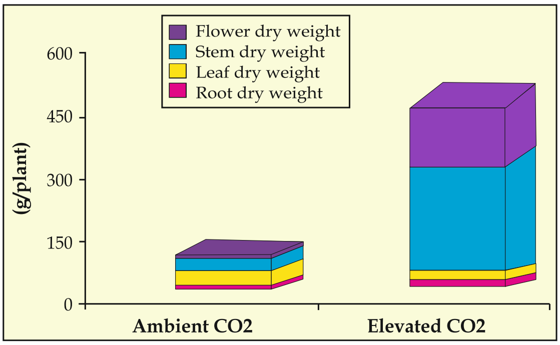


Figure 14. 4. Biomass partition in *A. viridis* under ambient and eCO_2

VIII. *Physalis peruviana* and *Physalis minima*

a. Effect of elevated CO_2 and temperature on *Physalis peruviana* and *Physalis minima*

The effect of eCO_2 (550 ± 50 ppm) and eTem (ambient + $2.0 \pm 0.5^{\circ}$ C) on *P. peruviana* and its weedy counterpart *P. minima* was studied in OTCs (DWR, 2016-17). Inherently, *P. peruviana* demonstrated more growth than *P. minima.* At 60 DAT, growth and development parameters (i.e., dry weight of shoot and root, dry matter of entire plant, leaf area, and relative growth rate) under eTem indicated a slight increase compared to plants grown under ambient. However, whether plants were cultivated under eCO_2 alone or in combination with eTem, a notable rise in these parameters was seen. In both species, photosynthesis occurred at a faster rate than ambient under all of the treatments. Different treatments had different effects on the activity of the antioxidant defense enzymes (SOD, GR, catalase, guaiacol peroxidase, and APX). In both ambient and changed climate circumstances, *P. peruviana* showed higher SOD, APX, and GR activity than *P. minima*.

b. Effect of elevated CO_2 and temperature on peptide profile (SDS-PAGE) in *Physalis peruviana* and *Physalis minima*

Changes in peptide profile were studied using SDS-PAGE in the leaves of two *Physalis* species (*P. minima* and *P. peruviana*) grown under ambient, eTem, eCO_2 and eTem +eCO_2 at 30 DAT (DWR, 2017-18). In *P. minima*, a maximum of 16 bands could be resolved, whereas a maximum of 18 bands could be resolved in *P. peruviana*. Two peptides (9th and 14th bands from top) in *P. minima* leaves showed differential expression in response to various treatments. The ninth band from the top appeared only at eCO_2 and eTem + eCO_2. On the other hand, band number 14 from top appeared only at eTem + eCO_2. In the leaves of *P. peruviana*, four peptides (6th, 10th, 14th and 16th bands from top) are expressed differentially in plants grown under different treatments. The sixth band from the top was present at eTem and under control conditions but was absent throughout subsequent treatments. The uppermost band, number 10, only appeared at eCO_2 and eTem + eCO_2.

Contrarily, band number 16 from the top was present only at eTem and eTem+ eCO_2. Based on the peptide pattern that emerged from the two *Physalis* species, it may be inferred that band number 9 in *P. minima* and band number 10 in *P. peruviana* appeared only at eCO_2 individually or in combination with eTem. In contrast, bands 14 and 16 in *P. peruviana* and *P. minima* may be unique eTem. *P. peruviana* band 6 appears species-specific and didn't exist in *P. minima* (Fig. 15).

