

## Review Article

### Effect of changing temperature and CO<sub>2</sub> concentration on weed dynamics and behaviour: A

#### Review

#### 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 changing temperature and CO<sub>2</sub> conditions. Climate change can affect crop-weed interactions by favouring C<sub>4</sub> 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<sub>2</sub>, temperature, C<sub>3</sub> weeds, C<sub>4</sub> 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<sub>2</sub> 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<sub>2</sub> concentration is anticipated to reach levels of 600-700 ppm by the end of 21<sup>st</sup> century, up from today's around 419.4 ppm (pre-industrial period) levels with an increase of 0.5 per cent. This CO<sub>2</sub> enrichment will have an global impact on weeds and crop yields directly or indirectly

[1] 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 [2]. 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 [1]. Weeds alone contribute to an annual economic loss of \$11 billion to India's produce [3]. Nevertheless, sustainable weed management can be a challenge in the context of global climate change [4]. 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 [5]. In general, both high temperatures and  $CO_2$  levels can alter dominant weed species and aggravate weed growth [6] by increasing their photosynthetic rates and biomass production than non-weeds in agro-ecosystems [7]. 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 [8].

According to Holm et al. [9], 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.,[10], 14 are  $C_4$ , whereas of the 86 plant

species which supply most of the world's food, only five are C<sub>4</sub> species [11]. Consequently, there are more than 450 “troublesome” weed species (both C<sub>3</sub> and C<sub>4</sub>) that associate with about 50 major crops all over the world. In India, the major weed species which are having C<sub>4</sub> photosynthetic pathway includes *Cynodondactylon*, *Cyperusrotundus*, *Eleusineindica*, *Dactylocteniumaegyptium* and *Echinochioacolona*. These plants with C<sub>4</sub> photosynthetic pathway are likely to exhibit a smaller response to elevated CO<sub>2</sub> concentration when compared to C<sub>3</sub>weeds which includes *Ageratum conyzoides*, *Chenopodium album*, *Argemone Mexicana* and *Alternantherasessilis* [11]. However, a varied range of C<sub>3</sub> and C<sub>4</sub> weeds are available in our Indian ecosystem (Table 1). This implies that, if a C<sub>4</sub> weed species does not respond to elevated CO<sub>2</sub>, there are few chances that a C<sub>3</sub> weed species will respond to it. Therefore, weeds with C<sub>3</sub> and C<sub>4</sub> photosynthetic pathways may show differential responses to higher CO<sub>2</sub> levels and temperatures, which can affect the dynamics of crop–weed competition which is discussed in detail in this review [12].

**Table 1: List of important weeds in India**

[13]; Manisankar and Ramesh, [14]; Naidu et al.,[15]

Weed species	Common name	Photosynthetic pathway	Life cycle	Family
<i>Ageratum conyzoides</i>	Goat weed	C <sub>3</sub>	Annual broad-leaved herb	Asteraceace
<i>Alternantherasessilis</i>	Sessile joyweed	C <sub>3</sub>	Perennial broad-leaved herb	Amaranthaceae
<i>Amaranthus spinosus</i>	Spiny pigweed	C <sub>4</sub>	Annual broad-leaved herb	Amaranthaceae
<i>Amaranthus viridis</i>	Slender amaranth	C <sub>4</sub>	Annual broad-leaved herb	Amaranthaceae
<i>Argemone mexicana</i>	Mexican poppy	C <sub>3</sub>	Annual broad-leaved herb	Papaveraceae
<i>Commelinabenghalensis</i>	Day flower	C <sub>3</sub>	Annual broad-leaved herb	Commelinaceae
<i>Chenopodium album</i>	Common lambsquarters	C <sub>3</sub>	Annual broad-leaved herb	Amaranthaceae
<i>Chloris barbata</i>	Purpletopchloris	C <sub>3</sub>	Annual or short-lived perennial grass	Poaceae
<i>Convolvulus arvensis</i>	Field bind weed	C <sub>3</sub>	Perennial broad-leaved climbing herb	Convolvulaceae
<i>Cyperus rotundus</i>	Purple nutsedge	C <sub>4</sub>	Perennial herb	Cyperaceae

