**Review Article**

# Effect of changing temperature and $CO_2$ 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. 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 $CO_2$ conditions. Climate change can affect crop-weed interactions by favouring $C_4$ weeds in increased temperature scenarios. Weeds can also shift their range by invading into new areas and higher latitudes or altitudes due to climatic variability. These factors helps in understanding the crop interactions, weed infestation and herbicide efficacy. This review paper summarizes the changes that occur due to climate change in weed behaviour.



***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 $21^{st}$ 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 [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 86plant species which supply most of the world's food, only five are $C_4$ species [11]. 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 *Cynodondactylon, Cyperus rotundus, Eleusine indica, Dactylocteniumaegyptium*and *Echinochioacolona.* 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* [11]. 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 [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 |
|---|---|---|---|
| *Ageratum conyzoides* | Goat weed | $C_3$ | Annual broad-leaved herb |
| *Alternanthera sessilis* | Sessile joyweed | $C_3$ | Perennial broad-leaved herb |
| *Amaranthus spinosus* | Spiny pigweed | $C_4$ | Annual broad-leaved herb |
| *Amaranthus viridis* | Slender amaranth | $C_4$ | Annual broad-leaved herb |
| *Argemone mexicana* | Mexican poppy | $C_3$ | Annual broad-leaved herb |
| *Commelinabenghalensis* | Day flower | $C_3$ | Annual broad-leaved herb |
| *Chenopodium album* | Common lambsquaters | $C_3$ | Annual broad-leaved herb |
| *Chloris barbata* | Purpletopchloris | $C_3$ | Annual or short- lived perennial grass |
| *Convolvulus arvensis* | Field bind weed | $C_3$ | Perennial broad-leaved climbing herb |
| *Cyperus rotundus* | Purple nutsedge | $C_4$ | Perennial herb |
| *Cynodondactylon* | Bermuda grass | $C_4$ | Perennial herb |
| *Dactylocteniumaegyptium* | Crowfoot grass | $C_4$ | Annual herb |
| *Digitariasanguinalis* | Large crabgrass | $C_4$ | Annual spreading grass herb |
| *Eleusine indica* | Goose grass | $C_4$ | Annual erect tufted grass |
| *Euphorbia hirta* | Garden spurge | $C_4$ | Annual deep rooted herb |
| *Echinochioacolona* | Jungle rice | $C_4$ | Annual grass herb |
| *Parthenium hysterophorous* | Congress grass | $C_3$-$C_4$ | Annual herb |

Weed competition is having increasing trend i.e., 45 % globally from 36% during 2006 (Alemu et 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 $CO_2$ and predicted climate change may benefit the establishment and proliferation of weeds over crops owing its wide genetic diversity (Malarkodi et al., [19] which can have negative impact on agricultural productivity (Peters et al.,[20], McConnell, [21]; Korreset al., [22] and quality (Pawar et al*.,*[23] by competing for nutrients, water and light. Ziska [24] 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. This indeed ongoing increase in atmospheric $CO_2$ concentration stimulates net photosynthetic growth rate in plants with the $C_3$ pathway (Calvin cycle) by increasing the $CO_2$ concentration gradient from the atmosphere to the inner wall of leaf and by reducing the loss of $CO_2$*via* photorespiration (Ghannoum et al*.,*[25]. 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 $CO_2$[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*. $C_3$ 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 [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 $CO_2$ 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 [32]. Weeds are more competitive over crops, colonising ability and enhanced aggressively hence weed management practice becomes a challenging task [33]. Malarkodi et al. [19] 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.

**1.3. Effect of elevated $CO_2$ on weeds**

Growth of plants increased in response to high atmospheric $CO_2$ 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 $CO_2$ rises. This rise in $CO_2$ levels are likely to be accompanied by higher temperature favouring $C_4$ weeds over $C_3$ crops [35]. Increasing $CO_2$ stimulated the crop-weed (i.e., the $C_3$/$C_4$) biomass ratio (Ziska and Bunce, [36]. Patterson [37] 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 [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].

