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Effect of Changing Temperature and CO_2 Concentration on Weed Dynamics and Behaviour: A Review

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Agriculture and climate change are interwoven with each other in various measures, as climate change is the main culprit of biotic and abiotic stresses, which has adverse impact on crops and weed flora and the effectiveness of weed management strategies. Indeed weed physiology and crop productivity has been greatly influenced by several means of climate variability. Climate change causes a shift in weed population dynamics by altering the physiological pathways with the

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changing temperature and CO_2 conditions. Climate change can affect crop-weed interactions by favouring C_4 weeds in increased temperature scenarios requiring adaptation and mitigation strategies. Weeds can also shift their range by invading into new areas and higher latitudes or altitudes due to climatic variability affecting weed diversity, establishment, and management. These factors helps in understanding the crop interactions, weed infestation and herbicide efficacy. This review paper summarizes the challenges that occur due to climate change in weed behaviour requiring more attention on sustainable agricultural production.

Keywords: Climate change; CO_2, temperature; C_3 weeds; C_4 weeds.

1. INTRODUCTION

"Climate plays a vital role in the growth and development of all living organisms specially crops. Crops are highly susceptible to any changes in climatic parameters as it is the key determinant of crop distribution at national and global levels. India is the world's third largest economy and the largest greenhouse gas emitter next to China and United States accounting for 7.5 % of global emissions. The rise in the CO_2 concentration in the atmosphere is one of the most important and indisputable phenomena that causes global climate change. If current emission trends continues, atmospheric CO_2 concentration is anticipated to reach levels of 600-700 ppm by the end of 21st century, up from today's around 419.4 ppm (pre-industrial period) levels with an increase of 0.5 per cent". This CO_2 enrichment will have an global impact on weeds and crop yields directly or indirectly (Chauhan et al. 2014) by altering the life cycle of various species and weed population dynamics in weed vegetation at a global scale. There are two varieties of crop species C_3 and C_4 based on photosynthetic pathway. Among the crops, C_3 crops comprises of 95% whereas C_4 species comprises 4 %, whereas among 15 weeds, 12 are C_4 and 3 are C_3 species.

According to IPCC 2014, "it is predicted that the atmospheric CO_2 concentration will range between 600 and 1000 ppm by the end of this century. Currently, in accordance with the most recent IPCC Sixth Assessment Report 2021, for 1850–1900 to 2013–2022 the updated calculations are 1.15 (1.00 to 1.25) °C for global surface temperature, 1.65 (1.36 to 1.90) °C for land temperatures. Climate change is the future global crisis and its effects on agricultural weeds have not been properly studied (Ramesh et al. 2017). The two important climatic factors *viz.,* CO_2 and temperature are associated with each other, and they both affect the whole biome, are expected to pose both direct and indirect impact on agricultural production, water availability, sustainability and therefore, food security" (Chauhan et al. 2014). Weeds alone contribute to an annual economic loss of $11 billion to India's produce (ICAR 2020). Nevertheless, sustainable weed management can be a challenge in the context of global climate change (Anwar et al. 2020). Weeds are generally, colonizers and have some unique biological traits and ecological amplitudes that enable them to successfully dominate crops in a habitat with changed environmental conditions.

1.1 Overview of Weeds

"Weeds are usually known as undesirable plant species that pose a major hindrance and yield losses (34 %) in crop production. Weeds have a superior genetic diversity than crop plants. Apart from this, they have various biological features of weeds which include dormancy, wide adaptability, competitive ability and high rate of seed production that allows these species to adapt to wide range of adverse environmental conditions" (Pagare et al. 2017). In general, both high temperatures and CO_2 levels can alter dominant weed species and aggravate weed growth (Ziska and Dukes 2011) increasing their photosynthetic rates and biomass production than non-weeds in agro-ecosystems (Kumar et al. 2023). Furthermore, changes in the climate worsen the problems caused by invasive alien weeds in agro-ecosystems at global scale resulting from their changes in population densities (Marambe and Wijesundara 2021).

According to Holm et al. (1997) most of the troublesome C_3 and C_4 weeds of the arable land are limited to tropical and subtropical regions, predominantly due to low temperatures at higher latitudes". Amid the 18 most troublesome weeds in the world (Holm et al. 1977), 14 are C_4, whereas of the 86 plant species which supply most of the world's food, only five are C_4 species (Patterson 1995). "Consequently, there are more than 450 "troublesome" weed species (both C_3 and C_4) that associate with about 50 major crops all over the world. In India, the major weed species which are having C_4 photosynthetic pathway includes *Cynodon dactylon, Cyperus rotundus, Eleusine indica, Dactyloctenium aegyptium* and *Echinochioa colona.* These plants with C_4 photosynthetic pathway are likely to exhibit a smaller response to elevated CO_2 concentration when compared to C_3 weeds which includes *Ageratum conyzoides, Chenopodium album*, *Argemone Mexicana* and *Alternanthera sessilis"* (Patterson, 1995). However, a varied range of C_3 and C_4 weeds are available in our Indian ecosystem (Table 1). This implies that, if a C_4 weed species does not respond to elevated CO_2, there are few chances that a C_3 weed species will respond to it. Therefore, weeds with C_3 and C_4 photosynthetic pathways may show differential responses to higher CO_2 levels and temperatures, which can affect the dynamics of crop–weed competition which is discussed in detail in this review (Billore 2019).