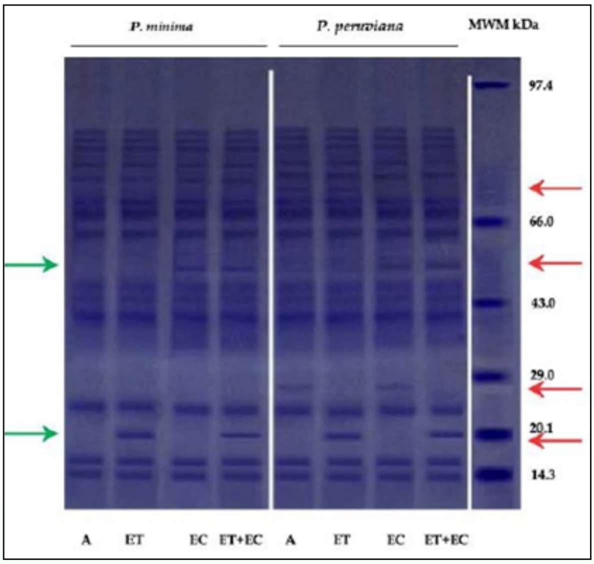


Figure 15. Effect of eTem and eCO_2 on pepetide profile (SDS-PAGE) in *P. peruviana* and *P. minima.*

3. Herbicide efficacy

a. Effect of elevated CO_2 on the efficacy of different herbicides (glyphosate, isoproturon, clodinafop, 2,4-D and sulfosulfuron)

The efficacy of different post-emergence herbicides against selected weeds was evaluated under ambient (360 ppm) and eCO_2 (550 ppm) conditions (DWR, 2006-07). The eCO_2 reduced the herbicides' efficacy and prolonged the weeds' mortality time (Table 8). Under eCO_2, there was a wide range of efficacy among the herbicides. The impact of eCO_2 on the efficacy was more on isoproturon (mortality was delayed by 9 days) followed by clodinafop (7 days), 2,4-D (5 days) and glyphosate (3 days) compared to ambient. Under both circumstances, sulfosulfuron's efficacy was greatly diminished, and *L. aphaca* was only partially controlled (Fig. 16).

Table 8. Effect of elevated CO_2 on the efficacy of different herbicides

Weed species	Herbicide	Dose (Kg/ ha)	No. of days taken for complete mortality		Mortality delayed by (Days)
			Ambient	eCO_2	
C. album	Glyphosate	2.0	7	10	3
P. minor	Isoproturon	1.5	6	15	9
A. fatua	Clodinafop	0.06	8	15	7
A. viridis	2,4-D	0.5	8	13	5
L. aphaca	Sulfosulfuron	0.03	No visible mortality symptoms		

Figure 16. Effect of clodinafop on the mortality of wild oat under ambient and elevated CO_2

b. Effect of elevated CO_2 and temperature on efficacy of sulfosulfuron against *P. minor*

The efficacy of sulfosulfuron was evaluated against *P. minor* in OTCs. *P. minor* seeds were sown in pots and kept in OTCs under ambient, eCO_2 (550 ± 50 ppm), eTem (ambient + 3.0 ±0.5° C), and eCO_2+ eTem (DWR, 2015-16). Under ambient conditions, sulfosulfuron completely (100%) controlled *P. minor*. However, only 60% and 40% of *P. minor* population were controlled under eTem alone and eCO_2+ eTem, respectively. Despite growth limitation, both treatments resulted in viable seed production from the surviving plants (eTem, eCO$_2$+eTem). The findings suggest that anticipated climatic changes (eTem and eCO$_2$) may impair sulfosulfuron efficacy, which could have a negative impact on weed management.

c. Efficacy of herbicides (bispyribac-Na, topramezone+atrazine and tembotrione+ atrazine) against target *Kharif* weeds under eCO$_2$ and eTem

Effect of eCO$_2$ (550±50), eTem (ambient + 2^{o} C) and eCO$_2$+eTem on the efficacy of different herbicides, *viz.*, bispyribac-Na, topramezone and tembotrione against *Dinebra retroflexa, E. colona, P. minima* and *A. sessilis* was studied in OTCs (DWR, 2019).