Ziska [40] reported that *Cirsium arvense* (L.) Scop where both roots and shoots accumulated more biomass when grown under increased $CO_2$ conditions, but the accumulation in root biomass was higher as compared to shoot biomass increased net leaf photosynthesis and water use efficiency in *Parthenium hysterophorus* with the increase in atmospheric $CO_2$ up to 700 ppm. Similar, results were given by Nguyen et al. [41] where the number of leaves produced per plant, leaf length, leaf area and plant biomass production of parthenium seedlings under the elevated $CO_2$ concentration was significantly higher. As it is parthenium weed is considered to be $C_3$/$C_4$ intermediate species. Few more authors have reported that it grew taller by producing larger number of capitula with higher number of seeds at a higher $CO_2$ concentration of 480 ppm as compared to the weed plants raised at an ambient $CO_2$ concentration of 360 ppm (Navie et al.,[42]. In another study, Shabbir et al. [43] reported a substantial increase in the height (52 %), biomass (55 %), branching (62%), leaf area (120 %), photosynthesis (94 %), and water use efficiency (400 %) of *P. hysterophorus* plants at an elevated $CO_2$ concentration (550 ppm) as compared to the plants at an ambient $CO_2$ concentration (380 ppm). Khan et al.[44] reported that *P. hysterophorus* biomass increased significantly at elevated $CO_2$ concentration (550 ppm) when it was grown alone or in combination with some grass and legume pasture species.

Navie et al.[42] 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*. It is reported that above-ground biomass production was significantly higher at 480 ppm $CO_2$ (light competition), than at 360 ppm $CO_2$. All the plants grown under higher $CO_2$ concentration had started flowering at 53 days after sowing, whereas only one of the plants grown at ambient $CO_2$ concentration had produced flowers at 70 days after sowing. Similarly, the plant height of *Partheiumhysterophorous* grown under 480 ppm $CO_2$ was nearly five times that of plants grown under 360 ppm of $CO_2$ with a 34 % increase in stem base area. Apart from this, they reached early maturity by early flowering within

53 days over 70 days than that of ambient (Ziska, [45]. 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) [46], in Canada thistle ($C_3$ plant type) (Ziska et al.,[47].

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 (Pilipaviciuset al., [48]. 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 *Commelinadiffusa* 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 $CO_2$[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 $CO_2$, but *Cyperus rotundus* and *Eleusine indica* did not respond to $CO_2$ enrichment [50].

A significant reduction in soybean seed yield was observed with either weed species *viz*., $C_3$ weed (*Chenopodium albu*m 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) [24]. 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. Similar results were also presented by Ziska and Teasdale [51] where when soybean cultivated together with either of *C. album* L. ($C_3$ weed) or *Amaranthus retroflexus* L. ($C_4$ weed), seed yield was attenuated at both ambient and elevated $CO_2$ relative to the weed-free control.

Elevated $CO_2$ had predetermined effect on reproduction and dispersal of weed species as in case of ragweed plants exposed to higher $CO_2$ concentrations predicted in the year 2100 doubled the quantity of pollen produced and was 61 % more than that of ambient $CO_2$[52]. Wayne et al.[53] also reported that stand-level pollen production was 61% higher in ragweed (*Ambrosia artemisiifolia* L.) in elevated versus ambient $CO_2$ environments, both increased shoot height by 9% and total seed mass by 31% were also greater in elevated $CO_2$.

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 and corresponding increase in WUE. 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 $CO_2$[55]. 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 [56].

**1.4. Effect of elevated $CO_2$ on weeds in crops**

The $CO_2$ concentration increment was 2 ppm/ year during past three years [57]. Steady increase in atmospheric $CO_2$ concentration is noted and predicted to reach 700 ppm at the end of the $21^{st}$ century [58].

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; [59]; peanut, *Arachis hypogaea* L.; [60] and $C_4$ crops (grain sorghum, *Sorghum bicolor* L. Moench; [61]. 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 [62]. 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 [23]. Valerio et al. [63] 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 [64]. Ziska [65] 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 [66] 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. [67] noticed that purple nutsedge (20.3%) had predominant weed biomass in terms greater leaf area, root length, numbers of tubers and more tillers under high $CO_2$. While in yellow nutsedge (5.2%), only tuber number increased under $CO_2$ enrichment. Leaf dry weight was greater for both species when grown under elevated $CO_2$. 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 and reduced seed quality in soybean (Reddy et al.,[68]. 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.,[50]. Similarly, *E. colona* and *I. rugosum* weed interference severely impaired the root nodule number in soybean crop. There was slight reduction in plant height by 13 %, dry weight was increased by 13.42 % under elevated $CO_2$ under weedy condition comparison with ambient. However, weed interference reduced the yield by 31.12% in comparison to ambient (Chander et al., [69].

Elevated $CO_2$ was found to increase the competitive density due to which the seed yield and biomass of weedy or wild rice increased compared to that of cultivated rice, indicating greater reduction in the yields of cultivated rice in the presence of $C_3$ weeds in future $CO_2$ concentrations. Meanwhile this indicated that weedy rice (*Oryza sativa* L.) responds more strongly than cultivated rice to rising $CO_2$ level with greater competitive ability (Ziska et al., [70]. 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.,[23].