Weed competition is having increasing trend i.e., 45 % globally from 36% during 2006 (Alemu et al. 2014 & Gharde et al*.* 2018). The total economic loss of about USD 11 billion was estimated due to weeds alone in 10 major crops of India *viz.,* groundnut (35.8%), soybean (31.4%), green gram (30.8%), pearl millet (27.6%), maize (25.3%), sorghum (25.1%), sesame (23.7%), mustard (21.4%), direct-seeded rice (21.4%), wheat (18.6%) and transplanted rice (13.8%). Besides this, Billore (2019) has stated that climate changes in environment might result in few weed reactions such as migration or range shift, acclimatisation within their phenotypic plasticity by both avoidance and tolerance followed by adaptation to climate changes by morphological, physiological, and genetic processes at the individual plant scale.

1.2 Crop–Weed Interaction

The increasing levels of CO_2 and predicted climate change may benefit the establishment and proliferation of weeds over crops owing its wide genetic (Malarkodi et al. 2017) which can have negative impact on agricultural productivity (Peters et al. 2016, McConnell 2016; Korres et al. 2016) and quality (Pawar et al. 2022) by competing for nutrients, water and light. Ziska (2000) concluded that under growth chamber and greenhouse experiments higher CO_2 favoured the growth of C_3 and C_4 species. In most of the experiments, indicates that vegetative growth of C_3 crops is favoured relative to C_4 weeds with rising CO_2, while primary results suggest that C_3 weeds may be favoured over C_3 crops as CO_2 increases due to C_3 pathway (Ghannoum et al. 2000). Therefore, if C_3 plants can successfully compete during the initial establishment stage in early spring meanwhile their survival ability will be greatly enhanced by high temperature stress and elevated CO_2 (Lee et al. 2011).

Climate change is expected to cause shifts in weed community compositions, specially their population dynamics may decline due to less phenotypic plasticity, life cycle, phenology and infestation pressure (Anwar et al. 2021; Peters et al. 2014). Ziska (2000) reported that crop/weed interactions vary considerably by geographical region, within a given region, depending on factors such as temperature, precipitation, *etc*. C_3 and C_4 crops may interact with both C_3 and C_4 weeds. Demographic traits, including seed biology, germination, life span and fecundity will be influenced by climate/ CO_2, with consequences for selection and adaptation (Ziska et al. 2018). "Apart from weed biology, its distribution, floral structure, weed floral composition, prevalence, invasiveness, proliferation and dispersal will be affected by climate change and most likely result in the failure of existing weed management practices" (Dayan 2019). Very fewer studies have been conducted on the effect of climate change on weeds in India. Hence, in this paper an effort has been made to review the impact of changing climate on distribution, growth and biology of weeds.

"A set of unique biological characteristics like persistence, tolerance, competitiveness, aggressiveness, adaptability, seed dispersal, regeneration capacity, evolutionary strategies and high fecundity, these superior characteristics enable weeds to survive in a wide range of adverse environmental conditions in crop fields or any other disturbed habitats" (Anwar et al. 2021). "Climatic variables control many plant physiology functions that impact flowering, fruiting, and seed dormancy. Weeds that rely on vegetative dispersal will not spread as quickly as weeds that have effective seed-dispersal systems (wind, water and birds). Perhaps, as temperature, climate and CO_2 change, it is expected that weed populations will change in parallel with cropping systems, with consequences for plant community, composition, off course, weed-crop interactions and chemical management" (Blumenthal et al. 2022). Weeds

Table 1. List of important weeds in India (Singh et al. 2011; Manisankar and Ramesh 2019; Naidu et al. 2015)