D. retroflexa, *E. colona*, *P. minima,* and *A. sessilis* responded differently to the herbicides bispyribac-Na, topramezone+atrazine, and tembotrione+atrazine (Table 9). Bispyribac-Na showed 2,5 and 8 days delayed effect aginst *E.colona* at eTem, eCO$_2$ and eCO$_2$+eTem, respectively (Fig. 17.1A). However, in *P. minima* 2 and 1 day, early response of this herbicide was noticed at eTem and eCO$_2$+eTem, respectively. A 5-day late response was observed at eCO$_2$ compared to ambient (Figure 17.1.B). Similarly, topramezone+ atrazine has a 4,7 and 1 days delayed effect on *D. retroflexa* at eTem, eCO$_{2,}$ and eCO$_2$+eTem, respectively, compared to ambient. However, under all circumstances, this herbicide's effectiveness was nearly equivalent on *E. colona* and *P. minima* (Fig. 17.2.A). Tembotrion + atrazine has 2,2 and 3 days delayed response on *D. retroflexa* at eTem, eCO$_2$ and eCO$_2$+eTem and almost similar efficacy of tembotrion + atrazine was observed on *E. colon* and *P. minima* at all condition (Fig. 17.2.B).

Table 9. Effect of elevated CO$_2$ and temperature on herbicide efficacy against *kharif* weeds

Herbicide	Weed	Treatments						
		Ambient	Elevated CO$_2$		Elevated temperature		Elevated CO$_2$+ Elevated temperature	
		DTTD	DTTD	DDE	DTTD	DDE	DTTD	DDE
Bispyribac sodium	*D. retroflexa*	-	-	-	-	-	-	-
	E. colona	12	14	+2	17	+5	20	+8
	P. minima	16	14	-2	21	+5	15	+1
	A. sessilis	10	15	+5	2	+2	16	+6
Tembotrion+ atrazin	*D. retroflexa*	11	15	+4	18	+7	12	+1
	E. colona	5	4	-1	5	0	4	-1
	P. minima	5	4	-1	5	0	4	-1
	A. sessilis	10	10	0	7	-3	7	-3
Tp[ramezone+ atrazine	*D. retroflexa*	11	13	+2	13	+2	14	+3
	E. colona	5	5	0	5	0	4	-1
	P. minima	5	5	0	5	0	4	-1
	A. sessilis	6	8	+2	10	+4	7	+1

DTTD: Days taken to total death of the plant; DDE: Days delay (+) or early response (-)

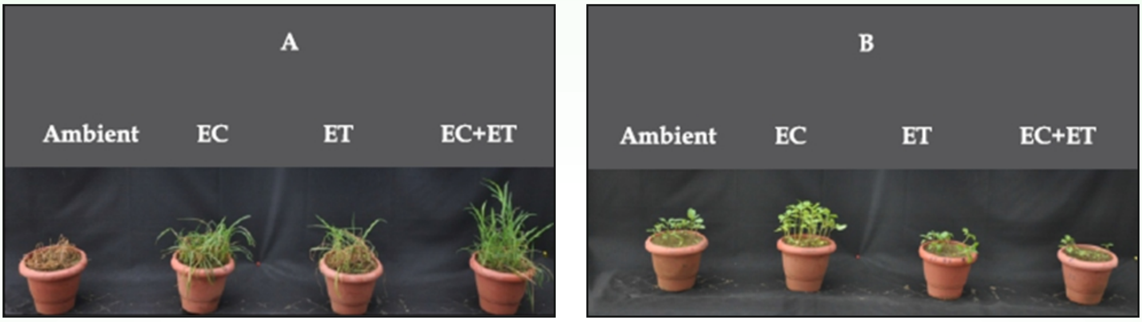


Figure 17.1. Effect of eCO_2 and eTem on the efficacy of bispyribac-Na against *E. colona* (A) and *P. minima* (B)