Similar increase in pod, seed yields and biomass accumulation of the $C_3$ weed (*Abutilon theophrasti*Medik.) were reported by Ziska et al. [71]. Elevated $CO_2$ increased the vegetative biomass and leaf area of common cocklebur (*Xanthium strumarium* L.) relative to that of sorghum crop (Ziska, [72] in competitive mixtures, showing that growth of $C_4$ crops could be reduced in the presence of $C_3$ weeds as future $CO_2$ levels increase (Varanasi et al., [73]. These all findings prove the fact that under present $CO_2$ levels, $C_4$ plants are more photosynthetically efficient than $C_3$ plants. It is also possible that in a $CO_2$ enriched atmosphere, important $C_4$ crops may become more vulnerable to increased competition from $C_3$ weeds [74].

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. [75] 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 [76] 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 compared to the plants grown under ambient $CO_2$ conditions [77]. 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 [15]. *Phalaris minor* was more competitive over wheat with $CO_2$ enrichment under drought condition [77]. In few cases, at ambient $CO_2$, RGR was 42.5, 375.4 and 61.5 mg $plant^{-1}$ $day^{-1}$ in green gram, *E. geniculata* and *C. diffusa*, respectively. However, at elevated $CO_2$, RGR increased to 132.5, 677.7 and 98.7 mg $plant^{-1}$ $day^{-1}$ in green gram, *E. geniculata*and *C. diffusa,* respectively. High RGR at ambient as well as at elevated $CO_2$ in *E. geniculata*(and its high biomass 17.4 g) indicates dominance over green gram of *E. geniculate* (143 %), *C. diffusa* (108 %) and green gram (53 %) compared to respective controls [49].

In sorghum crop, the increase in $CO_2$ was associated with a threefold increase in aboveground biomass of velvetleaf and a slight, but non-significant, increase in the aboveground biomass of redroot pigweed. Seed shattering stopped any estimate of reproductive effort for redroot pigweed. However, the average number of seed pods per velvetleaf plant approximately doubled (6.1

to 11.5) at the higher $CO_2$. 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 [40].

**1.5. Effect of temperature on weeds in crops**

Conversely, temperatures above 25°C hinders $CO_2$ assimilation and increase photorespiration in $C_3$ plants [78]. Conversely, increase in temperature has little effect on $CO_2$ assimilation in $C_4$ plants because $CO_2$ pumps in mesophyll cells maintain low photorespiration rates at all temperatures [79]. $C_4$ plants are minimally affected by temperature due to lower photorespiration and faster $CO_2$ fixation by PEP carboxylase in bundle sheath cells [80]. The increase in temperature had predominant effect on growth and development of different species. The growth of the crop 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 % whereas 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 [23]. 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, Tungate et al. [82] 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$^{o}$C) was 0.8, and it was 1.3 and 1.6 for*Sida spinosa* (at 36/31 $^{o}$C), and *Cassia obustutifolia* (at 36/31$^{o}$C), respectively.

Conversely, under warmer conditions, *Setariaviridis* (L.) P. Beauv. germinated later in the (August) season in maize fields [83]. 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 [28]. Chung

[84] reported that emergence and flowering of *Chenopodium album* advanced by 50 days with an increase of 4 °C in temperature.

**1.6. Effect of temperature rise on weeds in crops**

According to IPCC (2007) [85] 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 [86]. In few cases, Asseng et 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. This indeed prevented the seed dormancy. 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 $C_4$ 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 [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 [*Rottboelliiacochinchinensis* (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 [93]. In general this could be ascribed due to increasing temperature will increase sucrose synthesis, transport and utilization for $CO_2$-enriehed 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, $C_4$ 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 [50]. Likewise, weedy rice will compete more intensely with cultivated rice [70].

At both the ambient temperature and the 3 °C higher temperature, *Blyxaaubertii* 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 $C_4$ 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].

**1.7. 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 [73]. 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 [98]. Increase in $CO_2$ and warmer temperatures may induce faster growth in determinate crops such as cereals by stimulating photosynthesis and vegetative growth [86]. Increasing $CO_2$ 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 $C_3$ 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 [55]. 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 [103]. 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 [35]. 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 [14].

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 condition. In *Echinochloacolona* and *I. rugosum* weeds, 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 [93]. While, in few cases, Alberto et al.[104] 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 [105] 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$^{o}$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 [23].

Valerio et al. [63] 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. [104] 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(*Echinochloaglabrescens*). 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.

