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Weeds and Their Response to Changing Climate: A Review

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Authors' contributions

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Review Article

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ABSTRACT

Climate change is one of the most important parameters to cause alteration in weed composition, population growth, life processes, physiological development, and infestation pressure. A few of the weed species may become inactive, while the rest may become aggressive invaders. Weeds possess unique biological characteristics and ecological range that enable them to tolerate and successfully intrude in any ecosystem with varied environmental conditions. Rising carbon dioxide, will benefit C3 crops to expand their photosynthetic capacity, thus leading to increased biomass production and productivity, on the other hand increased temperatures will benefit the C4 crops. These differences in response of C3 and C4 crops to changing climate will influence crop-weed interaction, most likely at the expense of crop. Moisture is another important environmental factor which plays a major role in weed seed germination, thus the survival. Temperature and relative humidity influence the course of absorption, translocation, and metabolism of herbicides in plants,

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any change in their range leads to decreased herbicide efficacy and thus the weed control. Studies focussed on the performance of weeds under elevated environmental factors help to make strategic decisions on their management before having their impact on change in weed biological aspects, and foresee the future with elevated temperature and carbon dioxide conditions. Weeds such as *Parthenium hysterophorus*, *Sphagneticola trilobata*, *Prosopis juliflora* and Eichhornia crassipes, have been identified as potential future threats. Consequently, exploring the bioprospecting potential of these weeds is seen as an inevitable necessity.

Keywords: Climate change; C3-C4 weeds; carbon dioxide; glyphosate efficacy; herbicide efficacy; photosynthetic pathways; rainfall; temperature.

1. INTRODUCTION

Climate is the sum of weather conditions of a given area, quantified as long-term statistics of meteorological variables. Climatic variables include temperature, wind, precipitation and sunshine hours. Among these variables, temperature, moisture and light are very important as they determine the distribution and adaptation of weeds in a particular ecosystem. Climate has a pronounced role in deciding the agricultural production directly and indirectly. Besides soil fertility; temperature, rainfall, humidity should be optimum for good crop growth and productivity. These parameters affect crops directly as the various critical stages of the crop are sensitive to these factors. Climate change will affect both crops and its competitive counterpart weeds. Efficiency of these two groups of plants in responding and adapting to this change in climate determines the ultimate winners in a climatically altered future.

Doug Larson, defined weed as a plant that has mastered every survival skill except for learning how to grow in rows. There are some adaptive mechanisms to make their chance of survival under various agro-climatic conditions *viz*., prolific seed production, seed dormancy, different mechanisms for seed dissemination, various modes of propagation (Rhizomes, tubers, suckers, bulbs etc.) inherent hardiness, self-regeneration, selective invasion and weed succession – reasons for their ubiquitous nature. They are of our concern since they share the same trophic level with crops and competes for limited resources such as nutrients, soil moisture, solar radiation and space thereby affecting the crop productivity and quality. Weeds are the major pests causing largest yield reduction in crops among different biotic factors. The yield loss in direct seeded rice under unweeded conditions as measured by the weed index was 75.60 per cent with a benefit cost ratio (BCR) of 0.87 and in second year the yield loss reached its peak with a BCR of 0.70, indicating the detrimental impact of the seed bank accumulated during the previous year in unweeded areas [2]. In wet seeded rice, uncontrolled growth of *Schoenoplectus juncoides* resulted in an 81% decrease in net income compared to the most cost-effective weed management approach [51]. Co-occurrence of weedy rice plants at a density of 7.3 plants per m^2 or 175 g per m^2 in low land rice lead to 40.23 per cent loss in yield of cultivated rice [10].

2. IMPACT OF CLIMATE CHANGE ON WEEDS

Climate change can affect the variations in vegetative growth, vigour and competitiveness. Weeds undergo geographic range expansion by introduction and migration when its eco-physiological requirements get altered. The spreading of *Schoenoplectus juncoides* has been documented in wet seeded paddy fields through seeds, vegetative buds, and rhizomes [50]. Weed species make alterations in the life cycle so as to complete its growth and development before the approaching adversity, leaving weed seeds to replenish the seed bank. Anjaly et al [9] examined variations among weedy rice types in rice ecosystems of Kerala and observed that similarities between weedy and cultivated rice types have been increasing, indicating that the weedy type may be acquiring characteristics similar to those of cultivated rice.