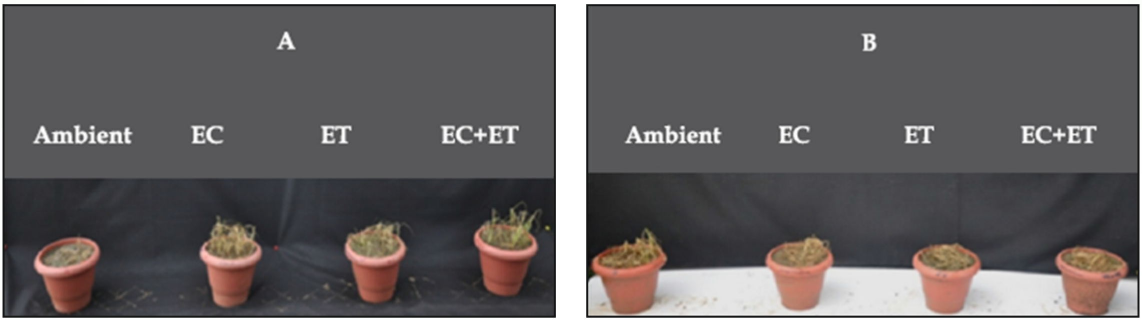


Figure 17.2. Effect of eCO_2 and eTem on the efficacy of topramezone + atrazine against *D. retroflexa* **(A)** and *E. colona* **(B)**

d. Effect of elevated CO_2 on efficacy of 2,4-D in rice

An experiment was conducted during *Kharif*-2021 to study the crop-weed interaction and efficacy of 2,4-D against *A. paronychioides* in rice under eCO_2 (550±50 ppm) in the FACE facility (DWR, 2021). The results indicated that the efficacy of herbicide was significantly reduced under eCO_2, resulting in higher growth and biomass of *A. paronychioides* when compared to ambient CO_2 level.

The growth and biomass of *A. paronychioides* attributes were significantly enhanced, i.e., plant height (99.33%), fresh weight (1.7fold) and dry weight (2.7fold) in the herbicide-treated region under eCO_2 compared to ambient (Fig. 18.2&4). However, in untreated herbicide region the growth and biomass of *A. paronychioides* were remarkably enhanced in terms of plant height (4.93%), fresh weight (31.80fold) and dry weight (14.27%) under eCO_2 in compared to ambient. Under eCO_2 growth of the rice plants were severely impaired by in terms of plant height, fresh weight and dry weight. The growth and biomass of rice were maximum in weed-free regions, followed by herbicide-treated regions at eCO_2 (Fig. 18.1&3).

The decrease in plant height, fresh weight and dry weight were recorded by 8.18%, 5.05% and 19.31% under eCO_2in herbicide untreated *A. paronychioides* region. In herbicide treated region, the plant height, fresh weight, and dry weight significantly decreased by 6.24%, 39.89% and 34.50% respectively under eCO_2compared to ambient .

However, a significant increase in plant growth was observed in weed free rice in terms of plant height (10.05%), fresh weight (18.15%) and dry weight (29.56%) was observed under elevated CO_2.

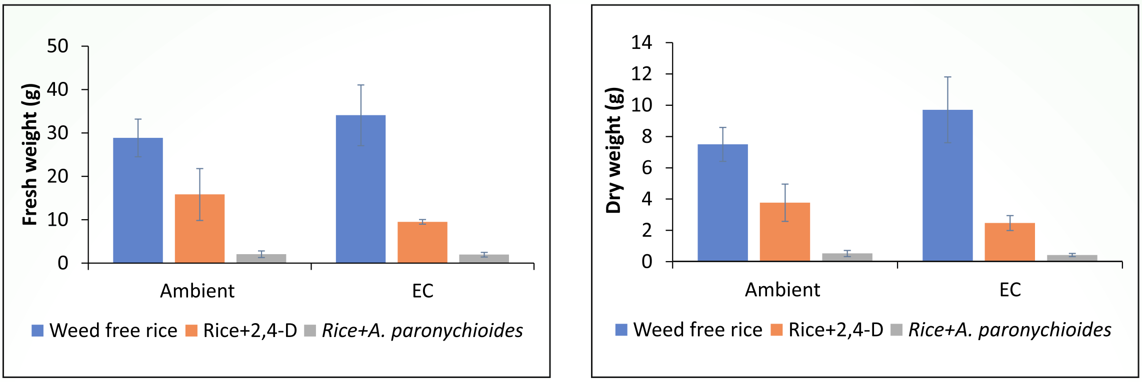
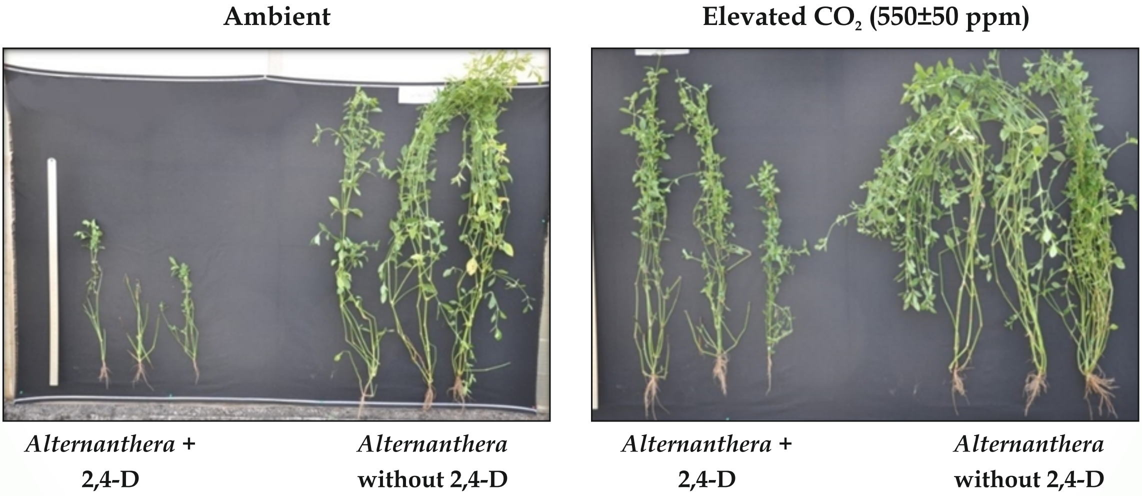