## 2.0Conclusion

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.

## REFERENCES:


[1] Chauhan BS, Mahajan G, Randhawa RK, Singh H and Kang MS. Global warming and its possible impact on agriculture in India. Advances in agronomy, 2014:123, 65-121.

[2] Ramesh K, Matloob A, Aslam F, Florentine SK and ChauhanBS. Weeds in a changing climate: vulnerabilities, consequences, and implications for future weed management. Frontiers in plant science, 2017:8, 95.

[3] Anonymous ICAR-DWR, Annual Report, ICAR-Directorate of Weed Research, Jabalpur, India, 2020: 33–37.

[4] Anwar MR, Wang B, Li Liu, D and Waters C. Late planting has great potential to mitigate the effects of future climate change on Australian rainfed cotton. Science of The Total Environment, 2020: 714, 136806.

[5] Pagare SA, Bhatia MA, Tripathi NI, Pagare SO, Kumar BH. Weeds: an introduction and their responses to climate change. Trends in Biosciences. 2017:10(12): 2123-9.

[6] Ziska LH and Dukes JS. Weed biology and climate change. Ames, IA: Blackwell Publishing2011.

[7] Kumar S, Gopinath KA, Sheoran S, Meena RS, Srinivasarao C, Bedwal S, Jangir CK, Mrunalini K, Jat R and Praharaj CS. Pulse-based cropping systems for soil health restoration,

resources conservation, and nutritional and environmental security in rainfed agroecosystems. Frontiers in Microbiology, 2023:13, 1041124.

[8] Marambe Band Wijesundara S. Effects of climate change on weeds and invasive alien plants in Sri Lankan agro-ecosystems: policy and management implications. Frontiers in Agronomy, 2021:3, 641006.

[9] Holm L, Doll J, HolmE, Pancho JV and Herberger JP. World weeds: natural histories and distribution. John Wiley & Sons1997.

[10] Holm L G, Plucknett D L, Pancho J V and Herberger JP. The world's worst weeds, distribution and biology, The Est-West Center, University of Hawaii press, Honolulu1977.

[11] Patterson DT. Weeds in a changing climate. Weed Science, 1995:43(4): 685-700.

[12] Billore SD.Weeds in Soybean vis-a-vis other Crops under Climate Change-A Review. 2019.

[13] Singh A, SinghD, Kang JS and AggarwalN. Management practices to mitigate the impact of high temperature on wheat: a review. IIOAB J, 2011:2(7): 11-22.

[14] Manisankar Gand Ramesh T. Response of weeds under elevated $CO_2$ and temperature: A review. Journal of Pharmacognosy and Phytochemistry, 2019:8(2S): 427-431.

[15] Naidu YR and Ojha A K. A hybrid version of invasive weed optimization with quadratic approximation. Soft Computing, 2015:19, 3581-3598.

[16] Alemu D, Lemessa F, Wakjira M and Berecha G. Inhibitory effects of some invasive alien species leaf extracts against tomato (*Lycopersicon esculentum* Mill.) bacterial wilt (*Ralstonia solanacearum*). Archives of Phytopathology and Plant Protection, 2014: 47(11): 1349-1364.

[17] Gharde Y, Singh PK, Dubey RP and Gupta PK. Assessment of yield and economic losses in agriculture due to weeds in India. Crop Protection, 2018:107, 12-18.

[18] Billore SD, Singh YV, Ramesh A, Verma RK, Halli HM, Hatti V and Goud BR. Weed management in conservation agriculture based soybean-wheat cropping system 2020.

[19] Malarkodi N, Manikandan Nand Ramaraj AP. Impact of climate change on weeds and weed management-A review. Journal of Innovative Agriculture, 2017:4(4): 1-7.

[20] Peters CJ, Picardy J, Darrouzet-Nardi AF, Wilkins JL, Griffin TS and Fick GW. Carrying capacity of US agricultural land: Ten diet scenarios. Elementa, 2016:4, 0116.

[21] McConnell LL, Kelly ID and Jones RL. Integrating technologies to minimize environmental impacts2016.

[22] Korres NE, Norsworthy JK, Tehranchian P, Gitsopoulos TK, Loka DA, Oosterhuis DM, Gealy DR, Moss SR, Burgos NR, Miller MR and Palhano M. Cultivars to face climate change effects on crops and weeds: a review. Agronomy for Sustainable Development, 2016:36, 1-22.

[23] PawarD, Sreekanth D, Chander S, Chethan CR, Sondhia S and Singh PK. Effect of weed interference on rice yield under elevated $CO_2$ and temperature2022.