2.1 Response of Weeds to Variation in Photosynthetic Pathways

Photosynthesis – a basic survival mechanism for both crop and weeds, efficacy of this process determines the futuristic flora in a climate changing scenario. This process reflects the role of climatic parameters in supporting life in the planet. Any change in the climate can drastically affect plants i.e., both crops and weeds. In C3 plants with (Calvin) pathway, CO_2 in the atmosphere enter the plants through stomata. Ribulose 1, 5- bis phosphate (RuBP) in the mesophyll cells fixes this CO_2 by carboxylation. Phospho Glyceric Acid (PGA, 3- Carbon compound) is the first stable compound produced in the presence of the enzyme RuBisCO (RuBP Carboxylase Oxygenase). PGA undergo reduction to form Glyceraldehyde tri-phosphate (G3-P, 3 C). A part of G3-P produces glucose (6 C) and the remaining G3-P regenerates to form RuBP again and completes the C3 cycle or Calvin cycle. Peters and Gerowitt [38] observed that under hot and humid conditions, RuBisCO has a higher affinity for O_2. The closure of stomata restricts the entry of CO_2 into the mesophyll cells and escape of O_2 to the atmosphere, resulting in high O_2: CO_2 concentration around RuBisCO. Since RuBisCO catalyses carboxylation and oxygenation, a higher O_2: CO_2 ratio leads to oxygenation in C3 plants by a process known as photorespiration.

Majority of the cultivated crops have C3 pathway. Cereals such as rice, wheat, oats, vegetables like tomato, chilli, brinjal, okra and fruit crops like banana, jack, mango, etc. are C3 crops. C3 weeds include grasses little seed canary grass (*Phalaris minor*), wild oats (*Avena fatua*) - major weeds in wheat, weedy rice (*Oryza sativa f sp. spontanea*) - major weed in rice, aquatic weeds such as water hyacinth (*Eichhornia crassipes*), parasitic weed (*Striga asiatica*) and other weeds like day flower (*Commelina benghalensis*), goat weed (*Ageratum conyzoides*), *Chenopodium album*, *Abutilon theophrastii*, sickle pod (*Cassia obtusifolia*), field bind weed (*Convolvulus arvensis*) and canada thistle (*Cirsium arvense*). *Cyperus difformis* with C3 and *Cyperus iria, Cyperus compressus and Fimbristylis miliaceae* with C4 photosynthetic pathway were the major cyperaceous weeds found at all the growth stages of semi dry seeded rice. [12] The abundant growth of C3 weed *Schoenoplectus juncoides* in the water channels, lowlands, undisturbed fields and field bunds as an annual/ perennial was reported by Umkhulzumet al [52].

In C4 plants with (Hatch and Slack) pathway, the first stable compound formed in the mesophyll cell is Oxaloacetic acid (OAA, 4C) in the presence of the enzyme, Phospho Enol Pyruvate (PEP) Carboxylase. OAA produces malate or aspartate, which undergo decarboxylation inside the bundle sheath cells thereby enhancing the CO_2 concentration in the area surrounding RuBisCO thus avoiding the photorespiration process. Batts et al [16] reported that under high temperatures, C4 pathway is more efficient due the absence of photorespiration.

Maize, sugarcane, sorghum (crop camel), minor millets and members of brassicaceae family such as cabbage and cauliflower are C4 crops. Three groups of weeds grasses, sedges and broad-leaf weeds (BLW) have species with C4 photosynthesis. Grasses like bermuda grass (*Cynodon dactylon*), crow-foot grass (*Dactyloctenium aegypticum*), barnyard grass (*Echinochloa sp*.), goose grass (*Eleusine indica*), sedges such as *Cyperus rotundus*, and *C. iria* and BLW like *Monochoria vaginalis* and *Amaranthus sp*. are the common C4 weeds. The most common C4 weed *C. rotundus* displayed the highest percentages of regrowth and viability of indicating that the newly formed tubers readily sprouted without showing any seasonal dormancy [5,6].

