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REVIEW ARTICLE

Crop-weed competition and herbicide bioefficacy: Implications in a changing climate

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ABSTRACT

Weeds in general cause 10-90% crop yield losses and are economically more harmful than insects, fungi or plant disease. Therefore, management of weeds in all agro-ecosystems is imperative to obtain sustainable crop production and to ensure food security to the increasing population. The agriculture practices and agricultural productivity are strongly impacted by the weather and climate change and likely to impact conventional aspects of farming practices and cropping systems. According to an estimate, approximately 10% yield losses caused by the weeds will be equal to the approximately ~2294 million metric tons. Global climate change, mainly increasing temperature and elevated carbon dioxide levels and its associated impact on weed management is one of the greater challenges which is expected to play an important role in the agricultural production systems across the globe. Due to the differential response of C_3 and C_4 plants under increasing CO_2 levels and temperature; chemical weed management strategies need to be revised to manage these weeds in the crop field. Reduced bioefficacy of several pre- and post-emergence herbicides of different mode of action under increasing CO_2 levels and temperature is reported such as, acetochlor, atrazine, bispyribac-sodium, carfentrazone, cyhalofop-butyl, fenoxaprop-p-ethyl, glufosinate, glyphosate, metsulfuron, paraquat, penoxsulam, pinoxaden, tribenuron-methyl etc. Decreased bioefficacy of herbicides due to higher temperatures is reported due to increased metabolism in targeted plants. Besides this, weed flora shift, crop-weed competitions and interference, optimization of herbicide doses, development of herbicide resistance in weeds, are some other major challenges in developing weed management package of practices under climate change scenarios. Changing climate is now a reality and poses a greater challenge which may further intensify weed problems due to the competition and adaptability in diverse climate situations than the crops. An integrated and holistic approach would be imperative to tackle weeds under climate change scenarios specifically in response to elevated CO_2 and rising temperature in the coming future.

Keywords: Climate Change, Global warming, Herbicide efficacy and metabolism, Resistance Temperature-dependent sensitivity, Weed management

INTRODUCTION

The global population reached nearly 8.2 billion by mid-2024 and is expected to reach over 9 billion by 2050 (UN News 2024). Weeds is considered as one of the most significant biotic constraints in crop production currently faced in global agriculture and cause approximately 30% crops yield losses (Sondhia and Mishra 2024) and the degree of losses varies by crop, cultivar, weed species, weed infestation level, location, and farming practices (Soltani *et al.* 2016). Climate change, characterized by elevated CO_2 (eCO_2) levels, increasing temperatures, and water scarcity, along with enhanced greenhouse gas (GHG) emissions, has emerged as a significant concern which has potential impact on agricultural production and pest dynamics as it affects the physical environment and ecosystems (Carbonbrief 2024). Atmospheric CO_2 level have been increasing at an unprecedented rate, reached to 426 parts per million (ppm) in mid-2024 (https://www.co2.earth/daily-co2), and are projected to exceed 700-1000 ppm by the end of the 21st century (IPCC 2014). Global surface temperature has increased faster since 1970 with an increase of 0.8°C to 1.3°C from 1850–1900 to 2010–2019 and over this period, greenhouse gases (GHGs) contributed a warming of 1.0°C to 2.0°C (IPCC, 2023), with future projections indicating an increase of 1.1 °C to 6.4 °C by the end of 21st century (IPCC, 2014) (**Figure 1**). Global warming has substantially affected the crop-weed interaction and crop productivity (Sondhia *et al.* 2024; Srikanth *et al.* 2024a, 2024b). Elevated temperatures (eT) is likely to be positively correlated with the altered weeds' growth and biology, phenology, dispersal and demography than the crop (Keller and Shea 2021). It has been reported that apart from eCO_2 levels, and rising temperature; greenhouse gas emissions, may also affect nutrient availability for plant growth and development (Reeves 2017).

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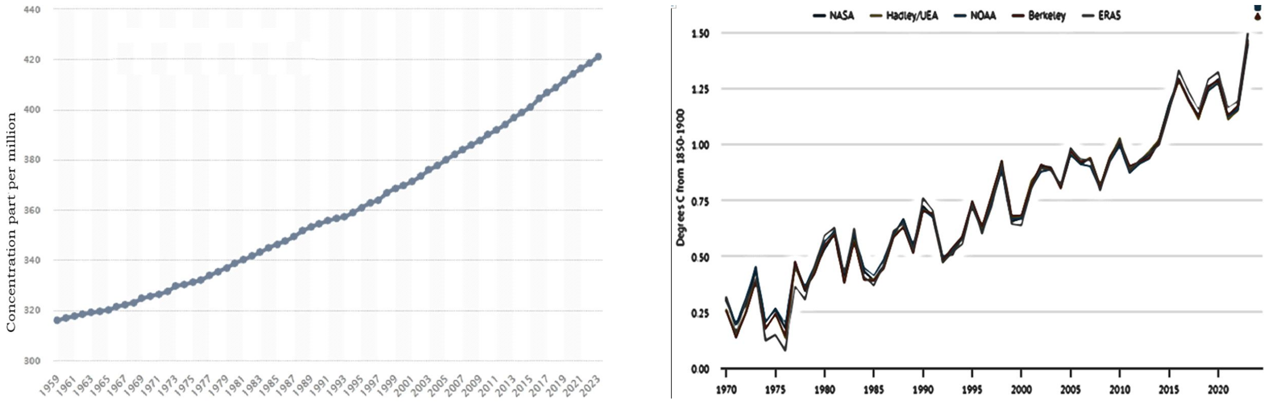

Figure 1. Average CO_2 level (ppm) since 1959 to 2023 (Source statistica 2024) and temperature level between 1980 to 2024 (Source: CarbonBrief 2024).