Weed species	Common name	Photosynthetic pathway	Life cycle	Family
Ageratum conyzoides	Goat weed	C_3	Annual broad-leaved herb	Asteraceace
Alternanthera sessilis	Sessile joy weed	C_3	Perennial broad-leaved herb	Amaranthaceae
Amaranthus spinosus	Spiny pigweed	C_4	Annual broad-leaved herb	Amaranthaceae
Amaranthus viridis	Slender amaranth	C_4	Annual broad-leaved herb	Amaranthaceae
Argemone mexicana	Mexican poppy	C_3	Annual broad-leaved herb	Papaveraceae
Commelina benghalensis	Day flower	C_3	Annual broad-leaved herb	Commelinaceae
Chenopodium album	Common lambsquaters	C_3	Annual broad-leaved herb	Amaranthaceae
Chloris barbata	Purpletop chloris	C_3	Annual or short- lived perennial grass	Poaceae
Convolvulus arvensis	Field bind weed	C_3	Perennial broad-leaved climbing herb	Convolvulaceae
Cyperus rotundus	Purple nutsedge	C_4	Perennial herb	Cyperaceae
Cynodon dactylon	Bermuda grass	C_4	Perennial herb	Poaceae
Dactyloctenium aegyptium	Crowfoot grass	C_4	Annual herb	Poaceae
Digitaria sanguinalis	Large crabgrass	C_4	Annual spreading grass herb	Poaceae
Eleusine indica	Goose grass	C_4	Annual erect tufted grass	Poaceae
Euphorbia hirta	Garden spurge	C_4	Annual deep rooted herb	Euphorbiaceae
Echinochioa colona	Jungle rice	C_4	Annual grass herb	Poaceae
Parthenium hysterophorous	Congress grass	C_3-C_4	Annual herb	Asteraceace

are more competitive over crops, colonising ability and enhanced aggressively hence weed management practice becomes a challenging task (Chongtham et al. 2019). Malarkodi et al. (2017) grouped crop–weed combinations in arable ecosystems into the following four categories: (a) C_4 weeds in C_3 crops; (b) C_3 weeds in C_3 crops; (c) C_3 weeds in C_4 crops; and (d) C_4 weeds in C_4 crops.

2. WEED RESPONSE TO CLIMATE CHANGE SCENARIOS

2.1. Effect of Elevated CO_2 on Weeds

Growth of plants increased in response to high atmospheric CO_2 in a species-specific manner. Treharne (1989) stated that the physiological plasticity and greater genetic diversity of weed species relative to modern crops would provide a greater competitive advantage as atmospheric CO_2 rises. This rise in CO_2 levels are likely to be accompanied by higher temperature favouring C_4 weeds over C_3 crops (Fuhrer 2003). Increasing CO_2 stimulated the crop-weed (i.e., the C_3/C_4) biomass ratio (Ziska and Bunce 2000). Patterson (1993) indicated that the relative increase in plant biomass in weeds and crops at doubling of CO_2 concentration might reach over 2.4 times in C_3 compared to 1.5 times in C_4, with weeds gaining more growth than crops in both the categories.

“Interactions between climate change and other processes (such as changes to land use), may also turn some currently non-threatening species (both native and non-native) into invasive species and may lead to ‘sleeper’ weeds becoming more actively weedy” (Irmaileh 2011). These are likely to alter the evolutionary basis for ecotype differentiation and the ability of weeds to disperse and colonize quickly resulting in destructive outbreaks (Trumble and Butler 2009).

Elevated CO_2 has resulted in increases in leaf area by 40%, 67%, and 24% and biomass by 39%, 83%, and 59% in *Chloris gayana* Kunth, *Eragrostis curvula* (Schrad.) Nees, and *Paspalum dilatatum* Poir, respectively, while there was a decrease in leaf area by 34% and biomass by 5% in *Sporobolus indicus* (L.) R.Br (Ziska & Bunce 2000). Conversely, the application of glyphosate on weeds grown under elevated CO_2 conditions resulted in a higher survival rate of *C. gayana, E. curvula,* and *P. dilatatum* as compared to the plants grown under normal CO_2 conditions, while there was no effect of increased CO_2 on the survival of *Sporobolus indicus* (L.) R. Br. (Manea et al. 2011).

Ziska (2003) reported that *Cirsium arvense* (L.) Scop where both roots and shoots accumulated more biomass when grown under increased CO_2 conditions (up to 700 ppm), but the accumulation in root biomass was higher as compared to shoot biomass in *Parthenium hysterophorus*. As it is parthenium weed is considered to be C_3/C_4 intermediate species. There was substantial increase in the height (52 %), number of leaves produced per plant, leaf length, biomass (55 %), branching (62 %), leaf area (120 %), net leaf photosynthesis (94 %), stem base area (34 %), plant biomass production, larger number of capitula with higher number of seeds and water use efficiency (400 %) of *P. hysterophorus* plants at an elevated CO_2 concentration (550 ppm) as compared to ambient CO_2 concentration (380 ppm) as reported by Shabbir et al. (2019), Navie et al. (2005), Nguyen et al*.* (2017) and Khan et al. (2015).