2.2 Response of weeds to elevated carbon dioxide

a. Response of crops and weeds with C_3 pathway

Poorter [40] observed that potentially fast-growing wild species and plants with nitrogen fixing roots gained more biomass than slow-growing species (54% vs. 23%) with increase in CO_2 from 300 to 720 ppm. Elevation in CO_2 concentration enhances the efficiency of C_3 pathway by increasing the CO_2: O_2 ratio around RuBisCO, thus favouring carboxylation and reducing photorespiration. C_4 plants are unaffected or the least affected by the elevation in atmospheric CO_2 concentration since they have an internal CO_2 concentrating mechanism.

Ziska et al [64] studied the response of rice (C_3 crop) and red rice (*Oryza sativa* fsp. *spontanea*, C_3 weed) in ambient (300 ppm) and elevated concentrations (400 and 500 ppm) of CO_2. He observed that the tiller number, panicle number, tiller weight, leaf weight, panicle weight and 50 seed weight of cultivated rice increased at 400 ppm but reduced at 500 ppm. Beyond 500 ppm rice showed no response. While, its C_3 weed counterpart- red rice had a linear increase in both biomass and seed yield with elevation in CO_2 from 300 ppm to 500 ppm. All the yield attributes were double for red rice at 300 ppm and four to five-fold more at 400 and 500 ppm when compared with cultivated rice. The difference in response is due to physiological plasticity and genetic diversity of red rice compared to cultivated rice. Anjaly et al [11] reported a strong response of weedy rice to elevated CO_2 as evident from a higher tiller production and plant height of weedy rice compared to two popular rice varieties in Kerala: Uma and Jyothi when grown in open top chamber. Weedy rice grown in an atmosphere with enriched CO_2 produced taller plants with high anthocyanin pigmentation compared those grown under open conditions with ambient concentration of CO_2.

b. Response of crops and weeds with C_4 pathway

Ziska and Bunce [60] conducted a study in four C_4 crops *viz.* grain amaranth (*Amaranthus hypochondriacus*)*,* sugarcane (*Saccharum officinarum*)*,* sorghum (*Sorghum bicolor*) and maize (*Zea mays*) and six weed species namely *Amaranthus retroflexus, Echinochloa crus-galli*, *Panicum dichotomiflorum*, *Setaria faberi, Setaria viridis* and *Sorghum halapense*. Both crops and weeds were grown at ambient (385 ppm) and elevated (680 ppm) concentrations of CO_2 up to 60 days after sowing (DAS). Photosynthesis of weeds increased by 19 percent, which was nearly double that of crops (10 %). Among the selected plants redroot pig weed (*Amaranthus retroflexus*) showed the maximum increase in photosynthesis (+30 percent) and the least photosynthetic stimulation was observed in maize (*Zea mays*) ie., +5 percent with elevation in CO_2 concentration. *Fimbristylis miliacea* with C3- C4 intermediate photosynthetic mechanism dominated in the double-cropped wetlands as reported by [45. Barnyard grass (*Echinochloa crus-galli*) a troublesome graminaceous weed infesting rice fields having C_4 photosynthetic pathway reduced rice grain yields by 58 per cent when it was planted at a density of 8 plants per square metre. Results revealed that barnyard grass reduced the Rubisco activity, leaf photosynthetic capacity, and energy conversion efficiency in rice [54].

c. Response of C_3 crop with C_4 weeds and C_4 crop with C_3 weeds

Generally, plants respond to elevated CO_2 by partial closure of stomata which reduces the transpiration loss. Hence, water requirement decreases and water use efficiency (WUE) increases with increase in the level of CO_2. Kriticos et al [28] opined that, if the WUE of C_3 and C_4 plants triggered to 70- 100 percent, there will be a threat of C_3 weed invasion into drier habitats.