Currently chemical weed management practices are widely adopted due to its higher weed control efficiency and will be likely to be adopted more frequently under climate change conditions. Globally, usage of herbicides occupies 44% of the total agrochemicals and it is 30% in India (Sondhia 2014). It has been described that successful chemical weed management relies not only on the chemical properties of a herbicide but also on its interaction with the plant and the environment. Herbicide absorption into the target plant largely depends on its interaction with atmosphere, soil, or the soil–atmosphere interface. Several environmental factors such as temperature, moisture, relative humidity, and solar radiation influence a plant's physiologic status and its susceptibility to herbicides. Climate change is expected to result in varying growth rates for both crops and weeds, which may have significant impacts on crop production and weed management. Among various pests, weeds are most responsive to the increasing CO_2 concentrations in Earth's atmosphere. Crop-weed interactions and competition are likely to vary depending on various regions and cropping systems. It has also been reported that increased CO_2 concentrations and temperature can reduce the herbicide bioefficacy against many weeds (Ziska *et al.* 2019). Among various climate change factors, assessment of the effects of global climate change factors particularly of eCO_2 concentrations and rising temperature on agricultural practices is particularly important to understand the vulnerability of crop production across the glob and to anticipate and adapt practices that maximize agricultural production in future climate scenarios. Therefore, the impact of climate change mainly due to eCO_2 and temperature on weed management and herbicide efficacy and its mitigation strategies on weeds and weed management is described here.

Impact on C_3 and C_4 plants

Ziska *et al.* (2019) described that eCO_2 and climate change will impose strong selection pressures on weeds and they will often have the capacity to respond with rapid adaptive evolution. In addition, shifts in the efficacy of biological constraints (*e.g.*, pathogens) and resultant selection shifts in affected weed species, climate-induced phenological shifts in weed distribution, demography, and suitability relative to crop systems; and understanding and characterization of epigenetics and the differential expression of phenotypic plasticity versus evolutionary adaptation may be required to develop effective weed manage practices in future. Many weeds have the C_4 pathway, which shows a minimal response to CO_2, whereas crops often have the C_3 pathway (**Table 1**), which shows a stronger response. Due to fertilization effect of rising CO_2 on plant photosynthesis, the conversion of ongoing CO_2 to sugars will stimulate C_3 photosynthesis and plant growth (~85% of plant species, including many weeds) and it was hypothesized that crops would outcompete weeds as CO_2 rose (Ziska *et al.* 2019) and at higher temperatures and increased drought, C_4 weeds can still benefit (Valerio *et al.* 2013) relative to C_3 crops (Elmore and Paul 1983) (**Table 2)**.

Additional evidence suggests that adaptation to recent changes, particularly the rapid increase in CO_2, i.e. 20% increase since 1980 (Waryszak *et al.* 2018), might have already altered the crops and weeds competition and adaptability. Comparisons of six cultivated and six wild or weedy biotypes of rice (*Oryza sativa* L.) indicated a greater overall growth response among wild relative to cultivated rice (*Oryza sativa* L.) to 300 to 400 ppm increases in CO_2 suggesting that rapid evolution of weedy biotypes may have increased their evolution relative to the crop. Higher seed yields were also recorded for Stuttgart, a weedy biotype, relative to ClearfieldTM, a cultivated rice line (Ziska *et al.* 2010, Franks *et al.* 2018), Seed of two temporally distinct populations of wild oat (*Avena fatua* L.) demonstrated different competitive abilities against a cultivated oat (*Avena sativa* L.) line at current CO_2 levels (Ziska 2017).

Seed of the annual weed birdsrape mustard (*Brassica rapa* L.) (C_3) collected before and after a severe drought demonstrated that drought exerts strong selection pressure, and *B. rapa* responded by evolving earlier flowering and lower water-use efficiency within a few generations (Franks 2011). Similarly, in a much wetter environment, the limestone grassland of Britain, 13 years of drought led to evolution of drought escape in the common weed buckhorn plantain (*Plantago lanceolata* L.) (C_3) (Ravenscroft *et al.* 2015). The annual invasive grass foxtail brome (*Bromus madritensis* L.), populations subjected to eCO_2 evolved through reduced stomatal conductance, allowing them to lose less water but still obtain sufficient CO_2 in the elevated environment, demonstrating rapid adaptive evolution to eCO_2 (Grossman and Rice 2014). This shift demonstrates that weeds are more competitive with crops, and has the potential to lower crop yields. As climatic conditions evolve, the composition of weed communities is also expected to change and may lead to a weed shift or a mixed population of C_3 and C_4 weed species, which further complicates weed management strategies through herbicides due to varying levels of herbicide selectivity and efficacy. Uneven and erratic rainfall and drought conditions may shift the timing of weed germination and growth, making it more difficult to manage weed infestations.

Differential response to herbicides of C_3 and C_4 weeds

C_3 and C_4 weeds exhibit differing responses to reported under eT and eCO_2 in climate change, potentially leading to shifts in weed populations that