[24] Ziska LH. The impact of elevated $CO_2$ on yield loss from a $C_3$ and $C_4$ weed in field-grown soybean. Global Change Biology, 2000:6(8): 899-905.

[25] GhannoumO, CaemmererSV, Ziska LH and Conroy JP. The growth response of $C_4$ plants to rising atmospheric $CO_2$ partial pressure: a reassessment. Plant, Cell & Environment, 2000:23(9): 931-942.

[26] Lee JS. Combined effect of elevated $CO_2$ and temperature on the growth and phenology of two annual $C_3$ and $C_4$ weedy species. Agriculture, ecosystems & environment, 2011:140 (3-4): 484-491.

[27] Anwar MP, Islam, AKMM, Yeasmin S, Rashid MH, Juraimi A S, Ahmed S and Shrestha A. Weeds and their Responses to Management Efforts in a Changing Climate. Agronomy, 2021: 11, 1921.

[28] Peters K, Breitsameter L and Gerowitt B. Impact of climate change on weeds in agriculture: a review. Agronomy for sustainable development, 2014:34, 707-721.

[29] Ziska LH, FleisherDHand Linscombe S. Ratooning as an adaptive management tool for climatic change in rice systems along a north-south transect in the southern Mississippi valley. Agricultural and Forest Meteorology, 2018:263, 409-416.

[30] Dayan FE. Current status and future prospects in herbicide discovery. Plants, 2019:8(9): 341.

[31] Anwar S, Naseem S, Karimi S, Asi, MR, Akrem A and Ali Z. Bioherbicidal activity and metabolic profiling of potent allelopathic plant fractions against major weeds of wheat-Way forward to lower the risk of synthetic herbicides. Frontiers in plant science, 2021:12, 632390.

[32] Blumenthal DM and Kray JA. Climate change, plant traits and invasion in natural and agricultural ecosystems. In Invasive species and global climate change GB: CABI. 2022:74-91.

[33] Chongtham SK, Devi EL, Singh RP, Jat AL, Lhungdim J, Bhupenchandra I and Rowndel, T.B.S.K. Crop-weed interactions and their management under climate change: A review. IJCS, 2019:7(3): 4498-4505.

[34] Treharne K. The implications of the 'greenhouse effect' for fertilizers and agrochemicals, in The Greenhouse Effect and UK Agriculture, CAS Paper 19, ed. R. C. Bennet (Reading: University of Reading Press). 1989:67–78.

[35] Fuhrer J. Agroecosystem responses to combinations of elevated $CO_2$, ozone, and global climate change. Agriculture, Ecosystems & Environment, 2003:97(1-3): 1-20.

[36] ZiskaLH and Bunce JA. Sensitivity of field-grown soybean to future atmospheric $CO_2$: selection for improved productivity in the 21$^{st}$ century. Functional Plant Biology, 2000:27(10): 979-984.

[37] Patterson DT. Implications of global climate change for impact of weeds, insects, and plant diseases. International Crop Science I, 1993:273-280.

[38] Irmaileh BA. Climate change impact on weeds. Food security and climate change in dry areas, 2011:170.

[39] TrumbleJT and ButlerCD. Climate Change Will Exacerbate California's Insect Pest Problems, California Agriculture, 2009:63, 73-78.

[40] Ziska LH. The impact of nitrogen supply on the potential response of a noxious, invasive weed, Canada thistle (*Cirsium arvense*) to recent increases in atmospheric carbon dioxide. Physiologia Plantarum, 2003:119(1): 105-112.

[41] Nguyen T, Bajwa AA, Navie S, O'donnell C and Adkins S. Parthenium weed (*Parthenium hysterophorus* L.) and climate change: the effect of $CO_2$ concentration, temperature, and water

deficit on growth and reproduction of two biotypes. Environmental Science and Pollution Research, 2017:4, 10727-10739.

[42] Navie SC, McFadyenRE, Panetta FD and AdkinsSW. The effect of $CO_2$ enrichment on the growth of a $C_3$ weed (*Parthenium hysterophorus* L.) and its competitive interaction with a $C_4$ grass (*Cenchrus ciliaris* L.). Plant Protection Quarterly, 2005:20(2):61-66.

[43] Shabbir A, Dhileepan K, Zalucki MP and Adkins SW. Biological control under a changing climate: The efficacy of the parthenium weed stem-galling moth under an atmosphere enriched with $CO_2$. Biological Control, 2019:139, 104077.

[44] Khan N, George D, Shabbir A, HanifZ and Adkins SW. Rising $CO_2$ can alter fodder–weed interactions and suppression of *Parthenium hysterophorus*. Weed Research, 2015:55(2):113-117.