Navie et al*.* (2005) reported elevated CO_2 had no effect on the above ground biomass and length of the longest tiller of *Cenchrus ciliaris* plants, but fewer tillers were produced by plants grown at 480 ppm CO_2 as compared to above-ground biomass production of both *P. hysterophorus* and *C ciliaris*. Apart from this, they reached early maturity by early flowering within 53 days over 70 days than that of ambient (Ziska 2011). There was 70 % increase in growth and development in *Cirsium arvense* L., an invasive perennial C_3 weed species, in *Amaranthus viridis,* in *Parthenium hysterophorous* (C_3 weed) (Naidu and Paroha, 2008), in Canada thistle (C_3 plant type) (Ziska et al. 2004).

“An increase in *Chenopodium album* L. biomass was observed even up to 1500 ppm CO_2 concentration. However, a further increase in CO_2 concentration to 3000 ppm reduces biomass accumulation in *C. album* but still, the biomass accumulation remained higher than that at 350 ppm” (Pilipavicius et al. 2015). Apart from this, the growth indices such as relative growth rate, net photosynthesis rate and biomass accumulation of two C_3 weeds, *Euphorbia heterophylla* L. and *Commelina diffusa* Burm. f. increased by 80.5%, 16.7%, 143% and 60.5%, 9.5%, 108%, respectively, under increased CO_2 conditions as compared to normal CO_2 (Awasthi et al. 2018). Again, the degree of response varied with weed species in a research conducted at Directorate of Weed Science, Jabalpur where *Dactyloctenium aegyptium* and *Echinochloa colona* responded to elevated CO_2, but *Cyperus rotundus* and *Eleusine indica* did not respond to CO_2 enrichment (Mahajan et al. 2012). Other studies indicate that significant morphological and dry matter production alterations were seen in invasive *M. micrantha* and *W. trilobata* as a result of the higher CO_2 levels Song et al. 2009.

"A significant reduction in soybean seed yield was observed with either weed species *viz*., C_3 weed (*Chenopodium album* L.) and a C_4 weed (*Amaranthus retroflexus* L.) relative to the weed-free control at either ambient CO_2 or elevated CO_2 (ambient + 250 ppm) (Ziska 2000). However, for lambsquarters the reduction in soybean seed yield relative to the weed-free condition increased from 28 to 39% as CO_2 increased, with a 65% increase in the average dry weight of lambsquarters at enhanced CO_2. On the contrary, for pigweed, soybean seed yield losses reduced with rising CO_2 from 45 to 30%, with no change in the average dry weight of pigweed. In a weed-free environment, elevated CO_2 resulted in a significant increase in vegetative dry weight and seed yield at maturity for soybean (33 and 24%, respectively) compared to the ambient CO_2 condition" (Ziska and Teasdale 2000).

Elevated CO_2 had predetermined effect on reproduction and dispersal of weed species as in case of ragweed (*Ambrosia artemisiifolia*) predicted in the year 2100 doubled the quantity of pollen produced by 61 % more than that of ambient CO_2 (Ziska and Caulfield 2000). Wayne et al. (2002) reported increased shoot height by 9% and total seed mass by 31% in elevated CO_2 in ragweed (*Ambrosia artemisiifolia* L.)

"Likewise, elevated CO_2 had significant effects on plant water relations in both C_3 and C_4 grass species, via reductions in stomatal conductance, reduced transpirational water loss. This indeed increases shoot water potential in grasses, indirectly it improves soil and leaf water relations" (Moutinho-Pereira 2004). Physiological traits like relative water content (RWC %), membrane stability index (MSI %), chlorophyll content, photosynthetic rate and TSS content were improved under elevated CO_2 (Dwivedi et al. 2015). Contradictorily, there are few studies where it is reported that both the photosynthetic pathways are the same, in general, the weed growth is favoured by CO_2 elevation over that of crop plants (Ziska and George 2004).

2.2 Effect of Elevated CO_2 on Weeds in Crops

The CO_2 concentration increment was 2 ppm/ year during past three years (Nalli et al. 2018). Steady increase in atmospheric CO_2 concentration is noted and predicted to reach 700 ppm at the end of the 21st century (Houghton et al. 1996).