Table 2. List of some important C_3 and C_4 weeds found in various crops

C_3 weeds		C_4 weeds	
Scientific name	Common name	Scientific name	Common name
Abutilon theophrasti	Velvet leaf, Chinese jute	*Amaranthus cviridis*	Slender amaranth
Alternanthera philoxeroides (Mart.) Griseb (C_3/C_4)	Alligator weed	*Amaranthus spinosus*	Spiny pigweed
Alternanthera paronychioides (C_3-C_4)	Smooth chaff flower	*Amaranthus viridis*	Slender amaranth
Anagallis arvensis	Scarlet pimpernel	*Amaranthus palmeri* S. Watson	Palmer amaranth
Ageratum conyzoides	Goat weed	*Amaranthus retroflexus*	Pig weed, Red root
Agropyron repens	Couch grass	*Boerhavia diffusa*	Red spiderling
Aegilops cylindrica	Jointed goat grass	*Cynodon dactylon* (L.) Pers.	Bermudagrass
Asphodelus tenuifolius	Onion weed	*Cyperus articulatus* L. (CYPAR)	Jointed flatsedge
Argemone mexicana	Mexican poppy	*Cyperus iria*	Rice flat sedge
Ammannia baccifera	Monarch redstem	*Cyperus rotundus* L.	Purple nutsedge
Alternanthera sessilis	Sessile joyweed	*Cyperus esculentus*	Yellow nutsedge, tiger nut,
Avena fatua	Wild oat	*Chloris barbata* Swartz. (CHRBA)	Swollen fingergrass
Bromus inermis Leyss	Bromegrass	*Digitaria sanguinalis* (L.) Scop. (DIGSA)	Large crabgrass
Bidens pilosa	Spanish needles	*Dactyloctenium aegyptium*	Crowfoot grass
Brassica rapa L.)	Birdsrape mustard	Digitaria ciliaris (Retz) Koel	Crab grass
Commelina benghalensis	Day flower,	*Dinebra retroflexa* (Vahl) Panz	Viper grass
Convolvulus arvensis	Field bindweed	*Echinochloa crus-galli* (L.) Beauv	Barnyard grass
Cirsium arvense	Canada thistle	*Euphorbia hirta*	Garden spurge
Chenopodium album L.	Lambsquar-ters	*Eleusine indica (*L.*)* Gaertn.	Indian goosegrass
Chloris barbata	Purple topchloris	*Echinochloa colona* (L.) Link	Jungle rice
Cyperus difformis	Small flower umbrella sedge	*Fimbristylis dichotoma*	Fimbry, fimbristyle
Chromolaena odorata	Siam weed	*Fimbristylis millacea*	Lesser Fimbristylis
Eclipta prostrata	False daisy	*Imperata cylindrica* (L.) Raeuschel	Cogon grass
Euphorbia geniculata	Wild poinsettia	*Ischaemum rugosum*	Wrinkled duck beak
*Eichhornia crassipes(*Mart.*) Solms*	Water hya-cinth	*Leptochloa chinensis*	Red sprangletop
Festuca arundinacea Schreb.	Tall fescue	*Paspalum orbiculare* Forst. (PASOR)	Ricegrass paspalum
Ipomea spp.	Water spinach	*Panicum virgatum* L.	Switchgrass
Monchoria vaginalis (Burm. f.) Persl.	Monchoria	*Panicum maximum* Iacq. (PANMA)	Guineagrass
Plantago lanceolata L.	Buckhorn plantain	*Portulaca oleracea*	Common purslane
Parthenium hysterophorus(C_3-C_4)	Congress grass	*Paspalum orbiculare* Forst	Ditch millet
Physalis minima	Sunberry	*Paspalum distichum*	Knot grass, water finger grass
Phyllanthus niruri	Stone breaker	*Rottboellia cochinchinensis (*Lour*)*	Itchgrass
Phalaris minor	Little seed canary grass	*Setaria glauca* (L.) Beauv.	Fox tail
Phalaris arundinacea L.	Reed canarygrass	*Setaria viridis* (L.) Beauv. (SETVO	Green foxtail
Rumex dentatus	Aegean dock Jangli palak	*Sorghum halepense* (L.) Pers.	Johnsongrass
Rumex acetosella L.	Red sorrel	*Saccharum officinarum* L.	Tiger grass
Striga asiatica	Witchweed	*Saccharum spontaneum*	Wild sugarcane
Tridax procumbens	Coat buttons	*Trianthema portulacastrum*	Horse purslane
Xanthium strumarium	Common cocklebur		

threaten crop productivity (Umkulzhum *et al.* 2024) (**Table 2**). Germination and growth of *Amaranthus patulus* (C_4) was higher at 25°C to 30°C, however, under eCO_2 conditions, germination and growth of *A. patulus* was not significantly different. Weed defines a mechanism also reported as a result of leaf thickening, and closure of stomata, thereby reduceing the amount of foliar-applied herbicide that is directly absorbed by plants (Jackson *et al.* 2011). Quackgrass (*Elymus repens,* (C_3) was reported to be more tolerant to glyphosate under eCO_2 concentration (720 µmol/mol). Another prominent effect of eCO_2 is 50% reduction in stomatal conductance in some plants, which can alter the transpirational flow and reduce the efficacy of both foliar- and soil-applied herbicides.

Increased CO_2 can also induce morphological, physiological, and anatomical changes in plants that could affect herbicide absorption and translocation rate (Manea *et al.* 2011). It is reported that plants (C_3 and C_4) grown under eCO_2 have thicker cuticle and increased leaf pubescence (Ainsworth and Long, 2005). These traits could reduce herbicide entry into plant leaves and further affect its efficacy. Apart from that, climate change is causing increases in weed biomass and shifts in population dynamics, and hence some species becoming more aggressive, while others may decline (Umkulzhum *et al.* 2024). While C_4 plants may benefit under eT, the broader effects of climate change on weed dynamics remain complex, with potential negative impacts on crop yields and ecosystem health. Species such as *Parthenium hysterophorus* (C_3/C_4) and *Eichhornia crassipes* have been identified as potential future threats due to their adaptability to changing climates. C_4 weeds may likely to expand into new regions, predominantly in mid-latitude dryland ecosystems, where their suitability under changing conditions will increase (Anderson *et al.* 2024).

The genetic diversity of weeds allows them to adapt more readily, enhancing their invasive potential, whereas, C_4 weeds are more tolerant to rising temperatures, enabling them to flourish as global temperatures increase. C_3 weeds, such as *Amaranthus retroflexus* and *Chenopodium album*, thrive under eCO_2, and are becoming more competitive against crops (Rakhmankulova *et al.* 2023). Higher CO_2 levels enhance C_4 photosynthesis, boosting biomass production and giving them a competitive advantage over C_3 crops (Umkulzhum *et al.* 2024). Increased temperature had a greater effect on plant survival than eCO_2 level. It is reported that under eT, eCO_2 level, glyphosate was more rapidly translocated out of the treated leaf to shoot meristems and roots and suggested that glyphosate may not be effective for weed control (Matzrafi *et al.* 2019).

Decreased efficacy of paraquat is reported to velvetleaf and large crabgrass at increased UV radiation due to lower absorption and efficacy (Wang *et al.* 2006). Efficacy of linuron was reported to be reduced by 15% in wild buckwheat (*Polygonum convolvulus*) (C_3) at eCO_2 levels (Archambault *et al.* 2001). In contrast, atrazine application in high air temperatures is reported to be more effective to control velvet leaf and common ragweed (Fluttert *et al.* 2022). However, high soil temperatures primarily affect the efficacy of soil-applied herbicides by decreasing permeability and increasing volatility and microbial breakdown. Impact of high soil temperature (25‘“C), is reported to increased volatilization of triallate from 14 to 60% and 7 to 41% in sandy and loamy soils, respectively (Atienza *et al.* 2001). Roots growth are reported to be stimulated and may reach deeper soil layers at eCO_2 levels henceforth prevents the uptake of soil-applied herbicides. Ziska *et al.* (2004) reported high root: shoot ratio of field-grown Canada thistle (*Circium arvense*) (C_3) under eCO_2 levels, which reduced the efficacy of glyphosate due to the dilution effect caused by large volume of roots. However, in few cases, high temperatures could enhance root uptake of herbicides due to a decrease in soil organic matter and high evaporation rates (Miraglia *et al.* 2009).