Sorghum (*Sorghum bicolor*) and common cocklebur (*Xanthium strumarium*) were provided with a higher concentration of CO_2. On taking observation 41 DAS, a higher leaf area and biomass production was obtained for cockle bur with C_3 pathway than the C_4 crop sorghum. Thus, [57] opined that in the presence of C_3 weeds the vegetative growth, competitiveness and yield of economically important C_4 crops gets reduced.

d. Response of C_3 / C4 crop in a C_3-C_4 weed association

Under field conditions, crop experiences competition from both C_3 and C_4 weeds. [56] conducted an experiment to study the response of a C_3 crop, soybean (*Glycine max*) to elevated CO_2, when grown in combination with a C_3 weed, *Chenopodium album* and a C_4 weed, *Amaranthus retroflexus.* Sole cropping of soybean increased the biomass and yield by 32 and 23 percent. Soybean, when grown along with *Chenopodium album*, the biomass reduction increased from 23 to 34 percent and consequently seed yield reduction increased from 28 to 39 percent. Soybean, grown in combination with C_4 weed *Amaranthus retroflexus* showed a decrease in yield reduction from 45 to 30 percent. C_3 crop get the benefit of elevated CO_2 when grown in isolation and C_3 weed have a greater competitive advantage over the crop, while C_4 weed competition decreased but not nil.

A study conducted by Ziska [58] revealed that sorghum when grown in a weed free environment with increased CO_2 had significant difference leaf weight and leaf area but there is no significant difference in terms of yield related to ambient CO_2condition. In the presence of C_3 weed - at ambient CO_2 condition, there is no significant loss in biomass or yield in sorghum but at elevated CO_2, sorghum yield was reduced by 16 percent and biomass by 14 percent. But in the presence of C_4 weed – at ambient and elevated CO_2concentrations, there is significant biomass and yield loss in sorghum. At elevated CO_2 condition, sorghum yield and biomass were reduced by 23 percent and 20 percent relative to elevated CO_2 weed-free condition.

e. Changes in weed biology

All the aspects of weed biology can be influenced by increased carbon dioxide concentration, temperature and precipitation [38]**.** Canada thistle (*Cirsium arvense*), a C_3 weed showed 70 percent increase in growth when exposed to elevated atmospheric CO_2 [59]. Naidu et al [31] observed higher growth and biomass accumulation by a C_4 weed, *Amaranthus viridis* with increase in CO_2. This observation can be explained by the result of Nelson and Langdale [33], in which they found out that developing leaves of C_4 plants use C_3 pathway until the complete differentiation of Krantz anatomy. Hence, all C_4 plants are C_3 during their early development and access all the benefits of elevated CO_2 as C_3 plants.

Alterations in weed biology give rise to tall and large sized plants. Ramesh et al [41] opined that increase in plant height and size help the wind dispersed invasive species such as *Cirsium arvense*, *Sonchus arvensis* and *Carduus nutans.* Ziska and Caulfield [61] analyzed the pollen production of common rag weed (*Ambrosia artemisiifolia*) in three concentrations (280, 370 and 600 ppm) of atmospheric CO_2. Pollen production shot up from 131 percent at 280 ppm to 320 percent at 600 ppm due to increase in the number and size of floral spikes. Floral weight decreased from 21 to 13 percent but the weight of total pollen increased from 3.6 to 6 percent between 280 and 600 ppm.

Naidu and Varshney [32] conducted an experiment in the Directorate of Weed Science Research at Jabalpur, to study the response wild oats (*Avena fatua*) to change in the CO_2 concentration. Ambient CO_2 concentration was 370 ± 20 ppm and the elevated CO_2 concentration was 550 ± 30 ppm. Wild oats showed early maturation (13 days prior to that under ambient CO_2 concentration) and seed shattering thus enriching the weed seed bank. Drought conditions prolong the viability of weed seed bank in the soil.

A study conducted by Jabran and Dogan [24] in three weed species namely *Bromus tectorum, Hordeum murinum,* and *Lactuca serriola* indicated that leaf area consistently responded to higher CO_2 concentration than a combination of high CO_2 concentration and elevated temperature. Growth and productivity of *Parthenium hysteroporous* observed under elevated CO_2 conditions and results revealed that under ambient CO_2 concentration, parthenium grew taller with a greater number of leaves, flowers, and dry biomass compared to the ambient CO_2 concentration.