The beneficial effects of elevated CO_2 on most crops is negated by elevated temperature and there are no beneficial effects of elevated CO_2 on C_3 crops (bean, *Phaseolus vulgaris* L; Prasad et al. (2002); peanut, *Arachis hypogaea* L.; Prasad et al. (2003) and C_4 crops (grain sorghum, *Sorghum bicolor* L. Moench; Prasad et al. (2006). In contrast, C_3 weeds (lambsquarters, velvetleaf (*A theophrasti*), common ragweed (*Ambrosia artemisiifolia*), and giant ragweed (*Ambrosia trifida*) will respond more favourably to increased CO_2 levels and offer stiffer competition to C_4 crops (maize, sorghum, sugarcane, *etc*.). At elevated CO_2 concentrations, relative yield and competitive ability of C_3 plants, soybean and lambsquarters were significantly higher than that of C_4 plants, millet and pigweed (Miri et al. 2012). The positive influence was more predominant on *Alternanthera paronychioides* in comparison to *Ludwikia chinensis* under elevated CO_2 and temperature. Therefore, *Alternanthera paronychioides* may become a major problematic weed in futuristic climate change scenario (Pawar et al. 2022). Valerio et al. (2013) reported that elevated CO_2 could potentially enhance the degree of weed damage from a C_4 weed, relative to a C_3 crop (tomato) in competitive mixtures, even at ambient temperature.

Increasing CO_2 concentration had no effect on growth and plant height in the C_4 species, *Amaranthus retroflexus,* Sorghum (*Sorghum halepense* (L.) Pers (C_4) *Festuca elatior* L. (C_3) A C_3 weed can be benefitted more than a C_4 at increased CO_2 levels (Carter and Peterson 1983). Ziska (2003) reported that crop–weed interactions resulted in increased weed biomass of weeds such as Velvetleaf (*Abutilon theophrasti*) (C_3) and Redroot pigweed (*Amaranthus retrojlexus*) (C_4) Sorghum (*Sorghum halepense* (L.) Pers (C_4) and reduced yield loss of sorghum at elevated CO_2. Likewise, Ziska and Goins (2006) found that long-term (seasonal) exposure to elevated CO_2 during the growing season facilitated the number and size of C_3 weeds relative to C_4 grasses from the weed seed bank with significant changes in weed demographics and populations.

Rogers et al. (2008) noticed that purple nutsedge (20.3%) had predominant weed biomass in terms greater leaf area, root length, numbers of tubers and more tillers while in yellow nutsedge (5.2%), tuber number alone under high CO_2. While in increased under CO_2 enrichment. Perhaps, the rate of yield reduction in crop could be aggravated with the increase in weed biomass. *E. colona* and *I. rugosum* are dominant weed species causing significant yield loss by 31.12%, slight reduction in plant height by 13 %, dry weight was increased by 13.42 % impaired the root nodule number and reduced seed quality in soybean (Reddy et al. 2016 and Chander et al. 2023). Likewise, the problems of *P. minor* and *A. ludoviciana* in wheat would aggravate with increase in CO_2 due to climate change (Mahajan et al. 2012).

In rice fields, weedy rice (*Oryza sativa* L.) responds more strongly than cultivated rice to rising CO_2 level with greater competitive ability (Ziska et al. 2010). Elsewhere, plant height was reduced by 20.78 %, panicle length by 31%, number of grains/panicle by 60.88 %, number of tillers/plant by 25 %, yield by 58.77%, test weight by 17.65 % at elevated CO_2 condition in rice crop (Pawar et al. 2022).

Similar increase in pod, seed yields and biomass accumulation of the C_3 weed (*Abutilon theophrasti* Medik.) were reported by Ziska et al. (2013). Elevated CO_2 increased the vegetative biomass and leaf area of common cocklebur (*Xanthium strumarium* L.) relative to that of sorghum crop (Ziska 2001) in competitive mixtures (Varanasi et al. 2016). These all findings prove the fact that under present CO_2 levels, C_4 plants are more photosynthetically efficient than C_3 weeds indeed important C_4 crops may become more vulnerable to increased competition from C_3 weeds (Jinger et al. 2017).

The other means by which the climate change affected the weeds and crops were crop mechanisms such as evapotranspiration, photosynthesis and water use efficiency. Drake et al. (2017) recorded evapotranspiration (ET) reduction by 17–22% in the C_3 and 28–29% in the C_4 community at elevated CO_2. Carlson and Bazzaz (1982) reported that ambient CO_2 enrichment from 300 to 600 ppm increased water use efficiency (WUE) of soybean (C_3) and corn (C_4) by 48% and 54%, respectively, conversely the same recorded for a C_3 weed, velvetleaf (*Abutilon theophrasti*) and a C_4 weed redroot pigweed (*Amaranthus retroflexus*) were 87% and 76%, respectively.

Apart from, increasing CO_2 had alleviated the multiplication by early flowering, early maturity and dispersal of reproductive parts easily. Elevated CO_2, wild oat (*Avena fatua*), seeds matured two weeks in advance as compared to the plants grown under ambient CO_2 conditions (Naidu 2011). For instance, C_3 weeds like *Phalaris minor* and *Avena ludoviciana* in wheat (C_3) would aggravate with the increase in CO_2 due to climate change (Naidu 2015). *Phalaris minor* was more competitive over wheat with CO_2 enrichment under drought condition (Naidu and Varshney 2011). In few cases, RGR increase was in green gram (42.5 to 132.5), *E. geniculate* (375.4 to 677.7) and *C. diffusa* (61.5 to 98.7 mg plant^{-1} day^{-1}) respectively from ambient to elevated CO_2 (Awasthi et al. 2018).