[45] Ziska LH. Global climate change and carbon dioxide: assessing weed biology and management. Handbook on climate change and agroecosystems: impacts, adaptation, and mitigation. Imperial College Press, London, 2011:191-208.

[46] NaiduVSGR and Paroha S. Growth and biomass partitioning in two weed species, *Parthenium hysterophorus* ($C_3$) and *Amaranthus viridis* ($C_4$) under elevated $CO_2$. Ecology Environment and Conservation, 2008:14(4): 9-12.

[47] Ziska LH, Faulkner Sand LydonJ. Changes in biomass and root: shoot ratio of field-grown Canada thistle (*Cirsium arvense*). a noxious, invasive weed, with elevated $CO_2$: implications for control with glyphosate. Weed Science, 2004:52(4): 584-588.

[48] Pilipavičius V. Influence of climate change on weed vegetation. In Global Warming-Causes, Impacts and Remedies. IntechOpen2015.

[49] Awasthi JP, Paraste KS, Rathore M, Varun M, Jaggi D and Kumar B. Effect of elevated $CO_2$ on Vigna radiata and two weed species: yield, physiology and crop–weed interaction. Crop and Pasture Science,2018: 69(6): 617-631.

[50] MahajanG, Singh S and ChauhanBS. Impact of climate change on weeds in the rice-wheat cropping system. Current science, 2012:102(9): 1254-1255.

[51] Ziska LH and Teasdale JR. Sustained growth and increased tolerance to glyphosate observed in a $C_3$ perennial weed, quackgrass (*Elytrigia repens*) grown at elevated carbon dioxide. Functional Plant Biology, 2000:27(2): 159-166.

[52] Ziska LHand Caulfield FA. Rising $CO_2$ and pollen production of common ragweed (*Ambrosia artemisiifolia* L.). a known allergy-inducing species: implications for public health. Functional Plant Biology, 2000:27(10): 893-898.

[53] WayneP, Foster S, Connolly J, Bazzaz F and Epstein P. Production of allergenic pollen by ragweed (*Ambrosia artemisiifolia* L.) is increased in $CO_2$ -enriched atmospheres. Annals of Allergy, Asthma & Immunology, 2002:88(3): 279-282.

[54] Moutinho-Pereira JM, Correia CM, Gonçalves BM, Bacelar EA and Torres-PereiraJM. Leaf gas exchange and water relations of grapevines grown in three different conditions. Photosynthetica, 2004:42, 81-86.

[55] Dwivedi SK, Kumar S, Prakash V, Mondal S and Mishra JS. Influence of rising atmospheric $CO_2$ concentrations and temperature on morpho-physiological traits and yield of rice genotypes in sub humid climate of eastern India. American Journal of Plant Sciences, 2015:6(14): 2239.

[56] ZiskaLH and George KATE. Rising carbon dioxide and invasive, noxious plants: potential threats and consequences. World Resource Review, 2004:16(4): 427-447.

[57] Nalli TW. Program and Book of Abstracts: Undergraduate Research Celebration2018.

[58] Houghton R A. Terrestrial sources and sinks of carbon inferred from terrestrial data. *T ellus* 1996:48, 420–432.

[59] Prasad PV, BooteKJ, Allen Jr LH and Thomas JM. Effects of elevated temperature and carbon dioxide on seed-set and yield of kidney bean (*Phaseolus vulgaris* L.). Global Change Biology, 2002:8(8): 710-721.

[60] Prasad V PV, Boote KJ, Hartwell Allen JLand Thomas JM. Super-optimal temperatures are detrimental to peanut (*Arachis hypogaea* L.) reproductive processes and yield at both ambient and elevated carbon dioxide. Global Change Biology, 2003:9(12): 1775-1787.

[61] PrasadPV, Boote KJ and Allen Jr LH. Adverse high temperature effects on pollen viability seed-set, seed yield and harvest index of grain-sorghum [*Sorghum bicolor* (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperatures. Agricultural and forest meteorology, 2006:139 (3-4): 237-251.

[62] MiriH R and Rastegar A. Effect of $CO_2$ enrichment on growth and competitiveness of soybean and millet against lambsquarters and pigweed 2012.

[63] ValerioM, Tomecek M, Lovelli S and Ziska L. Assessing the impact of increasing carbon dioxide and temperature on crop-weed interactions for tomato and a $C_3$ and $C_4$ weed species. European journal of agronomy, 2013:50, 60-65.