2.3 Response of Weeds to Rising Temperature

Soil and above ground temperature are important, in governing the reproduction and establishment of weeds. Weed species distribution in a geographical area was indicated by atmospheric temperature [37]. As most of the physiological processes such as photosynthesis, respiration and transpiration are highly temperature dependent, any changes in temperature might affect plant growth. [29] opined that phenological development of plant was more influenced by increased temperature than elevated CO_2. Increased temperature alters the weed proliferation and competitive advantage in crop stands.

Under normal warm conditions, Dekker [19] explained the presence of a temporal non-synchrony between the C_4 weed – green foxtail (*Setaria viridis*) and C_4 crop - maize (*Zea mays*) during seedling emergence, such that *Setaria* emerges only after the establishment of maize crop. Lee [38] observed that higher temperature result in synchronous emergence of *Setaria viridis* and maize, leading to competition at the emergence stage. High temperature triggers the germination and subsequent emergence of *Setaria* seeds. Hence, at higher atmospheric temperature minor weeds may pose threat to the crop. Ramesh et al [41] observed that a 4ºC rise in temperature, caused early emergence of *Chenopodium album* and *Setaria viridis* by 26 and 35 days and flowering advanced by 50 and 31.5 days, respectively.

Tungate et al[49] analyzed the variations in the root: shoot ratio of soybean, prickly sida (*Sida spinosa*) and sickle pod (*Cassia obustifolia*) with rise in temperature. A higher photosynthate translocation to the plant roots was observed in *Cassia obustifolia* at 36ºC (day temperature) and 31ºC (night temperature). Root:shoot ratio of *Sida spinosa* and C. *obustifolia* was 1.3 and 1.6 respectively, and that of soybean was 0.8. Thus, it is evident that under high atmospheric temperature, weed has advantage over the crop, since the underground propagules remain viable and helps in the regeneration of the plant after the high temperature stress, while the crop has very low re-growth potential. The resilience of *C. rotundus* under various pressures originates from its strong underground tuber system, where each tuber produces multiple active buds, enabling continuous growth in conjunction with its allelopathic impact [7].

2.4 Response of Weeds to Changes in Rainfall

For a species to have its optimum growth and development, specific moisture regime is required. In arable and non-arable lands, moisture stress is likely to happen as a result of climate change with prolonged drought and floods. When compared to crops, weeds have greater physiological plasticity and genetic variations and are believed to sustain better under adverse climatic fluctuations.

Yaduraju et al. [55] analyzed the floristic diversity of the basin and observed two alien weed species in the rice fields, which eradicated the native *Echinochloa* sp. It was inferred that the amphibious adaptation (survival both under flood and residual moisture) of the two alien species: *Marsilia quadrifolia and Leptochloa chinensis* resulted in the weed shift. Rodenburg et al[44] opined that under excess rainfall, *Rhamphicarpa fistulosa* **-** a parasitic weed in cereals would pose a serious threat to the crop.

Patterson and Highsmith [36] reported that *Anoda cristata and Abutilon theophrastii* are two common C_3 weeds in cotton. Prevalence of drought leads to severe competition of these two weeds with cotton, causing a yield reduction in cotton. Rodenburg et al [44] predicted the infestation of the parasitic weed, *Striga hermonthica* under conditions of prolonged drought. Past research gave thrust in the manipulation of species response to CO_2 enrichment and not on associated increase in temperature or drought [20]. [23] forecasted the changes in temperature and moisture, and explained that changes will have implications on germination, spatial and temporal emergence of weed seeds and seedlings. In reality, crops and weeds get exposed to a multitude of climatic changes. Hence, considering a combination of climate change consequences is of significance.

2.5 Response of Weed to Change in Carbon Dioxide and Temperature

Hofstra and Hesketh [22] opined that at low and high temperatures, growth enhancement due to elevated CO_2 decreases. On the contrary, Baker et al [15] observed that CO_2 enriched atmosphere provided extreme temperature tolerance to plants**.** Tremmel and Patterson [48] reported the amelioration of high temperature-induced stress in quack grass (*Agropyron repens*) in an atmosphere with elevated CO_2 concentration.