In sorghum crop, the increase in CO_2 was associated with a threefold increase in aboveground biomass of velvetleaf and doubled number of seed pods per plant (6.1 to 11.5), but non-significant, increase in the aboveground biomass of redroot pigweed. At elevated CO_2, significant reductions in leaf area and weight, as well as in average seed weight were observed for sorghum when grown with redroot pigweed (Ziska 2003).

2.3 Effect of Temperature on Weeds

Conversely, temperatures above 25°C hinders CO_2 assimilation and increase photorespiration in C_3 plants (Ogren 2005). While in C_4 plants because CO_2 pumps in mesophyll cells maintaining low photorespiration rates by PEP carboxylase in bundle sheath cells at all temperatures (Hatch 1987 and Hadi 2020). The growth and development of the different crop species was reduced at elevated temperature in presence of weeds like in case of rice crop, the plant height was reduced by 21.72 %, panicle length by 11.81 %, number of grains/panicle by 47.87 %, number of tillers/plant by 31.58 %, yield by 62.73 % and test weight by 3.63 %. Meanwhile, under both elevated temperature and elevated CO_2 the plant height was reduced by 23.20 %, panicle length by 6.39 %, number of grains/panicle by 51.45 %, number of tillers/plant by 23.08%, yield by 50.68% and test weight by 7.87 (Pawar et al. 2022). This indicates and proves the fact that the dramatic reduction was more under combination rather than that of individual effect.

Higher mean annual temperatures favour assimilate partitioning towards root biomass in introduced exotic species *Prosopis juliflora* in southern India (Kathiresan 2006). For example, Tungate et al. (2007) studied the effect of temperature on soybean, *Sida spinosa* (*prickly sida*) and *Cassia obustutifolia* (sickle pod) reported that there was an increasing trend in root: shoot ratio in all species with increasing temperatures, however, the weeds steadily had higher root: shoot ratios. At temperatures where maximum growth occurred, the root: shoot growth ratio of soybean (at 32/ 27^oC) was 0.8, and it was 1.3 and 1.6 for *Sida spinosa* (at 36/31 ^oC), and *Cassia obustutifolia* (at 36/31^oC), respectively.

Similarly, Oleti et al. (2025) reported that the average chlorophyll content was the highest under elevated temperature conditions up to week 6 and began decreasing after that for yellow foxtail and palmer amaranth. The more vigorous growth and higher photosynthetic efficiency was observed in both the weed species. Although weeds like *Datura stramonium* L., a weed that exhibits high growth under high temperatures, is expected to become a more aggressive competitor in the face of altered climatic conditions (Jiménez-Lobato et al. 2018).

Conversely, under warmer conditions, *Setaria viridis* (L.) P. Beauv. germinated later in the (August) season in maize fields (Dekker 2003). “This was a beneficial temporal non-synchrony with emergence of a maize crop, avoiding crop-weed competition. In contrast, a recent study indicated that this species would be a problematic weed in maize-based cropping systems erstwhile through synchrony with maize emergence, which is probably due to stimulation by increased temperature” (Peters et al. 2014). Chung (2011) reported that emergence and flowering of *Chenopodium album* advanced by 50 days with an increase of 4 °C in temperature.

2.4 Effect of Temperature Rise on Weeds in Crops

According to IPCC (2007) report, has projected that by 2100 earth’s mean temperature will rise by 1.4 to 5.8 °C. The rise in temperature has a differential response on different weeds and their growth and development. Increase in temperature is known to have little effect on CO_2 assimilation in C_4 plants because CO_2 pumps in mesophyll cells maintain low photorespiration rates at all temperatures. Effect of temperature can be of two types; elevated and low temperature (chilling or freezing injury). High temperature curtails the growth phase and grain filling duration through pollen sterility, lowering test weight and poor anthesis (Kadam et al. 2014). In few cases, Asseng et al. (2004) reported that increasing average temperatures reduced flowering time, total biomass, and grain yield.