Figure 18.1. Effect of 2,4-D and *A. paronychioides* on rice under eCO_2


Ambient

Elevated CO_2 (550±50 ppm)

***Alternanthera* + 2,4-D**

***Alternanthera* without 2,4-D**

***Alternanthera* + 2,4-D**

***Alternanthera* without 2,4-D**

Figure 18.2. Effect of 2,4-D on *A. paronychioides* growth and biomass under eCO_2


Ambient

Elevated CO_2

Figure 18.3. Effect of *A. paronychioides* on rice growth and biomass under eCO_2

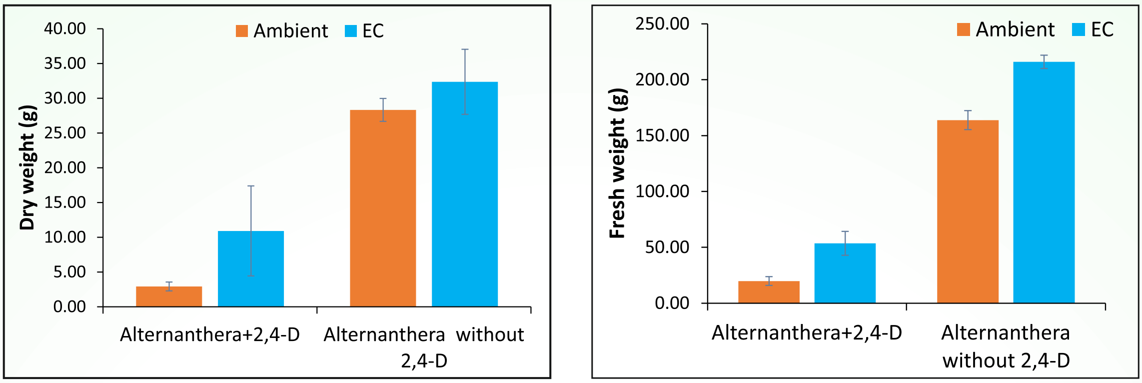


Figure 18.4. Effect of 2,4-D on *A. paronychioides*

e. Efficacy of herbicides against *Phalaris minor* and *Medicago polymorpha* under drought stress

An experiment was conducted on the effect of drought stress on herbicide efficacy [Clodinafop (60 g ai/ha)+ Metsulfuron (4 g ai/ha)] against *P. minor* and *M. polymorpha* in wheat during *Rabi* 2021-22. The findings of the study revealed that in weed-free wheat, the yield was significantly reduced by 33.94% under drought, compared to control. Effect of herbicide was reduced under drought compared to ambient. Weed interference altered the physiological parameters like RWC, MSI and Total chlorophyll content and was found to be lowered under drought. The content of phenol and proline was significantly by weed interference under drought. *M. polymorpha* will become a major problematic weed in a water scarcity environment (Fig. 19).