O'Donnell and Adkins [35] observed that at high temperature of 23ºC day temperature and 19ºC of night temperature, wild oats (*Avena fatua*) completed its development faster. Since maturation is faster, more seeds get deposited in soil seed bank thereby increasing the plant number. At 480 ppm CO_2, 44 percent more seeds were produced, compared to 397 ppm. At high temperature and light intensity during midday C_4 weeds like redroot pigweed (*Amaranthus retroflexus)* and Johnson grass (*Sorghum halapense)* efficiently fix CO_2 than C_3 crops like soybean and cotton. Bunce [17] reported that high temperature increases the evaporative demand. Since C_4 plants have high water use efficiency and CO_2 compensation point they are best adapted to an atmosphere with high CO_2, temperature and light intensity.

Naidu and Varshney [32] reported that infestation of *Phalaris minor* in wheat, aggravate with increase in CO_2 due to climate change and the condition may worsen with water scarcity. With CO_2 enrichment, wheat gain biomass against P. *minor*. Under water stress conditions, P. *minor* survived better and had an advantage over wheat. Valerio et al [53] assessed the response of tomato (*Solanum lycopersicum*) and *Amaranthus retroflexus* at three different levels of CO_2 *viz.* 400, 600 and 800 ppm, with and without water stress. Without water stress, leaf photosynthetic rates, plant height, leaf area and biomass increased with elevation in CO_2 concentration for tomato. The plant height and biomass of *Amaranthus retroflexus* increased even under water stress.

Mandal et al [30] conducted a study to know the response of *Cynodon dactylon* growth under elevated temperature and moisture conditions with three temperature levels ambient (0ºC), +2ºC and +4ºC increase over the ambient and with two moisture levels viz., supply of moisture at 100 percent of evaporation and 60 percent of evaporation occurred previous day. The results inferred that, because of its high acclimatization capacity *C. dactylon* produced more growth under elevated temperature of +4ºC with sufficient moisture. C_4 photosynthetic pathway might have helped the weed to utilize moisture and temperature more efficiently even under stress conditions.

3. WEED MANAGEMENT IN CHANGING CLIMATE

The growth of underground parts such as roots and rhizomes are highly stimulated than that of shoots under elevated CO_2, which makes mechanical tillage less efficient since, it helps in the dispersal of weed propagules [62]. Anjaly et al [9] observed significant differences in morphometric characteristics of weedy and cultivated rice during early growth stages. Variations were noted in culm thickness and ligule length and the most notable distinction was found in tiller count, with 87% of weedy rice variants exhibiting a higher number of tillers per plant (ranging from 11 to 20) compared to cultivated rice varieties (Jyothi (Ptb-39) and Uma-MO-16 had 10 and 9 tillers, respectively). Weedy rice plants were observed to be taller and lankier (ranging from 105 to 115.67 cm) with predominantly round culms, sometimes displaying anthocyanin pigmentation at the nodal regions. They also tended to have shorter ligules, early flowering times compared to cultivated rice, a greater number of tillers per plant, and predominantly awned grains. The study concluded that morphological adaptations displayed by these morphotypes in response to the changing climatic conditions strongly suggested the potential for weedy rice to pose a persistent threat to rice cultivation.

3.1 Herbicide Efficacy in Changing Climate

Herbicides are the chemicals used for killing undesired plants in the cultivated field. The toxic component (active ingredient) binds with the target site of the plant and affects the normal functioning of metabolic pathways, thereby suppressing the plant to death. Environmental factors are known to interact significantly with the performance of herbicide on plants causing marked variation in the site of action of plants, both in time and space. Umkhulzum et al [51] found that applying ethoxysulfuron at a rate of 15g per hectare at 15 days after sowing followed by hand weeding at 35-40 DAS, proved to be an effective strategy for controlling *Schoenoplectus juncoides* (Roxb.) Palla in wet seeded rice. Herbicide-environment interaction may be caused by the elements of edaphic and atmosphere in two ways: Firstly, by modifying morphology, physiology and course of biochemical reaction in plants. Secondly, by influencing herbicide availability at the site of its uptake by plants at intended rate and in desired quantity. Continuous advancement in herbicides with distinctive mechanisms of action, characterized by high selectivity, gradual resistance development, and environmental friendliness, is essential for tackling both new and existing challenges posed by herbicide resistance [25].