Conversely, Entz and Fowler (1991) has reported that “higher temperatures accelerated the rate of plant development and reduced the length of the growing period in crop”. For example, the predicted increase in ambient temperature is likely to advance the development of parthenium weed, inducing rapid development and a shorter life span span (Mainali et al. 2015; Bajwa et al. 2019). Nguyen et al*.* (2017) also reported similar findings where Parthenium seedlings showed greater plant height, leaf length, mean dry biomass, seed numbers, seed viability number of filled seeds per plant grown under the warm, dry conditions, survived longest (236 days) whilst the plants grown under cool and wet conditions were short lived (173 days) comparatively. Warm conditions will also promote the reproductive ability of parthenium weed, by promoting seed production and seed fill percentages, promoting dormant seed production and producing seed with the capacity to live longer in the soil seed bank. Apart from this, the parthenium seedlings grown under the warm, dry conditions commenced flowering first (after 40 days) and set seed first (54 days), whilst the plants grown under the cool and wet conditions, flowered last (after 65 days) and set seed last (90 days). Similarly, the plants grown under warm conditions flowered first (after 49 days) and set seed first (62 days), whilst the plants grown under cool conditions flowered last (after 57 days) and set seed last (81 days). The plants grown under dry conditions also flowered first (after 44 days) and set seed first (62 days), whilst the plants under wet conditions flowered last (61 days) and set seed last (80 days).

The growth rate of itch grass (*Rottboellia cochinchinensis*), a highly competitive C_4 weed in many cropping systems, including sugarcane, corn, cotton, soybean, grain sorghum and rice systems, is projected to increase and cause the weed to invade many parts of the world with only an increase of 3°C in temperature [95]. Similar results were also represented by Ziska and Bunce (2007) where 88 % increase in biomass and 68 % increase in leaf area of itch grass [*Rottboelliia cochinchinensis* (Lour.) W.D. Clayton] were observed in response to a 3°C increase in temperature.

An increase in temperature by 2ºC decreased the plant height by 6.25% in weed free soybean over the ambient condition. Whereas, the plant height of soybean was found to be significantly reduced by 49.47% due to weed interference. However, weed interference had a profound effect on yield and yield attributes of soybean and it was observed that the plant height, plant dry weight, the number of pods/plant and yield decreased by 47.80 %, 95.42 % and 56.40 % respectively, over the ambient condition (Chander et al. 2023). In general, this could be ascribed due to increasing temperature will increase sucrose synthesis, transport and utilization for CO_2-enriched herbaceous plants and decrease carbohydrate accumulation within the leaf (Farrar and Williams 1991). In contrast, elevated temperatures decrease carbohydrate accumulation within source and sink regions of a plant and decrease root: shoot ratios.

Under higher temperature and drought conditions, C_4 weeds such as *Amaranthus retroflexus* tend to dominate C_3 crops (e.g., soybean). The infestation of *Phalaris minor* is expected to worsen in wheat fields with CO_2 increase (Mahajan et al. 2012). Likewise, weedy rice will compete more intensely with cultivated rice (Ziska et al. 2010).

At both the ambient temperature and the 3°C higher temperature, *Blyxa aubertii* had the highest density. While *Echinochloa* has the lowest density at a 2°C temperature rise, *Bidens pilosa* has the lowest density at a 3°C temperature increase and in ambient conditions (maximum average 27.2°C) (Reddy et al. 2023).

The response to temperature has been documented well in advance at the time of seed germination itself where the soil temperature is the primary determinant for weed species specially, when there is temperature fluctuations (Zimdahl 2007). It is likely that the C_4 weed species are more favoured at higher temperature to produce greater biomass than others (Singh et al. 2011). Other than this, the rise in temperature has predominant effect on ontogeny in a case where with an increase of 4 °C in temperature, the timings of emergence were advanced by approximately 26 days for *C. album* and approximately 35 days for *S. viridis*. The flowering times were also advanced, by 50 days for *C. album* and by 31.5 days for *S. viridis* (Lee et al. 2011).

2.5 Interactive Effect of Elevated CO_2 and Temperature on Weeds

"Weeds are likely to show greater resilience and better adaptation to changes in CO_2 concentrations and rising temperature in competition with crops due to their diverse gene pool and greater physiological plasticity" (Varanasi et al. 2016). "The beneficial effects of elevated CO_2 on C_3 plants results in higher photosynthetic rate than plants grown in ambient CO_2 conditions. However, beyond crop's optimum level, if elevated CO_2 is combined with high temperature level the increase in yield may decline or get reversed" (Backlund et al. 2008). "Increase in CO_2 and warmer temperatures may induce faster growth in determinate crops such as cereals by stimulating photosynthesis and vegetative growth" (Kadam et al. 2014). Increasing CO_2 and altered temperature and precipitation are therefore likely to affect all aspects of weed biology (Peters et al. 2014), including establishment (Clements et al. 2021), competition (Valerio et al. 2011), distribution (Bradley et al. 2010) and management (Waryszak et al. 2018). Weeds comes under C_3 pathway may dominate under elevated CO_2 conditions, whereas in elevated temperature, C_4 weeds may dominate.