Impact of elevated temperature on herbicides bioefficacy against weeds

In the field, higher survival of musk thistle, with more production of capitula, and taller heights were reported under eT than at ambient temperatures (Zhang *et al.* 2011). The interaction effect of temperature and genotype on the translocation of ^{14}C-cyhalofop-butyl was not significant. It is also reported that under eT, *E. colona* will establish faster and compete with the rice crop more vigorously early in the season as *E. colona* is a C_4 plant (Giussani *et al.* 2001) and it responds more to high temperature than the rice, which is a C_3 crop. Keller and Shea (2021)

Table 2. C_3 and C_4 photosynthetic pathway of various crops (Still *et al.* 2003)

C_3	C_4
Alfalfa, Barley, Cotton, Groundnut, Oats, Pea, Rye, Rice, Sunflower, Sorghum, Soybean, Tobacco, Wheat Chilli, Carrot, Cucumber, Garlic, Lettuce, Onion, Potatoes, Spinach, Sugar Beets Tomato, Pumpkin,	Maize, Millets, Cassava (Some Varieties), Sugarcane, Sorghum, Sweet Potato (Some Varieties),

demonstrated that under eT, musk thistle (*Carduus nutans*) was survived through early flowering, grew to taller heights, and production of more flowering capitula compared to plants grown under ambient conditions, A changing climate may alter weed growth and spread directly through differential selective pressures on weed species and indirectly through changes in the abiotic and biotic aspects of the ecosystems or through mediated changes in human management. Direct selection pressures are responsible for how eCO_2 and higher temperatures differentially alter weed growth, leaf production, plant height, and seed production (Liu *et al.* 2017). In warmer regions, under increases in temperature, weeds are also likely to select for tolerance or avoidance of drought and heat (Franks *et al.* 2018).

Higher temperature stimulates stomatal conductance, reducing the viscosity of epicuticle waxes, thus increased the penetration and diffusion of herbicides which result in changes in the composition and the permeability of the cuticle (Rodenburg *et al.* 2011). However, mostly higher temperatures enhance herbicide metabolism, which consequently decreases herbicidal activity on targeted plants. Under higher relative humidity, cuticle hydration and stomatal conductance increases, therefore the permeability and translocation of hydrophilic herbicides increases into the leaves. Similarly, under higher irradiance, stomata stay open, photosynthetic rate increases consequently increasing absorption, penetration and subsequent phloem translocation of post-emergence systemic herbicides in weed tissue. Drought may cause an increase in cuticle thickness and leaf pubescence, which subsequently reduces herbicide absorption into the leaves. Rainfall after post-emergence herbicides application might affect their efficiency through dilution and washing out effects. Increased frequency and intensity of precipitation will further have a negative effect on absorption, translocation, and activity of preemergence herbicides.

Successful use of herbicides for weed management depends on environmental conditions that prevails before, during, and after the herbicide application. The herbicides persistence in different environmental conditions vary significantly, ranging from those that break down quickly into nontoxic by-products, to those that persist in the environment with toxic/nontoxic metabolites (Sondhia *et al.* 2023). Climate change impact related to increasing temperature will become more pronounced, as certain herbicides can be vulnerable to volatilization, which may cause them to loos efficacy (**Table 3**). Under such conditions excess and extensive herbicides use may be required for effective weed management, however this may further burden the environmental load as well as contribute in development of resistance in weeds to herbicides.

Apart from CO_2, and temperature, other environmental factors, such as light, soil moisture, relative humidity, rainfall and wind can also directly affect herbicide efficacy by altering the penetration and translocation of herbicides within the plant or indirectly by changing the growth and physiological characteristics of the plant. While foliar herbicides are influenced by many environmental factors, soil-applied herbicides are influenced mainly by soil moisture and temperature (Varanasi *et al.* 2015). However, in a reported case, the absorption of ^{14}C-cyhalofop-butyl into leaves of *Echinochloa* sps. seedlings was not declined under eCO_2 and absorption in herbicide-susceptible and multiple-resistant *E. colona* does not change under eCO_2 or eT (Rodenburg *et al.* 2011). Elevated CO_2 or eT increases the resistance level of *E. colona* to cyhalofop-butyl which is a ACCase-inhibitor (Refatti *et al.* 2019).

Impact of elevated CO_2 on weeds and herbicide bioefficacy

Carbon dioxide-induced changes in leaf morphology or variation in root: shoot ratio can affect herbicide uptake and distribution. Elevated CO_2 stimulated root over shoot growth of Canada thistle [*Cirsium arvense* (L.) Scop.], due to diluting effect on shoot-applied herbicide and failed to kill roots, which resulted in regeneration of the whole plant (Ziska *et al.* 2004). Similar increasing trend in root: shoot ratio have been observed for several other invasive weeds in response to eCO_2 (Ziska *et al.* 2019). Higher CO_2 concentration levels have been shown to be beneficial mostly to C_3 weed species such as Japanese honeysuckle (*Lonicera japonica* Thunb.) (Belote *et al.* 2003), cherry laurel (*Prunus laurocerasus* L.) (Hattenschwiler and Korner 2003), red brome (*Bromus rubens* L.) (Smith *et al.* 2000), mile-a-minute (*Mikania micrantha* Kunth.), Chinese wedelia (*Wedelia chinensis* L. Pruski.), and *Dalmatian toadflax* [*Linaria dalmatica* (L.) Mill.] (Blumenthal *et al.* 2013), however enhanced growth of beach morning glory [*Ipomoea pes-caprae* (L.) R. Br.] which is a C_4 weed is also reported (Song *et al.* 2009). The effects of climate change on herbicide efficacy may also depend on herbicide mode of action. Elevated CO_2 could alter pigment production, photosynthesis, and overall metabolic activity. In contrary, atrazine (photosystem II inhibitor) and amitrole (pigment inhibitor), become more effective where CO_2 or temperature stimulate plant growth. Contrariwise, there is general recognition that rising CO_2 and/or rising temperatures could reduce protein levels in a wide range of plant tissues (Loladze 2014) which result in less demand for aromatic and branched-chain amino acids that caused declines in glufosinate and glyphosate efficacy (Varanasi *et al.* 2015).