<i>Cynodondactylon</i>	Bermuda grass	C <sub>4</sub>	Perennial herb	Poaceae
<i>Dactylocteniumaegyptium</i>	Crowfoot grass	C <sub>4</sub>	Annual herb	Poaceae
<i>Digitariasanguinalis</i>	Large crabgrass	C <sub>4</sub>	Annual spreading grass herb	Poaceae
<i>Eleusineindica</i>	Goose grass	C <sub>4</sub>	Annual erect tufted grass	Poaceae
<i>Euphorbia hirta</i>	Garden spurge	C <sub>4</sub>	Annual deep rooted herb	Euphorbiaceae
<i>Echinochioacolona</i>	Jungle rice	C <sub>4</sub>	Annual grass herb	Poaceae
<i>Partheniumhysterophorous</i>	Congress grass	C <sub>3</sub> -C <sub>4</sub>	Annual herb	Asteraceace

Weed competition is having increasing trend i.e., 45 % globally from 36% during 2006 (Alemuet al., [16]Ghardeet al.[17]. 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 [18] 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<sub>2</sub> and predicted climate change may benefit the establishment and proliferation of weeds over crops owing its wide genetic diversity (Malarkodiet al., [19] which can have negative impact on agricultural productivity (Peters et al.,[20], McConnell, [21]; Korreset al., [22] and quality (Pawaret al.,[23] by competing for nutrients, water and light. Ziska[24] concluded that under growth chamber and greenhouse experiments higher CO<sub>2</sub> favoured the growth of C<sub>3</sub> and C<sub>4</sub> species. In most of the experiments, indicates that vegetative growth of C<sub>3</sub> crops is favoured relative to C<sub>4</sub> weeds with rising CO<sub>2</sub>, while primary results suggest that C<sub>3</sub> weeds may be favoured over C<sub>3</sub> crops as CO<sub>2</sub> increases due to C<sub>3</sub> pathway (Ghannoumet al.,[25]. Therefore, if C<sub>3</sub> 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<sub>2</sub>[26].

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.,[27]; Peters et al., [28]. Ziska[24] reported that crop/weed interactions vary considerably by geographical region, within a given region, depending on factors such as temperature, precipitation, *etc.* C<sub>3</sub> and C<sub>4</sub> crops may interact with both C<sub>3</sub> and C<sub>4</sub> weeds. Demographic traits, including seed biology, germination, life span and fecundity will be influenced by climate/ CO<sub>2</sub>, with consequences for selection and adaptation [29]. 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 [30]. 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 [31]. 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<sub>2</sub> 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 [32]. Weeds are more competitive over crops, colonising ability and enhanced aggressively hence weed management practice becomes a challenging task [33]. Malarkodiet al. [19] grouped crop–weed combinations in arable ecosystems into the following four categories: (a) C<sub>4</sub> weeds in C<sub>3</sub> crops; (b) C<sub>3</sub> weeds in C<sub>3</sub> crops; (c) C<sub>3</sub> weeds in C<sub>4</sub> crops; and (d) C<sub>4</sub> weeds in C<sub>4</sub> crops.

## **2. Weed response to climate change scenarios**

### **2.1. Effect of elevated CO<sub>2</sub> on weeds**

Growth of plants increased in response to high atmospheric CO<sub>2</sub> in a species-specific manner. Treharne [34] 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<sub>2</sub> rises. This rise in CO<sub>2</sub> levels are likely to be accompanied by higher temperature favouring C<sub>4</sub> weeds over C<sub>3</sub> crops [35]. Increasing CO<sub>2</sub> stimulated the crop-weed (i.e., the C<sub>3</sub>/C<sub>4</sub>) biomass ratio (Ziska and Bunce, [36]. Patterson [37] indicated that the relative increase in plant biomass in weeds and crops at doubling of CO<sub>2</sub> concentration might reach over 2.4 times in C<sub>3</sub> compared to 1.5 times in C<sub>4</sub>, 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 [38]. 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 [39].