Figure 19. Effect of drought stress on herbicide efficacy

f. Impact of drought stress on herbicide efficacy in mungbean and its major weeds *Trianthema portulacastrum* and *Echinochloa colona*

Effect of drought on herbicide efficacy was carried out using imazethapyr against *E. colona* and *T. portulacastrum* in summer-2022. The results of the study indicated that the efficacy and effect of herbicide was lowered and delayed respectively under drought compared to control. This delay in herbicide efficacy further affected the physiological and biochemical indices of mungbean. Under drought stress interference of *E. colona* the rate of photosynthesis was significantly reduced by 78.37% compared to weed-free control (Table 10). This further resulted in a reduction in mungbean yield. In summary, the study revealed that the drought stress lowered the herbicide efficacy against *E. colona* compared to *T. portulcastrum*.

Table 10. Effect of drought and weeds on mungbean leaf gaseous exchange paramters

Treatment	Photosynthetic rate (P_N-µmol CO_2 m^{-2} sec^{-1}) Mean± SE	Stomatal conductance (gs-mmol m^{-2} sec^{-1}) Mean± SE	Transpiration rate (E-mmol H_2O m^{-2} sec^{-1}) Mean± SE
Weed free mungbean (Control)	23.90±1.64a	0.031±0.001a	2.54±0.08a
Weed free mungbean (Drought)	20.73±1.17	0.028±0.004a	2.32±0.29ab
Mungbean + *T. portulacastrum* (Control)	19.57±0.73bc	0.021±0.004abc	1.75±0.35abc
Mungbean + *T. portulacastrum*+ Herbicide (Control)	22.13±0.93ab	0.025±0.006ab	2.12±0.47ab
Mungbean + *T. portulacastrum* (Drought)	14.03±0.90de	0.010±0.009cd	0.81±0.72cd
Mungbean + *T. portulacastrum*+ Herbicide (Drought)	16.87±0.68cd	0.013±0.007bcd	1.13±0.55bcd
Mungbean + *E. colona* (Control)	13.63±1.88de	0.005±0.001d	0.47±0.13d
Mungbean + *E. colona*+ Herbicide (Control)	10.11±1.05ef	0.007±0.004cd	0.66±0.33cd
Mungbean + *E. colona* (Drought)	5.17±1.25g	0.004±0.003d	0.35±0.05d
Mungbean + *E. colona*+ Herbicide (Drought)	7.97±1.82	0.005±0.002d	0.39±0.28d

g. Impact of drought stress on herbicide efficacy in rice (*Alternanthera paronychioides* and *Echinochloa colona*)

A study on the impact of drought stress was conducted in *Kharif*-2022 using cyhalofop-butyl + penoxsulam against *E. colona* and *A. paronychioides*. The finding of the study revealed that efficacy of herbicide was delayed under drought stress against *A. paronychioides* and *E. colona*. This delay in herbicide efficacy certainly showed a detrimental effect on crop-weed interaction, rice physiological traits like gaseous exchange parameters, relative water content and membrane stability index, etc., ultimately reducing yield. In rice the rate of photosynthesis was adversely affected in the presence of *E. colona* under drought stress (Table 11). In summary, *E. colona* will become a major problematic weed in a futuristic water scarcity environment.