Perennial weeds may become more difficult to control in increasing CO_2 concentration and rising temperature, if increased photosynthesis stimulates greater production of rhizomes and other storage organs. Zeng *et al.* (2011) reported altered competition between rice and barnyard grass (C_4) in paddy fields in favour of rice under eCO_2 concentration due to enhanced biomass, tillers, leaf area index (LAI) and net assimilation rate (NAR), absolute uptake of C, N, P, K of rice, but reduced in barnyard grass after elongation. CO_2 differentially affects the extent of *E. colona* (C_4) injury between resistant and susceptible genotypes from cyhalofop-butyl treatment. Under eCO_2, cyhalofop-butyl did not completely kill the susceptible plants, however, the herbicide efficacy on resistant plants also declined significantly (Scott *et al.* 2018). At eT, the efficacy of cyhalofop-butyl on the susceptible genotype remained high, but the efficacy on the resistance genotype declined significantly to about 50% (Rodenburg *et al.* 2011). Enormous research reports showed reduction in stomatal conductance and transpiration, improved water-use efficiency, higher rates of photosynthesis, and increased light-use efficiency under eCO_2 in plants (Wang 2022).

Combined impact of elevated CO_2 and temperature on weed and herbicide bioefficacy

The ideal range for spraying most herbicide is reported from 20°C to 30°C due to favouring absorption and its fluidity in membranes and the optimum activity of the enzyme Rubisco (Ribulose 1,5 bisphosphate carboxylase oxygenase), which is responsible for carbon fixation in the plant. Advancement in the seasonal timing of stem elongation, flowering, and growth cessation is reported under eT (Keller and Shea, 2021). Research indicates that currently used herbicides may lose efficacy against C_3 and/or C_4 weed under eCO_2 and eT, and suggest necessary modifications in weed management strategies (Kumar *et al.* 2023, Sondhia *et al.* 2024). Mowing is widely recommended to reduce musk thistle seed production and plant height, which reduces dispersal distances of wind-dispersed seeds and plant height (Skarpaas and Shea 2007).

Matzrafi *et al.* (2019) reported decreased efficacy to ACCase inhibitors pinoxaden under eT. The levels of the inactive glucose-conjugated pinoxaden product (M5) were found significantly higher under high than low temperature and demonstrated an increased risk for the evolution of herbicide-resistant in weeds under eT. Reduced efficacy of herbicides at high temperature generally may be due to increased metabolism as a consequence of maximal physiological conditions (Godar *et al.* 2015). The activity of mesotrione on Palmer amaranth (C_4) declined when the temperature increased from 25 to 40°C. Reduction in activity of pinoxaden on *Brachypodium hybridum* (C_3) under high temperature is correlated with significantly higher levels of the glucose-conjugated metabolite in *B. hybridum* compared to low temperature along with faster metabolism of pinoxaden at eT.

Weeds with C_3 and C_4 photosynthetic pathways may exhibit distinct responses to higher CO_2 levels and temperatures, which can affect the dynamics of crop–weed competition. Elevated CO_2 and temperatures can reduce herbicide efficacy by influencing absorption and translocation within plants. In our study undertaken in open top carbon chambers (OTC) at Directorate of Weed research, Jabalpur; growth of the wheat was significantly reduced by interference of *P. minor* under eT, eCO_2 and eT+eCO_2 conditions. *P. minor* (C_3) interference significantly reduced the relative water content of wheat by 19.0% to 15.5% under eT and eT+eCO_2 compared to weed free ambient. *P. minor* interference significantly reduced the wheat yield (45.9%) under eT conditions compared to ambient. The rate of photosynthesis was significantly reduced under eT in comparison to weed free ambient in the presence of *P. minor* (**Figure 2**) (Sondhia *et al.* 2024).

Relative water content (RWC) and membrane stability index (MSI) of wheat was also reduced remarkably (15.7% and 3.25%, respectively) at eT and combination of eCO_2 and eT by *P. minor* interference compared to weed free ambient (**Figure 2**). However, eCO_2 had a positive impact on the rate of photosynthesis of *P. minor* which increased by 22.37% in comparison to ambient. Overall, eCO_2 had a positive impact on growth and biomass production of *P. minor* in comparison to ambient, eT and e CO_2+eT. These results predict that management of *P. minor* weed in wheat crop under eCO_2 and temperature will be a challenge in a futuristic climate change scenario (Sondhia *et al.* 2024). Weed competition and cyhalofop-butyl + penoxsulam bioefficacy (x, 1.5x and 2x doses) impact was evaluated under eCO_2 and eT and their combined effects among, *E. colona*, *Alternanthera paronychioides, Dinebra retroflexa* and *Cyperus iria* weeds with rice crop under FACE. Significant reduction in cyhalofop-butyl + penoxsulam efficacy and yield was found especially with *E. colona* (**Figure 3**) (Sondhia *et al.* 2024).

In addition to its positive impact on weed growth, climate change factors could influence the efficacy of many herbicides, making weed management a major challenge for sustainable crop production (Varanasi *et al.* 2015). Environmental factors such as CO_2, light, temperature, relative humidity, and soil moisture differentially affect the uptake, translocation, and activity of different herbicide chemistries. Differential response of same mode of action of herbicides is reported in literature. However, neither temperature nor CO_2 affect cyhalofop-butyl absorption into the leaf or efficacy against *Echinochloa colona* genotypes (Refatti *et al.* 2019). In order to predict precise impact of climate change factors especially, $eCO_{2,}$ eT and, their interactions on herbicides is necessary for implications for weed management in future climate scenarios.