[64] Carter, D.R. and Peterson, K.M., 1983. Effects of a CO 2-enriched atmosphere on the growth and competitive interaction of a $C_3$ and a $C_4$ grass. Oecologia, 58, pp.188-193.

[65] Ziska LH. Evaluation of yield loss in field sorghum from a $C_3$ and $C_4$ weed with increasing $CO_2$. Weed Science, 2003:51(6): 914-918.

[66] Ziska LHand GoinsEW. Elevated atmospheric carbon dioxide and weed populations in glyphosate treated soybean. Crop Science, 2006:46(3): 1354-1359.

[67] Rogers HH, RunionGB, Prior SA, Price AJ, TorbertHA and Gjerstad DH. Effects of elevated atmospheric $CO_2$ on invasive plants: comparison of purple and yellow nutsedge (*Cyperus rotundus* L. and *C. esculentus* L.). Journal of environmental quality, 2008:37(2): 395-400.

[68] Reddy KR, Patro H, Lokhande S, Bellaloui N and GaoW. Ultraviolet-B radiation alters soybean growth and seed quality. Food and Nutrition Sciences, 2016:7(01): 55.

[69] Chander S, Dibakar Ghosh, Deepak Pawar, Dasari Sreekanth, CR Chethan and PK Singh. Elevated $CO_2$ and temperature influence on crop-weed interaction in soybean Indian Journal of Weed Science 2023:55(3): 287–293.

[70] Ziska LH, Tomecek MB and Gealy DR. Competitive interactions between cultivated and red rice as a function of recent and projected increases in atmospheric carbon dioxide. Agronomy Journal, 2010:102(1): 118-123.

[71] ZiskaLH, Tomecek MB and Gealy DR. Assessment of cultivated and wild, weedy rice lines to concurrent changes in $CO_2$ concentration and air temperature: determining traits for enhanced seed yield with increasing atmospheric $CO_2$. Functional Plant Biology, 2013:41(3): 236-243.

[72] Ziska LH. Changes in competitive ability between a $C_4$ crop and a $C_3$ weed with elevated carbon dioxide. Weed Science, 2001:49(5): 622-627.

[73] Varanasi A, Prasad PV and JugulamM. Impact of climate change factors on weeds and herbicide efficacy. Advances in agronomy, 2016:135, 107-146.

[74] Jinger D, Kaur R, Kaur N, Rajanna GA, Kumari K and Dass A. Weed dynamics under changing climate scenario: A Review. Int. J. Curr. Microbiol. A Sci, 2017:6(3): 2376-2388.

[75] Drake BL, Hanson DT, LowreyTK and SharpZD. The carbon fertilization effect over a century of anthropogenic $CO_2$ emissions: Higher intracellular $CO_2$ and more drought resistance among invasive and native grass species contrasts with increased water use efficiency for woody plants in the US Southwest. Global change biology, 2017:23(2): 782-792.

[76] Carlson RW and Bazzaz FA. Photosynthetic and growth response to fumigation with $SO_2$ at elevated $CO_2$ for $C_3$ and $C_4$ plants. Oecologia, 1982:54, 50-54.

[77] Naidu VSGR and Varshney JAYG. Interactive effect of elevated $CO_2$. Indian Journal of Agricultural Sciences, 2011:81(11): 1026-9.

[78] Ogren WL. Affixing the O to Rubisco: discovering the source of photorespiratory glycolate and its regulation. Discoveries in Photosynthesis, 2005:911-921.

[79] Hatch MD. $C_4$ photosynthesis: a unique lend of modified biochemistry, anatomy and ultrastructure. Biochimica et Biophysica Acta (BBA)-Reviews on Bioenergetics, 1987: 895(2): 81-106.

[80] HadiA, Naz N, RehmanFU, Kalsoom M, Tahir R, Adnan M, Saeed MS, Khan AU and Mehta J. Impact of climate change drivers on $C_4$ plants: A review. Current Research in Agriculture and Farming, 2020:1(4): 13-18.

[81] Kathiresan RM. Effect of global warming on invasion of alien plants in Asia. In India Symposium, Annamalai University, Tamil Nadu, India2006.

[82] Tungate KD, Israel DW, Watson DM, Rufty TW. Potential changes in weed competitiveness in an agroecological system with elevated temperatures. Environmental and Experimental Botany. 2007:60(1):42-49.

[83] Dekker J. The foxtail (*Setariaitalica*) species-group. Weed science, 2003:51(5): 641-656.

[84] Chung Y, Kim M and Lee, B. Cytotaxonomical Study of the *Chenopodium album* and its Related Species in Korea. Korean Journal of Plant Taxonomy, 2011:41(4): 324-328.