Table 11. Impact of drought, *A. paronychioides*, *E. colona* on leaf gaseous exchange parameters of rice

Treatment	**Photosynthetic rate (P_N-µmol CO_2 m^{-2} sec^{-1}) Mean± SE**	**Stomatal conductance (gs-mmol m^{-2} sec^{-1}) Mean± SE**	**Transpiration rate (E-mmol H_2O m^{-2} sec^{-1}) Mean± SE**
Weed-free rice (Control)	22.70±0.74a	0.64±0.01a	9.49±0.55a
Weed-free rice (Drought)	14.±0.73b	0.32±0.01ab	5.43±0.67ab
Rice+*A. paronychioides* (Control)	11.78±0.76cd	0.51±0.00ab	6.43±0.80abc
Rice+*A. paronychioides* + Herbicide (Control)	16.35±0.65 c	0.54±0.01abc	7.24±0.19abc
Rice+*A. paronychioides* (Drought)	9.43±0.50de	0.28±0.01bcd	5.19±0.25cd
Rice+*A. paronychioides* + Herbicide (Drought)	12.73±0.91ef	0.35±0.02abc	5.96±0.17lbcd
Rice+*E. colona* (Control)	9.20±0.34ef	0.28±0.01ab	4.84±0.35cd
Rice+*E. colona* (Control)	10.45±0.99cd	0.33±0.01ab	5.80±0.26abc
Rice+*E. colona* (Drought)	8.31±0.45fg	0.22±0.01d	3.83±0.27d
Rice+*E. colona* + Herbicide (Drought)	9.41±0.77g	0.28±0.01cd	4.18±0.49bcd

4. Conclusion

Weeds are major biotic stress components in crop ecosystems that can and will be strongly affected by climate change. Under the change, weed management would be more complex and expensive. The anticipated increase in CO_2 levels, eTem, and drought will directly impact weed infestation. Several research findings indicated that the efficacy of herbicides appeared to be declining in the context of climate change. Synchronization with the weed life cycle in the timing of control methods would be needed because this would be impacted by climate change. In addition, significant changes in weed species composition and distribution patterns may result from climate change. Periodic changes in temperature and precipitation will significantly impact the timing of herbicide applications and other weed management strategies. Overall, study results have demonstrated that greater dosages of several herbicides may be needed at regular intervals. However, such usage will not increase agricultural productivity and will have adverse environmental effects. Additionally, under such conditions, more weeds can acquire herbicide resistance more quickly, creating new problems for weed control. To investigate the complex interactions between various climatic factors and weed growth and herbicide efficiency, comprehensive research efforts encompassing ecological, physiological, and molecular investigations are required than relying solely on single-component tests. Long-term field studies on weed management based on a forecast of the future climate need to be carried out for better prediction with greater accuracy. More emphasis should be placed on studies examining climate change's effects on different crop-weed competition in various locations with different cropping systems.

5. Way forward

1. In order to understand such events, concerted efforts must be made to predict them in advance and evaluate their effects on crop-weed interaction and herbicide efficacy.
2. Although initiatives to evaluate the effectiveness of herbicides and the interactions between crops and weeds under eCO_2, temperature and drought were started in essential crops like rice, wheat, and greengram at ICAR-DWR, Jabalpur. In light of the projected increase in the frequency and severity of climate extremes, it is necessary to step up these efforts across several other cereals, millets, and oil seeds, etc., under various abiotic stresses like salt and drought, etc., needs to be considered.
3. Besides screening recommended doses of herbicides, there is a need to screen different dose levels under climate change in view of future preparedness.
4. Integration of tools and technologies of several disciplines, like phenomics and metabolomics, transcriptomics, etc., must be implemented in the crop-weed interaction and herbicide efficacy studies.
5. Research on weed biology and the emergence pattern of different weed seeds needs to be considered in futuristic climate change studies.
6. Apart from the studies on crop-weed interaction and herbicide efficacy, research needs to be initiated on evaluating the traits contributing to weed competitiveness in crops and their connections to genes are currently receiving more attention. These traits can be incorporated to a desired agronomic background by traditional and/or molecular breeding methods.
7. Unraveling the molecular mechanisms underlying the reduction of herbicide efficacy needs to be explored to identify a novel mode of action for addressing the futuristic climate change scenario.
8. Effectiveness of biocontrol agents on weeds under changing climate needs to be addressed.
9. Understanding the mechanism of herbicide resistance under eCO_2, temperature and drought needs to be focused.

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