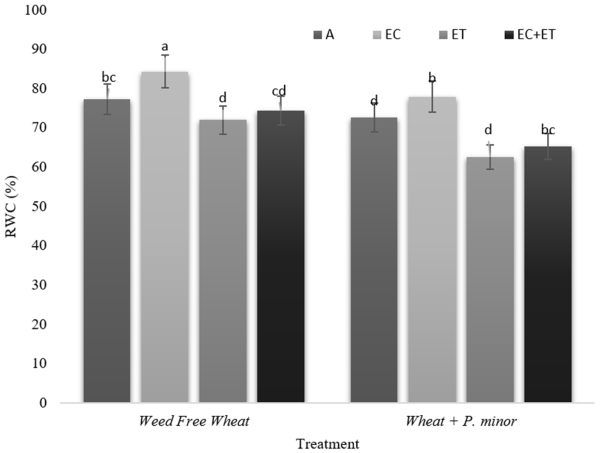

Figure 2. Effect of elevated CO_2 and temperature on relative water content of wheat and *Phalaris minor* in open top chambers

The efficacy of the soil-applied herbicides (Alachlor, ethalfluralin, linuron, and metolachlor) in *A. patulus*, and foliar herbicides (Glufosinate-ammonium, bentazone, and mecoprop) was reported to be higher at 30 °C; in contrarily, glyphosate isopropylamine showed similar efficacy regardless of the temperature (Park *et al.* 2021). Reduced glyphosate sensitivity was observed in *Conyza canadensis* (C_3) and *Chenopodium album* under eT, eCO_2 level, and the combination of both factors. Photosynthetic capacity is also expected to increase further when CO_2 and temperature are not limiting. High atmospheric CO_2 or high temperature reduces sensitivity of weed species to various herbicides. A higher weed pressure will also enhance application frequencies and volumes. In addition, increased temperature and CO_2 can change the leaf surface characteristics by increasing leaf thickness, or changing the viscosity of the cuticle wax, with subsequent reductions in herbicide absorption (Ziska *et al.* 2019). Under eT and eCO_2 the ecological dynamics are also likely to be affected and that there is a close coupling between ecological and evolutionary dynamics (Ravenscroft *et al.* 2015).

Impact on herbicide persistence and dissipation

The efficacy of herbicides is greatly influenced by soil properties including moisture and climate change (Sondhia 2014, Robinson, 2019). Effective pre-emergence herbicides are mainly dependent on

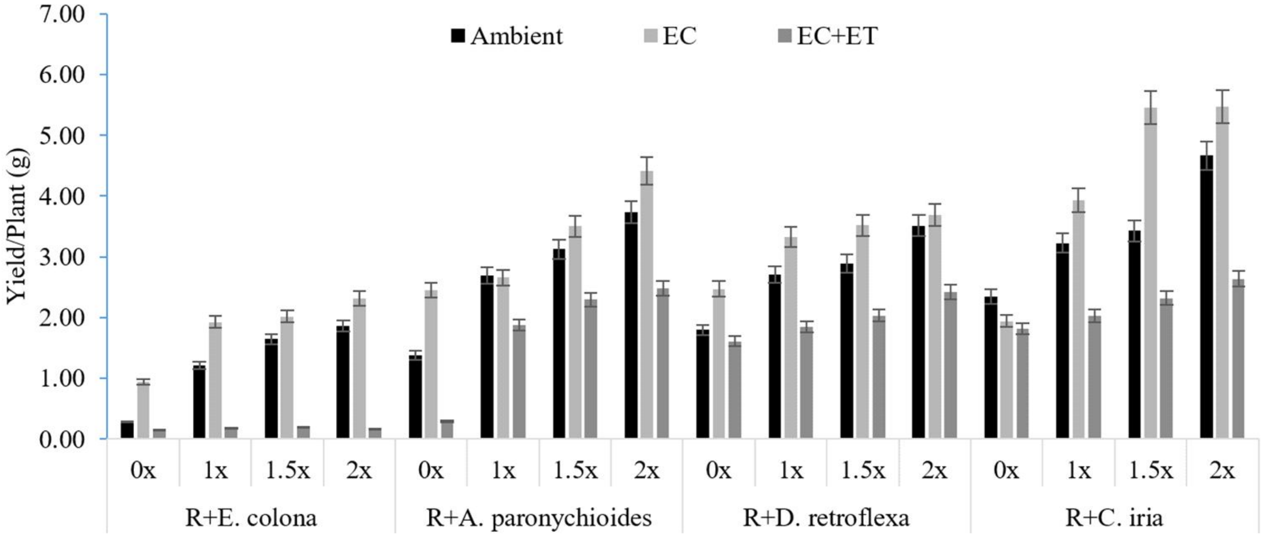

Figure 3. Effect of crop-weed interaction under elevated CO_2 and temperature on rice yield

soil moisture content for movement into the zone of weed seed germination. Sunlight tends to degrades mostly pre-emergence herbicides on the soil surface, and less moisture availability may result in poor weed management. Herbicides, after their application, undergo biochemical degradation (Sondhia 2013). Under dry conditions, microbial degradation slows and herbicide persistence in the soil is prolonged, however, in humid and warmer conditions, herbicide persistence will be shortened (Sondhia 2014, Sondhia and Waseem 2020).

Volatile herbicides are likely to dissipate quicker than less volatile herbicides (Sondhia 2023). Due to high vapour pressure of clopyralid, fluchloralin, pendimethalin, trifluralin, they will remain in the vapour and particulate form in the field atmosphere (**Table 3**). Temperature can affect herbicide performance directly through its effects on the rate of herbicide diffusion, viscosity of cuticle waxes, and physicochemical properties of spray solutions (Price 1983). The dissipation of 2,4-D, bromoxynil, and thifensulfuron-methyl increased with increasing temperature (Cessna *et al.* 2017). However, rise in temperature above 20 °C reduced the efficacy of carfentrazone against weeds (Sondhia *et al.* 2024). Dicamba and 2,4-D are prone to volatility, and can move long distances with slight breezes. A lower herbicide residue, due to quick dissipation in the soil and crops as a result of eCO_2, and eT will result in an increased vulnerability to weeds and in the future, necessitate more spray often during the crop growing season that will further enhance environmental contamination.

Impact of greenhouse gas emissions on herbicide bioefficacy

CH_4 and N_2O are the major greenhouse gases and mostly responsible for global warming. Agriculture accounted for approximately 50% of the CH_4 and 60% of the N_2O global anthropogenic emissions in 2005 (IPCC 2014). Irrigated paddy fields assumed to be a major anthropogenic source of atmospheric CH_4 (IPCC 2014). Most soil-evolved N_2O is produced by nitrification and denitrification processes (Kool *et al.* 2010).