There are many factors affecting the efficacy of herbicide *viz.,* temperature, relative humidity, wind and light. Anderson et al [8] reported the significance of relative humidity (RH) on the phytotoxic action of glufosinate- ammonium as it changes the cuticle hydration leading to droplet drying. Employing a combination of stale seedbed followed by glyphosate plus oxyfluorfen application, then cyhalofopbutyl plus carfentrazone ethyl, effectively suppressed the germination and establishment of *C. iria* and *M. vaginalis* during the initial stages of wet-seeded rice cultivation [46].

3.2 Mechanisms of Herbicide Resistance

Gene mutations in the target site leads to a modified target site such that the herbicide molecule would not recognize the actual site of action. This leads to target site resistance. Any hindrance in the herbicide's translocation path leads to non-target site resistance. Non-target site resistance occurs due to several reasons: (a) Fast metabolism of toxic herbicide molecules into safe, non-toxic forms (b) decreased translocation of the applied herbicide due to drought or high temperature (c) reduced leaf uptake due to certain modifications in the leaf structure and (d) sequestration of the herbicide molecule in the vacuole.

Gaines et al [21] observed a new mechanism of herbicide resistance called 'gene amplification' in *Amaranthus palmeri* where, 5-enol pyruvyl shikimate 3-phosphate synthase (epsps), the target site of glyphosate undergo amplification by increasing the copy number of epsps, to 160-fold. The combined post-emergent herbicide penoxsulam + cyhalofopbutyl exhibited significantly higher efficacy in terms of weed dry weights, effectively controlling grasses, sedges, and broadleaf weeds in wet-seeded rice [42].

3.3 Changes in Leaf under Elevated Carbon Dioxide and Herbicide Resistance

Assmann [14] observed depolarisation of guard cells, stomatal closure and reduced stomatal conductance under elevated CO_2. Ainsworth and Long [1] observed the changes in outer cuticle as increased cuticle thickness and leaf pubescence. In wet-seeded rice, bensulfuron-methyl + pretilachlor demonstrated the highest weed control efficiency and was comparable to pyrazosulfuron-ethyl, effectively controlling grasses, sedges, and broadleaf weeds [43].

3.4 Causes for Reduction in Glyphosate Efficiency

Glyphosate, popularly known by its trade name- Roundup is a non-selective, post-emergent, systemic herbicide used worldwide for general weed control. Advent of roundup ready crops has enabled the use of glyphosate in cropped fields also, since the crops are modified genetically for showing resistance to roundup. Glyphosate, either alone or in combination with 2,4-D, has exhibited potential in managing *C. rotundus* growth due to its rapid translocation to the tubers [3]. Glyphosate has lost its efficiency as a total weed killer due to various adaptations in the weeds to cope up with climate change. Seedling stage is the herbicide sensitive stage of weeds, hence shortening of this stage results in reduced efficacy of herbicides. Eg. *Chenopodium album* spent 5 days less on seedling stage [63]. Closure of stomata, reduced stomatal number and stomatal conductance during dry conditions affect the entry and translocation of glyphosate, thereby reducing its efficacy, as it is post emergent (foliage applied). Increased cuticular thickness and starch deposition affects the penetration and entry of herbicide. Arya and Ameena [13] found that regardless of whether herbicides were applied before or after plant emergence, they persisted in the active surface soil, causing fluctuations in soil enzyme activities across different post-treatment days in semi-dry rice. Profuse underground growth help weeds to re-grow and produce new flushes after the destruction of above ground portion by the herbicide. This leads to herbicide dilution, since the recommended dose of the herbicide is not sufficient to control the weeds. Ameena et al [4] documented a decrease in tuber viability (20-23.3%) and regeneration (6-8 sprouts per m^2) when using a stale seedbed in combination with pre-plant application, followed by directed post-emergence glyphosate application for *C. rotundus* management. Heavy rains after herbicide spray would wash off the herbicide from foliage. Unpredictable rains reduce rain safe period that is required after herbicide application. Roundup Ready crops facilitate the use of glyphosate in cropped fields for selective killing of weeds. But, [39] inferred that Roundup Ready Soybean translocated more C_{14}-glyphosate to meristematic tissues at 35°C than at 15°C, indicating a potentially higher glyphosate injury at higher temperatures.