Elevated CO<sub>2</sub> 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 [36]. Conversely, the application of glyphosate on weeds grown under elevated CO<sub>2</sub> conditions resulted in a higher survival rate of *C. gayana*, *E. curvula*, and *P. dilatatum* as compared to the plants grown under normal CO<sub>2</sub> conditions, while there was no effect of increased CO<sub>2</sub> on the survival of *Sporobolus indicus* (L.) R. Br. Manea et al., [40]

Ziska [41] reported that *Cirsium arvense* (L.) Scop where both roots and shoots accumulated more biomass when grown under increased CO<sub>2</sub> 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<sub>3</sub>/C<sub>4</sub> 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<sub>2</sub> concentration (550 ppm) as compared to ambient CO<sub>2</sub>

concentration (380 ppm) as reported by Shabbiret al. [44], (Navieet al., [43], Nguyen et al. [42] and Khan et al. [45].

Navieet al. [43] reported elevated CO<sub>2</sub> had no effect on the above ground biomass and length of the longest tiller of *Cenchrusciliaris* plants, but fewer tillers were produced by plants grown at 480 ppm CO<sub>2</sub> 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, [46]. There was 70 % increase in growth and development in *Cirsiumarvense* L., an invasive perennial C<sub>3</sub> weed species, in *Amaranthusviridis*, in *Partheniumhysterophorous* (C<sub>3</sub> weed) [46], in Canada thistle (C<sub>3</sub> plant type) (Ziska et al., [48].

An increase in *Chenopodium album* L. biomass was observed even up to 1500 ppm CO<sub>2</sub> concentration. However, a further increase in CO<sub>2</sub> concentration to 3000 ppm reduces biomass accumulation in *C. album* but still, the biomass accumulation remained higher than that at 350 ppm (Pilipaviciuset al., [48]. Apart from this, the growth indices such as relative growth rate, net photosynthesis rate and biomass accumulation of two C<sub>3</sub> weeds, *Euphorbia heterophylla* L. and *Commelinadiffusa* Burm. f. increased by 80.5%, 16.7%, 143% and 60.5%, 9.5%, 108%, respectively, under increased CO<sub>2</sub> conditions as compared to normal CO<sub>2</sub> [49]. Again, the degree of response varied with weed species in a research conducted at Directorate of Weed Science, Jabalpur where *Dactylocteniumaegyptium* and *Echinochloacolona* responded to elevated CO<sub>2</sub>, but *Cyperusrotundus* and *Eleusineindica* did not respond to CO<sub>2</sub> enrichment [51]. Other studies indicate that significant morphological and drymatter production alterations were seen in invasive *M. micrantha* and *W. trilobata* as a result of the higher CO<sub>2</sub> levels [52].

A significant reduction in soybean seed yield was observed with either weed species viz., C<sub>3</sub> weed (*Chenopodium album* L.) and a C<sub>4</sub> weed (*Amaranthusretroflexus* L.) relative to the weed-free control at either ambient CO<sub>2</sub> or elevated CO<sub>2</sub> (ambient + 250 ppm) [25,52]. However, for lambsquarters the reduction in soybean seed yield relative to the weed-free condition increased from 28 to 39% as CO<sub>2</sub> increased, with a 65% increase in the average dry weight of lambsquarters at enhanced CO<sub>2</sub>. On the contrary, for pigweed, soybean seed yield losses reduced with rising CO<sub>2</sub> from 45 to 30%, with no change in the average dry weight of pigweed. In a weed-free environment,

elevated CO<sub>2</sub> 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<sub>2</sub> condition.

Elevated CO<sub>2</sub> 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<sub>2</sub>[53]. Wayne et al.[54] reported increased shoot height by 9% and total seed mass by 31% in elevated CO<sub>2</sub>in ragweed (*Ambrosia artemisiifolia* L.)

Likewise, elevated CO<sub>2</sub> had significant effects on plant water relations in both C<sub>3</sub> and C<sub>4</sub> 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 [54]. Physiological traits like relative water content (RWC %), membrane stability index (MSI %), chlorophyll content, photosynthetic rate and TSS content were improved under elevated CO<sub>2</sub>[57]. 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<sub>2</sub> elevation over that of crop plants [57].

## **2.2. Effect of elevated CO<sub>2</sub> on weeds in crops**

The CO<sub>2</sub> concentration increment was 2 ppm/ year during past three years [57]. Steady increase in atmospheric CO<sub>2</sub> concentration is noted and predicted to reach 700 ppm at the end of the 21<sup>st</sup> century [59].