Impact of herbicides use to control weeds in croplands and their impact on greenhouse gas emissions were demonstrated by Jiang (2015). Decreaes in herbicides efficacy of acetochlor, fenoxaprop-p-ethyl + tribenuron-methyl under eCO_2, and significantly reduced N_2O emissions by 31% compared with no herbicide use in the wheat growing season due to low soil ammonium nitrogen and less abundance of denitrifying bacteria is reported. Bensulfuron-methyl and butachlor significantly reduced CH_4 emissions by 27% and 58% in rice growing season due to high soil nitrate nitrogen and urease activity.

Table 3. Herbicide with higher volatilization property

Herbicide	Vapour pressure (mmHg)	Henry's law constant (Pa m^{3}/mol)
Alachlor	2.2 x 10-^{5}	3.20 x 10^{-3}
Anilofos	1.6 x10-^{5}	1.42 x10^{3}
Butachlor	2.9 x10-^{6}	3.74 x 10^{-3}
Clomazone	1.4 x10-^{4}	4.13 x 10^{-8}
Clopyralid	5.99 x10-^{4}	1.80 10^{-11}
Dicamba	1.25 x10-^{5}	1.0 x 10^{-4}
Fluchloralin	3 x10-^{5}	6.49 X 10-^{4}
Metamifop	1.13 x10-^{5}	0.065
Metolachlor	3.14 x10-^{5}	2.40 x 10^{-3}
Pendimethalin	3 x10-^{5}	2.73 x 10^{-3}
Pretilachlor	5 x10-^{6}	8.10 x 10^{-4}
Thiobencarb	2.2 x10-^{4}	3.68 x 10^{-2}
Trifluralin	1.99 x10-^{4}	10.2

Similarly, application of prosulfuron was found to decrease N_2O emissions over short period of time (Kinney *et al.* 2005). In contrary, butachlor inhibited CH_4 emissions by 20% in a direct-seeded flooded rice field and prosulfuron is reported to stimulate N_2O emissions and CH_4 consumption in a fertilized Colorado grassland soil by as much as 1600% and 1300%, respectively. Das and Debnath (2006) also demonstrated increased N_2O and CH_4 emissions due to combined application of the bensulfuron-methyl and pretilachlor. Methane oxidation in soil is an important ecological process. Methane gas, which is removed from the environment *via* reactions with the hydroxyl radicals in the troposphere 2, 3, and also biologically through oxidation by methanotrophic and to a lesser extent by ammonia oxidising bacteria in surface soils. 2,4-D has been shown to inhibit methane oxidation, an important ecological process in soil.

Impact on altered herbicide metabolism and resistance in weeds

In agronomic systems, herbicides represent strong selective pressures, and hence the evolutionary potential of weeds is rapid and resulted in widespread herbicide resistance (Ravet *et al.* 2018). Presently, 532 unique cases of herbicide-resistant weed globally and with 273 species (156 dicots and 117 monocots) (Heap 2019, Croplife 2024,). Climate changes may necessitate changes in adaptation of modified agronomic practices. Weeds have evolved resistance to 21 of the 31 known herbicide sites of action and to 168 different herbicides (weedscience.org/Home.aspx).

It is also concerning that cases of resistance, or multiple resistance to herbicides are increasing among key rice weeds, in comparison to other crops (Roma-Burgos *et al.* 2019). Based on literature it is expected that initially, increased temperatures could increase herbicide efficacy by accelerating absorption and translocation of foliar herbicides; along with induced rapid metabolism, which reduces herbicide efficacy in target plants (Johnson and Young 2002). Non-target-site-based resistance mechanisms in weeds cause reduced absorptionm translocation, enhances herbicide metabolism, and overproduction of herbicide target (Délye 2013) and greatly influenced by changes in climate (Roma-Burgos *et al.* 2019). Recently increasing cases of non-target-site-based resistance to acetyl-CoA carboxylase (ACCase) inhibitors is reported (Heap 2019) through detoxification and increased production of monooxygenases (cytochrome P450s), that facilitate phase I detoxification reactions and increased activity of glutathione-S-transferase (GST) enzymes, which in turn facilitate phase II detoxification (Délye 2013).

Through rapid metabolism, diclofop-methyl, pinoxaden, tralkoxydim are inactivated in plants through hydroxylation, by cytochrome P450s in phase I detoxification reactions (Wenger *et al.* 2012) and further conjugation by GTs or GSTs in phase II reactions (Brazier *et al.* 2002). Resistance to ACCase inhibitors in large crabgrass (*Digitaria sanguinalis* L.) (C_4) is reported due to overexpression of ACCase (Laforest *et al.* 2017). Few other studies have shown reduced herbicide efficacy under eCO_2 for C_3 and C_4 weedy species (Manea *et al.* 2011). Reduced efficacy of glyphosate under eCO_2 against *Eragrostis curvula* (Schrad.) Nees(C_4) and *Paspalum dilatatum* Poir (C_4) is reported (Manea *et al.* 2011). Therefore, to mitigate rapid resistance evolution in weed, management practitioners must implement measures to reduce the herbicide selection pressure.

Reported experimental evidence demonstrated increasing gene flow between herbicide-resistant crops and weedy relatives under climate change. In a long-term USDA study comparing between cultivated and weedy rice at three different CO_2 concentrations (300, 400 and 600 ppm) showed greater synchronicity in flowering times and enhanced outcrossing rates between a cultivated rice mutant that is resistant to imidazolinone, ClearfieldTM 161 and a weedy red rice accession (StgS). Consequently, as CO_2 increased, the number of weedy herbicide-resistant hybrid offspring also increased (Ziska *et al.* 2019). Climate change may also alter the efficacy of weed biological control through changes in plant nutrient content, which often declines with eCO_2 alongwith increases in insect activity with temperature; and shifts in phenology of both agents and host weeds (Reeves 2017). However, adaptive responses to such changes are difficult to predict, because biological control agents and host weeds, both will have the potential to adapt to new selective pressures (Holt and Hochberg 1997).

Ziska *et al.* (2010) demonstrated that increasing CO_2 resulted in significant increases in initial leaf area and root weight of the red rice, as early as 27 d after sowing (DAS) at 500 ìmol/mol and showed a greater physiological plasticity and genetic diversity among red rice relative to cultivated rice. Significant interactive effects of CO_2 and water availability have also been reported which altered the competitiveness between C_3 and C_4 species due to decrease in specific leaf area and stomatal conductance under eCO_2 (Elizabeth *et al.* 2004). Wing *et al.* (2021) reported C_3 (*Abutilon theophrasti*) species may not have been at a disadvantage comparison to *Amaranthus retroflexus* (C_4), species in response to low CO_2 and severe drought. Furthermore, C_4 species may have an advantage over C_3 species in response to eCO_2 and severe droughts.