4. FUTURE WEED THREATS

4.1 *Sphagneticola trilobata*

Sphagneticola trilobata has attained the status of an invasive plant in the open areas of Kerala due to its profuse growth and insensitivity to herbicides. High heat stress tolerance of this plant is due to its highly thermostable photosynthetic apparatus. Song et al [47] reported that under high temperature the potential damage was minimized by effective partitioning of energy to photosystem II complex thus helping the weed to retain greater capacity for carbon assimilation.

4.2 *Datura stramonium*

High temperature triggers profuse growth of *Datura stramonium* (thorn apple). Hence [18] opined that, this plant is a potential candidate under climate change scenario.

4.3 *Lantana camara*

Lantana camara, also known as Spanish Flag or West Indian Lantana, is a species of flowering plant belonging to Verbenaceae family is a native of American tropics. It has the ability to occupy over wide range of environments as birds help in effective dispersal of berries thus, expanding its range. Once established it will survive under drought for long periods. Kriticos et al [27] opined that biological control of *Lantana* would not be effective because of the effect of altered climate on the distribution of biocontrol agents.

4.4 *Parthenium hysterophorus*

Parthenium hysterophorus is an invasive weed species introduced to India. It possesses a C_3-C_4 intermediary pathway of photosynthesis. Nguyen et al [34] observed an increased growth and seed output in P. *hysterophorus* at an elevated concentration of CO_2 (550 ppm) and at cooler (30°C day temperature and 15°C night temperature) and wetter conditions. During warm temperature, taller plants with greater biomass, shorter life span, high seed production, seed filling and seed longevity were produced.

4.5 *Eichhornia crassipes*

Eichhornia crassipes, commonly known as water hyacinth, is a perennial fast growing broadleaved aquatic plant, native to tropical and sub-tropical South America. It is a highly problematic invasive species introduced to India. Mode of propagation is by offsets, increased rainfall intensity with frequent floods helps in the easy dispersal of offsets and thus it's entry to new areas.

4.6 *Prosopis juliflora*

Prosopis juliflora is an invasive species introduced in 1877 from Central America to India. It has invaded nearly 6.0 M ha of land contributing to 1.8% of the total geographical area of the country [26]. Greater assimilate partitioning towards roots lead to enlargement of roots, rapid regeneration of the plant after mechanical lopping. It has the ability to tolerate extreme climatic situations *viz.,* summers with high temperatures and a monsoon with water inundation and flooding thus, making the management of this weed nearly impossible.

5. CONCLUSION

Ability of weeds to adapt to the changing climate makes them more efficient in competing with the crops. Due to the presence of profuse underground growth, C_4 pathway and C_3-C_4 intermediate pathways, perennial weeds are expected to pose more threat in a changed climate, since they cannot be effectively controlled by herbicides due to dilution effect and several weed adaptations. Modifications in the morphology of leaves and the development of resistance within the weeds result in reduced efficacy of herbicides. Being more efficient in adverse environmental conditions, C_4 pathway plants are benefitted. Rice, being our staple food crop needs to be improved in production. Since it is a C_3 crop, the performance of the crop gets affected with climate change. Hence, development of rice with C_4 mechanism needs a higher thrust. Weeds evolve effectively during stress and climate change is inevitable so weed utilization by bioprospecting helps in managing the weeds in a useful manner. A weed dominated future gives us the opportunity to identify potential crops from weeds.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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