The beneficial effects of elevated CO<sub>2</sub> on most crops is negated by elevated temperature and there are no beneficial effects of elevated CO<sub>2</sub> on C<sub>3</sub> crops (bean, *Phaseolus vulgaris* L.; [60]; peanut, *Arachishypogaea* L.; [61] and C<sub>4</sub> crops (grain sorghum, *Sorghum bicolor* L. Moench; [62]. In contrast, C<sub>3</sub> weeds (lambsquarters, velvetleaf (*A theophrasti*), common ragweed (*Ambrosia artemisiifolia*), and giant ragweed (*Ambrosia trifida*) will respond more favourably to increased CO<sub>2</sub> levels and offer stiffer competition to C<sub>4</sub> crops (maize, sorghum, sugarcane, etc.). At elevated CO<sub>2</sub> concentrations, relative yield and competitive ability of C<sub>3</sub> plants, soybean and lambsquarters were significantly higher than that of C<sub>4</sub> plants, millet and pigweed [63]. The positive influence was more predominant on *Alternantheraparonychioides* in comparison to *Ludwikiachinensis* under elevated CO<sub>2</sub> and temperature. Therefore, *Alternantheraparonychioides* may become a major problematic weed in futuristic climate change scenario [24]. Valerio et al. [64] reported that elevated CO<sub>2</sub> could potentially

enhance the degree of weed damage from a C<sub>4</sub> weed, relative to a C<sub>3</sub> crop (tomato) in competitive mixtures, even at ambient temperature.

Increasing CO<sub>2</sub> concentration had no effect on growth and plant height in the C<sub>4</sub> species, *Amaranthus retroflexus*, Sorghum (*Sorghum halepense* (L.) Pers (C<sub>4</sub>) *Festuca elatior* L. (C<sub>3</sub>) A C<sub>3</sub> weed can be benefitted more than a C<sub>4</sub> at increased CO<sub>2</sub> levels [65]. Ziska [66] reported that crop–weed interactions resulted in increased weed biomass of weeds such as Velvetleaf (*Abutilon theophrasti*) (C<sub>3</sub>) and Redroot pigweed (*Amaranthus retroflexus*) (C<sub>4</sub>) Sorghum (*Sorghum halepense* (L.) Pers (C<sub>4</sub>) and reduced yield loss of sorghum at elevated CO<sub>2</sub>. Likewise, Ziska and Goins [67] found that long-term (seasonal) exposure to elevated CO<sub>2</sub> during the growing season facilitated the number and size of C<sub>3</sub> weeds relative to C<sub>4</sub> grasses from the weed seed bank with significant changes in weed demographics and populations.

Rogers et al. [68] 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<sub>2</sub>. While in increased under CO<sub>2</sub> 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., [69] and (Chanderet al., [70]. Likewise, the problems of *P. minor* and *A. ludoviciana* in wheat would aggravate with increase in CO<sub>2</sub> due to climate change (Mahajan et al., [51].

In rice fields, weedy rice (*Oryza sativa* L.) responds more strongly than cultivated rice to rising CO<sub>2</sub> level with greater competitive ability (Ziska et al., [71]. 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<sub>2</sub> condition in rice crop (Pawaret al., [24].

Similar increase in pod, seed yields and biomass accumulation of the C<sub>3</sub> weed (*Abutilon theophrasti* Medik.) were reported by Ziska et al. [72]. Elevated CO<sub>2</sub> increased the vegetative biomass and leaf area of common cocklebur (*Xanthium strumarium* L.) relative to that of sorghum crop (Ziska, [73] in competitive mixtures (Varanasi et al., [74]. These all findings prove the fact that under present

CO<sub>2</sub> levels, C<sub>4</sub> plants are more photosynthetically efficient than C<sub>3</sub> weeds indeed important C<sub>4</sub> crops may become more vulnerable to increased competition from C<sub>3</sub> weeds [75].