Weed management strategies under climate change

Climate change is expected to result in varying growth rates for crops and weeds, which may have significant impacts on weed management and crop production. However, impact of climate change on crop-weed interactions are likely to based on various region and cropping systems. To address these challenges, effective mitigation strategies to reduce eCO_2, eT and other greenhouse gases are crucial at global level. Shifts in temperature and CO_2 levels are anticipated to exert direct effects on weeds. These changes may alter the crop-weed diversity and interacting and may promote weed infestation. Therefore, a comprehensive understanding of how climate change particularly eCO_2, higher temperatures, along with other climate variable affects crop-weed dynamics is crucial for evaluating the vulnerability in crop production (Valerio *et al.* 2013). Consequently, information about changes in weed shifts, weed mortality, fecundity, and phenology can be used to make effective weed management strategies in various crops in context to climate change.

Reducing climate change variables by Robust policies and actions aimed should be adopted to address root causes of climate change. Carbon dioxide, high temperatures, and other climate variables all impact herbicide efficacy, but herbicide chemistries respond differently to these variables.

The target weed specie also matters; certain weeds become less susceptible to some herbicides and others more susceptible. When utilizing herbicides in a hot/dry or cool/wet seasons, effective weed management practices become increasingly important. Hence, best management practices include identification of correct weed species, differential response of C_3/C_4 weeds and understanding use of optimized doses of herbicides at certain interval according to weather conditions, along with use of suitable adjuvant/surfactant and the right nozzle. However, such frequent applications will have negative impacts on environment and also enhance chances of a development of herbicide resistance in weeds at a faster rate, creating further challenges for weed management.

Therefore, understanding the effects of climate change on weed growth and herbicide activity is important to optimize herbicide applications for weed management in increasing carbon dioxide and temperature. The Intergovernmental Panel on Climate Change (Porter *et al.* 2014) emphasized use of physical, cultural, or biological weed control under Climate Change. Mechanical weed control techniques, such as hand-pulling, hoeing, tilling, and mowing, are widely used methods for limiting the spread and growth of weeds (Ross and Lembi 2009), but their effectiveness under climate change is undefined (Birthisel *et al.* 2021). Weed management by Drones or Robotic coupled with by improved plant-weed recognition software and sophisticated global positioning system which are currently not the popular weed management practice will be further researched as a potential means to control weeds under climate change scenario (Raja *et al.* 2020).

Additionally, herbicide effectiveness against weeds may be affected by changes in $CO_{2,}$ rainfall patterns and temperature which alter herbicide selectivity, efficacy and could lead to a mixed population of C_3 and C_4 weed species and further complicating weed management strategies. Use of non or less volatile formulation of herbicides may also be encouraged to avoid dissipation and rapid metabolism due to eCO_2 and temperature. Use of adjuvant, low volatile herbicides and their mixtures, slow release herbicide formulation may also be studied to be used for effective weed management under eCO_2 and temperature.

Reduction of the soil seedbank with use of herbicide mixture with multiple herbicide modes of action will be beneficial and this will also limit in rapid herbicides resistance evolution in weeds. Supplementing herbicides with mechanical weed control where possible, crop rotation with weed-competitive crops, use of weed-competitive cultivars, use of weed-suppressive cover crops, and other recommended practices for integrated weed management will further contribute in effective weed management under climate change. Elevated temperature and eCO_2 levels also responsible in affecting phenology and life cycle of many plants species (Brownsey *et al.* 2017), hence weed management practices especially timing of application of herbicide should be optimized for better weed management (Hatfield *et al.* 2011, Sondhia 2024).

Use of non-genetically modified or non GM crop specific for a specific herbicide can be used for effective weed management under climate situation, however, this may enhance herbicide persistence. Raising herbicide resistant crops can also significantly change weed community composition. Projected climate change scenario particularly eCO_2 and eT is of major concern and will require extensive research to understand impact of frequent use of herbicides for weed control and environmental sustainability. Comprehensive extensive research efforts that include ecological, physiological, and molecular analyses are needed to study the interactive effects of different climate variables on plant growth and herbicide performance. Adaptive management has the potential to help to tackle these changes in the systems (Williams & Brown, 2012). Integrating physical, chemical and biological control management practices under e CO_2 and temperature should be encouraged and adopted. There is also a strong need for research on development of integrated and more sustainable weed management practices in current and future climates for minimizing risk of weeds and to safeguarding the environment. Use of advanced technologies for real-time weed detection and precision herbicide application can increase management efficiency while minimizing environmental impacts (Rao and Korres 2023). Adoption of climate resilient and or stress-tolerant crop varieties, use of micro-irrigation, crop diversification, raised-bed planting, nutrient-smart practices, crop residue management may also contribute in margining weeds in climate change scenario.

Conclusions

Future weed management and agricultural production are likely to threatened by continuous rising CO_2 levels and resulting changes in global precipitation, temperature, relative humidity, and radiation. The competition among weed species and crops is influenced by changes in atmospheric CO_2, temperature, precipitation, and other changing growth factors. In addition, interactions among these environmental traits can have unanticipated consequences in weed growth and evolution. Most weed spread through seeds however, many weeds reproduce by vegetative propagation. Even some weeds produce allelopathic compounds that enable them to coexist and compete with crops. Due to predicted reduced efficacy of currently used herbicides; crop growth and productivity will be severely affected. Therefore, a broader understanding of the potential interactions between crops and weeds in context of climate change, particularly elevated CO_2, and high temperature, is essential to achieve higher crop production. The rapid increase and spread of herbicide resistance is another mega challenge under changing climate. Demographic behaviours, including germination, seed biology, life span, and fecundity will be influenced by increasing atmospheric CO_2 and temperature and will affect selection and adaptation processes. To tackle these challenges a more efficacious approach on basic research in weed biology to understand weed evolution, crop-weed interaction, effectiveness of herbicides, along with other weed management practices is required for deriving refined weed management strategies for ensuring higher crop productivity in future. A number of mitigation and adaptation strategies can be adopted to reduce the adverse impact of climate change on agricultural sustainability.

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