[85] IPCC. Summary of policy makers. (In) Climate change: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. (In) Soloman S, Qin D, Manning M, Chen Z, Marquis M, Averty K B, Tignor M and Miller H L (Eds) Cambridge University press, Cambridge, UK2007.

[86] KadamNN, Xiao G, Melgar RJ, Bahuguna RN, Quinones C, TamilselvanA, Prasad PVV and Jagadish K.S. Agronomic and physiological responses to high temperature, drought, and elevated $CO_2$ interactions in cereals. Advances in agronomy, 2014:127, 111-156.

[87] Asseng S, Jamieson PD, Kimball B, Pinter P, Sayre K, Bowden JW and Howden SM. Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric $CO_2$. Field Crops Research, 2004: 85(2-3): 85-102.

[88] Entz MH and Fowler DB. Agronomic performance of winter versus spring wheat. Agronomy Journal, 1991:83(3): 527-532.

[89] Mainali KP, Warren DL, Dhileepan K, McConnachie A, Strathie L, Hassan G, Karki D, Shrestha BB and Parmesan C. Projecting future expansion of invasive species: comparing and improving methodologies for species distribution modelling. Global change biology, 2015:21(12): 4464-4480.

[90] Bajwa AA, Wang H, Chauhan BS and Adkins SW. Effect of elevated carbon dioxide concentration on growth, productivity and glyphosate response of parthenium weed (*Parthenium hysterophorus* L.). Pest management science, 2019:75(11): 2934-2941.

[91] PattersonDT, Westbrook JK, Joyce RJV, Lingren PD and Rogasik J. Weeds, insects, and diseases. Climatic change, 1999:43(4):711-727.

[92] Ziska LH and BunceJA. Predicting the impact of changing $CO_2$ on crop yields: some thoughts on food. New Phytologist, 2007:175(4):607-618.

[93] Chander S, Ghosh D, Pawar D, Dasari S, Chethan CR and Singh PK. Elevated $CO_2$ and temperature influence on crop-weed interaction in soybean2023.

[94] Farrar JF and Williams ML. The effects of increased atmospheric carbon dioxide and temperature on carbon partitioning, source-sink relations and respiration. Plant, Cell & Environment, 1991:14(8): 819-830.

[95] ReddyV, KulkarniS, Chavan M and Ajayakumar MY. Effects of Integrated Weed Management Practices on Weed Parameters and Yield of Bt Cotton (*Gossypium hirsutum* L.). International Journal of Environment and Climate Change, 2023:13(11): 324-331.

[96] ZimdahlWand Pavón D. Interacting holographic dark energy. Classical and Quantum Gravity, 2007:24 (22): 5461.

[97] Singh RP, Singh RK and Singh MK. Impact of climate and carbon dioxide change on weeds and their management-a review2011.

[98] Backlund P, Janetos A and Schimel D. The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States. Synthesis and Assessment Product 4.3. Washington, DC: US Environmental Protection Agency, Climate Change Science Program.2008: 240.

[99] Clements, DR and Jones, VL. Ten ways that weed evolution defies human management efforts amidst a changing climate. Agronomy, 2021:11(2):284.

[100] ValerioM, Tomecek MB, Lovelli S and Ziska LH. Quantifying the effect of drought on carbon dioxide-induced changes in competition between a $C_3$ crop (tomato) and a $C_4$ weed (*Amaranthus retroflexus*). Weed Research, 2011:51(6): 591-600.

[101] Bradley BA, Wilcove DS and Oppenheimer M. Climate change increases risk of plant invasion in the Eastern United States. Biological Invasions, 2010:12, 1855-1872.

[102] Waryszak P, Lenz TI, Leishman MR and Downey PO. Herbicide effectiveness in controlling invasive plants under elevated $CO_2$: sufficient evidence to rethink weeds management. Journal of Environmental Management, 2018:226, 400-407.

[103] Jinger DDass A, KumarV, Kaur R and Kumari K. Weed Management. Indian Farming, 2016:66(9): 09-13.

[104] Alberto A M Ziska L H, Cervancia C R and Manalo PA. The influence of increasing carbon dioxide and temperature on competitive interactions between a $C_3$ crop, rice (*Oryza sativa*) and a $C_4$ weed (*Echinochloaglabrescens*). Functional Plant Biology, 1996: 23(6):795-802.

[105] O'Donnell CC and Adkins SW. Wild oat and climate change: The effect of $CO_2$ concentration, temperature, and water deficit on the growth and development of wild oat in monoculture. Weed Science, 2001:49(5): 694-702.