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. [76] recorded evapotranspiration (ET) reduction by 17–22% in the C<sub>3</sub> and 28–29% in the C<sub>4</sub> community at elevated CO<sub>2</sub>. Carlson and Bazzaz [77] reported that ambient CO<sub>2</sub> enrichment from 300 to 600 ppm increased water use efficiency (WUE) of soybean (C<sub>3</sub>) and corn (C<sub>4</sub>) by 48% and 54%, respectively, conversely the same recorded for a C<sub>3</sub> weed, velvetleaf (*Abutilon theophrasti*) and a C<sub>4</sub> weed redroot pigweed (*Amaranthus retroflexus*) were 87% and 76%, respectively.

Apart from, increasing CO<sub>2</sub> had alleviated the multiplication by early flowering, early maturity and dispersal of reproductive parts easily. Elevated CO<sub>2</sub>, wild oat (*Avena fatua*), seeds matured two weeks in advance as compared to the plants grown under ambient CO<sub>2</sub> conditions [78]. For instance, C<sub>3</sub> weeds like *Phalaris minor* and *Avena ludoviciana* in wheat (C<sub>3</sub>) would aggravate with the increase in CO<sub>2</sub> due to climate change [16]. *Phalaris minor* was more competitive over wheat with CO<sub>2</sub> enrichment under drought condition [78]. In few cases, RGR increase was in green gram (42.5 to 132.5), *E. geniculata* (375.4 to 677.7) and *C. diffusa* (61.5 to 98.7 mg plant<sup>-1</sup> day<sup>-1</sup>) respectively from ambient to elevated CO<sub>2</sub> [50].

In sorghum crop, the increase in CO<sub>2</sub> 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<sub>2</sub>, significant reductions in leaf area and weight, as well as in average seed weight were observed for sorghum when grown with redroot pigweed [41].

### **2.3. Effect of temperature on weeds**

Conversely, temperatures above 25°C hinders CO<sub>2</sub> assimilation and increase photorespiration in C<sub>3</sub> plants [79] while in C<sub>4</sub> plants because CO<sub>2</sub> pumps in mesophyll cells maintaining low photorespiration rates by PEP carboxylase in bundle sheath cells at all temperatures [80],[81]. 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<sub>2</sub> 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 [24]. 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 [81]. For example, Tungateet al. [83] studied the effect of temperature on soybean, *Sidaspinosa* (*prickly sida*) and *Cassia obustifolia* (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°C) was 0.8, and it was 1.3 and 1.6 for *Sidaspinosa*(at 36/31 °C), and *Cassia obustifolia* (at 36/31°C), respectively.

Similarly, Oleti et al. [84] 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 *Daturastramonium* 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 [85].

Conversely, under warmer conditions, *Setariaviridis* (L.) P. Beauv. germinated later in the (August) season in maize fields [85]. 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 [29]. Chung [86] 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) [86] 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<sub>2</sub>

assimilation in C<sub>4</sub> plants because CO<sub>2</sub> 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[86]. In few cases, Assenget al. [87] reported that increasing average temperatures reduced flowering time, total biomass, and grain yield.

Conversely, Entz and Fowler [88] 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 [89]; [90]. Nguyen et al.[41] 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 (*Rottboelliacochinchinensis*), a highly competitive C<sub>4</sub> 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 [91]. Similar results were also represented by Ziska and Bunce [92] where 88 % increase in biomass and 68 % increase in leaf area of itch grass [*Rottboelliacochinchinensis* (Lour.) W.D. Clayton] were observed in response to a 3°C increase in temperature.

An increase in temperature by 2°C 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 [93]. In general this could be ascribed due to increasing temperature will increase sucrose synthesis, transport and utilization for CO<sub>2</sub>-enriched herbaceous plants and decrease carbohydrate accumulation within the leaf (Farrar and Williams, [94]. 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<sub>4</sub> weeds such as *Amaranthus retroflexus* tend to dominate C<sub>3</sub> crops (e.g., soybean). The infestation of *Phalaris minor* is expected to worsen in wheat fields with CO<sub>2</sub> increase [50]. Likewise, weedy rice will compete more intensely with cultivated rice [70].

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) [95].

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 [96]. It is likely that the C<sub>4</sub> weed species are more favoured at higher temperature to produce greater biomass than others [97]. 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*[26].