"Under elevated CO_2 and temperature conditions, it is known to improve physiological traits (RWC, membrane stability, chlorophyll content, photosynthetic rate and TSS) may benefit rice genotypes" (Dwivedi et al. 2015). It seems that under elevated CO_2, only when weed is C_4 and crop is C_3, crop is likely to be benefitted, whereas in all other cases weeds are projected to outwit crop in a crop-weed competition situation (Jinger et al. 2016). The interactive effect of elevated CO_2 and temperature showed that C_4 weeds dominate over C_3 weeds. For example, C_3 crop such as rice and wheat, elevated CO_2 may have positive effects on crop competitiveness with C_4 weeds (Furher 2003). "Crop-weed competition was low at elevated CO_2 whereas high under elevated temperature. The interactive effect of elevated CO_2 and temperature on crop-weed competition was high. Hence, weed management is considered as a major threat to future agriculture" (Manishankar and Ramesh, 2019).

However, weed interference had a negative effect under the combined effect of elevated CO_2 and temperature. It was observed that the plant height, dry weight, the number of pods/plant and yield of soybean was significantly decreased by 6.01%, 18.78%, 49.70% and 33.42% in comparison to weed-free ambient conditin. In quack grass (*Elytrigia repens*) (Tremmel and Patterson 1993). increasing CO_2 improved the effects of high temperature on and increased growth and reproduction, and also *Echinochloa colona* and *I. rugosum* weeds. Lim et al. (2015) showed positive growth performance in terms of the plant height, dry weight, number of tillers/plant and biomass under elevated CO_2, elevated temperature and combined effect of elevated CO_2 and elevated temperature, respectively over ambient conditions (Chander et al. 2023). While, in few cases, Alberto et al. (1996) reported that CO_2 concentration had no effect, increasing growth temperature resulted in a significant reduction in time to maturity (91 and 72 days, 62 and 34 days) for rice and *E. glabrescens* at the 27/21 and 37/29°C temperatures, respectively. Conversely, O'Donnell and Adkins (2001) proposed that "ratio of root to shoot weight, values for wild oats lines grown with elevated CO_2 were relatively twice that of plants grown in ambient CO_2. Whereas the wild oats grown at high temperature 23/19 °C (day/night) completed their development faster than those grown at normal temperature 20/16°C. If the maturation rate is faster relative to the crop, more seeds may be deposited in the soil with a consequent increase in seed bank of wild oat plants".

"Similarly, the weed interference severely impaired rice grain yield and yield attributes under elevated CO_2 and temperature. It was also observed that the response of *Alternanthera paranochioides* was more under elevated CO_2 compared to *Ludwikia chinensis*. Elevated CO_2 had a positive effect on yield and yield attributes of weed free rice, whereas, elevated temperature had deleterious effect. Under the combined effect of elevated CO_2 and temperature the negative effect of elevated temperature was negated by elevated CO_2 in weed free rice" (Pawar et al. 2022).

Valerio et al. (2013) found that increasing CO_2 from 400 to 800 ppm reduced the crop losses due to *Chenopodium album* and *Amaranthus retroflexus* in tomato from 33% to 32%, but when both CO_2 concentration and temperature were increased from 400 to 800 ppm and 21/12 °C to 26/18 °C day/night respectively, then crop losses due to weed infestation increased from 55% to 61%. Aberto et al. (1996) reported that increasing CO_2 may also result in elevated growth temperatures, the response of rice to each CO_2 concentration was also examined day/night temperatures of 27/21 and 37/29 °C. At 27/ 21˚C, increasing the CO_2 concentration resulted in a significant increase in above ground biomass (+47%) and seed yield (+55%) of rice when averaged over all mixtures. Grain yield of rice almost doubled relative to the weedy species (*Echinochloa glabrescens*). Increasing CO_2, concentration and increasing growth temperature per se resulted in a significant increase (+41 %) and significant decrease (-13%) in the above-ground biomass of individual rice plants. Likewise, in a study conducted by Jabran and Dogan (2018) in *Bromus tectorum*, *Hordeum murinum*, and *Lactuca serriola* showed that leaf area consistently responded to higher CO_2 concentration than a combination of high CO_2 concentration and elevated temperature.

3. CONCLUSION

The future line of interest will become the study on management of invasive weed species as influenced by climate change. In addition to this, weed dynamics or weed shift needs to be studied in both cropped and non-cropped areas. Under this changing climate scenario, the right adaptive mechanism, or strategy need to be focused upon in a cost effective way. Based on this elevated CO_2 or increasing temperature condition the dosage of herbicide has to be altered accordingly in order to overcome herbicide resistance or tolerance to keep the weeds under the bay. This review is mainly focused on the discussion of changes in temperature and CO_2 as both direct (CO_2 stimulation of weed growth) and indirect effects (climatic variability on weed biology). Rising CO_2 may be a selection factor in weed species dominance.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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