## **2.5 Interactive effect of elevated CO<sub>2</sub> and temperature on weeds**

Weeds are likely to show greater resilience and better adaptation to changes in CO<sub>2</sub> concentrations and rising temperature in competition with crops due to their diverse gene pool and

greater physiological plasticity [73]. The beneficial effects of elevated CO<sub>2</sub> on C<sub>3</sub> plants results in higher photosynthetic rate than plants grown in ambient CO<sub>2</sub> conditions. However, beyond crop's optimum level, if elevated CO<sub>2</sub> is combined with high temperature level the increase in yield may decline or get reversed [98]. Increase in CO<sub>2</sub> and warmer temperatures may induce faster growth in determinate crops such as cereals by stimulating photosynthesis and vegetative growth [86]. Increasing CO<sub>2</sub> and altered temperature and precipitation are therefore likely to affect all aspects of weed biology [28], including establishment [99], competition [100], distribution [101] and management [102]. Weeds comes under C<sub>3</sub> pathway may dominate under elevated CO<sub>2</sub> conditions, whereas in elevated temperature, C<sub>4</sub> weeds may dominate.

Under elevated CO<sub>2</sub> and temperature conditions, it is known to improve physiological traits (RWC, membrane stability, chlorophyll content, photosynthetic rate and TSS) may benefit rice genotypes [55]. It seems that under elevated CO<sub>2</sub>, only when weed is C<sub>4</sub> and crop is C<sub>3</sub>, crop is likely to be benefitted, whereas in all other cases weeds are projected to outwit crop in a crop-weed competition situation [103]. The interactive effect of elevated CO<sub>2</sub> and temperature showed that C<sub>4</sub> weeds dominate over C<sub>3</sub> weeds. For example, C<sub>3</sub> crop such as rice and wheat, elevated CO<sub>2</sub> may have positive effects on crop competitiveness with C<sub>4</sub> weeds [35]. Crop-weed competition was low at elevated CO<sub>2</sub> whereas high under elevated temperature. The interactive effect of elevated CO<sub>2</sub> and temperature on crop-weed competition was high. Hence, weed management is considered as a major threat to future agriculture [14].

However, weed interference had a negative effect under the combined effect of elevated CO<sub>2</sub> 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 condition. In quack grass (*Elytrigia repens*) [104], increasing CO<sub>2</sub> improved the effects of high temperature on and increased growth and reproduction, and also *Echinochloa colona* and *I. rugosum* weeds [105], showed positive growth performance in terms of the plant height, dry weight, number of tillers/plant and biomass under elevated CO<sub>2</sub>, elevated temperature and combined effect of elevated CO<sub>2</sub> and elevated temperature, respectively over ambient conditions [93]. While, in few cases, Alberto et al. [105] reported that CO<sub>2</sub> 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 [105] proposed that ratio of root to shoot weight, values for wild oats lines grown with elevated CO<sub>2</sub> were relatively twice that of plants grown in ambient CO<sub>2</sub>. 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<sub>2</sub> and temperature. It was also observed that the response of *Alternanthera paranochioides* was more under elevated CO<sub>2</sub> compared to *Ludwigiachinensis*. Elevated CO<sub>2</sub> 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<sub>2</sub> and temperature the negative effect of elevated temperature was negated by elevated CO<sub>2</sub> in weed free rice [23].

Valerio et al. [63] found that increasing CO<sub>2</sub> 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<sub>2</sub> 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. [106] reported that increasing CO<sub>2</sub> may also result in elevated growth temperatures, the response of rice to each CO<sub>2</sub> concentration was also examined day/night temperatures of 27/21 and 37/29 °C. At 27/21 °C, increasing the CO<sub>2</sub> 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<sub>2</sub> 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 [107] in *Bromus tectorum*, *Hordeum murinum*, and *Lactuca serriola* showed that leaf area consistently responded to higher CO<sub>2</sub> concentration than a combination of high CO<sub>2</sub> concentration and elevated temperature.

### **3.0 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<sub>2</sub> 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<sub>2</sub> as both direct (CO<sub>2</sub> stimulation of weed growth) and indirect effects (climatic variability on weed biology). Rising CO<sub>2</sub> may be a selection factor in weed species dominance.

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