

Weeds and their response to changing climate: A Review

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, 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*, *Sphagneticolatrilobata*, *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.

Key words: 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

33 are very important as they determine the distribution and adaptation of weeds in a
34 particular ecosystem. Climate has a pronounced role in deciding the agricultural
35 production directly and indirectly. Besides soil fertility; temperature, rainfall, humidity
36 should be optimum for good crop growth and productivity. These parameters affect crops
37 directly as the various critical stages of the crop are sensitive to these factors. Climate
38 change will affect both crops and its competitive counterpart weeds. Efficiency of these
39 two groups of plants in responding and adapting to this change in climate determines the
40 ultimate winners in a climatically altered future.

41 Doug Larson, defined weed as a plant that has mastered every survival skill except for
42 learning how to grow in rows. There are some adaptive mechanisms to make their chance
43 of survival under various agro-climatic conditions *viz.*, prolific seed production, seed
44 dormancy, different mechanisms for seed dissemination, various modes of propagation
45 (Rhizomes, tubers, suckers, bulbs etc.) inherent hardiness, self-regeneration, selective
46 invasion and weed succession – reasons for their ubiquitous nature. They are of our
47 concern since they share the same trophic level with crops and competes for limited
48 resources such as nutrients, soil moisture, solar radiation and space thereby affecting the
49 crop productivity and quality. Weeds are the major pests causing largest yield reduction in
50 crops among different biotic factors. The yield loss in direct seeded rice under unweeded
51 conditions as measured by the weed index was 75.60 per cent with a benefit cost ratio
52 (BCR) of 0.87 and in second year the yield loss reached its peak with a BCR of 0.70,
53 indicating the detrimental impact of the seed bank accumulated during the previous year in
54 unweeded areas [2]. In wet seeded rice, uncontrolled growth of *Schoenoplectus juncooides*
55 resulted in an 81% decrease in net income compared to the most cost-effective weed
56 management approach [51]. Co-occurrence of weedy rice plants at a density of 7.3 plants
57 per m² or 175 g per m² in low land rice lead to 40.23 percent loss in yield of cultivated rice
58 [10].

59

60 **2. IMPACT OF CLIMATE CHANGE ON WEEDS**

61 Climate change can affect the variations in vegetative growth, vigour and
62 competitiveness. Weeds undergo geographic range expansion by introduction and
63 migration when its eco-physiological requirements get altered. The spreading of
64 *Schoenoplectus juncooides* has been documented in wet seeded paddy fields through seeds,
65 vegetative buds, and rhizomes [50]. Weed species make alterations in the life cycle so as to
66 complete its growth and development before the approaching adversity, leaving weed seeds

67 to replenish the seed bank. [9] examined variations among weedy rice types in rice
68 ecosystems of Kerala and observed that similarities between weedy and cultivated rice
69 types have been increasing, indicating that the weedy type may be acquiring characteristics
70 similar to those of cultivated rice.

71

72 **2.1. Response of weeds to variation in photosynthetic pathways**

73 Photosynthesis – a basic survival mechanism for both crop and weeds,
74 efficacy of this process determines the futuristic flora in a climate changing scenario. This
75 process reflects the role of climatic parameters in supporting life in the planet. Any change
76 in the climate can drastically affect plants i.e., both crops and weeds. In C₃ plants with
77 (Calvin) pathway, CO₂ in the atmosphere enter the plants through stomata. Ribulose 1, 5-
78 bis phosphate (RuBP) in the mesophyll cells fixes this CO₂ by carboxylation.
79 PhosphoGlyceric Acid (PGA, 3- Carbon compound) is the first stable compound produced
80 in the presence of the enzyme RuBisCO (RuBP Carboxylase Oxygenase). PGA undergo
81 reduction to form Glyceraldehyde tri- phosphate (G3-P, 3 C). A part of G3-P produces
82 glucose (6 C) and the remaining G3-P regenerates to form RuBP again and completes the
83 C₃ cycle or Calvin cycle. [38] observed that under hot and humid conditions, RuBisCO has
84 a higher affinity for O₂. The closure of stomata restricts the entry of CO₂ into the
85 mesophyll cells and escape of O₂ to the atmosphere, resulting in high O₂: CO₂
86 concentration around RuBisCO. Since RuBisCO catalyses carboxylation and oxygenation,
87 a higher O₂: CO₂ ratio leads to oxygenation in C₃ plants by a process known as
88 photorespiration.

89 Majority of the cultivated crops have C₃ pathway. Cereals such as rice, wheat, oats,
90 vegetables like tomato, chilli, brinjal, okra and fruit crops like banana, jack, mango, etc. are
91 C₃ crops. C₃ weeds include grasses little seed canary grass (*Phalaris minor*), wild oats
92 (*Avena fatua*) - major weeds in wheat, weedy rice (*Oryza sativa f sp. spontanea*) - major
93 weed in rice, aquatic weeds such as water hyacinth (*Eichhornia crassipes*), parasitic weed
94 (*Striga asiatica*) and other weeds like day flower (*Commelinabenghalensis*), goat weed
95 (*Ageratum conyzoides*), *Chenopodium album*, *Abutilon theophrastii*, sickle pod (*Cassia*
96 *obtusifolia*), field bind weed (*Convolvulus arvensis*) and canada thistle (*Cirsium*
97 *arvense*). *Cyperus difformis* with C₃ and *Cyperus iria*, *Cyperus compressus* and
98 *Fimbristylismiliacea* with C₄ photosynthetic pathway were the major cyperaceous weeds
99 found at all the growth stages of semi dry seeded rice.[12]The abundant growth of C₃ weed

100 *Schoenoplectus juncooides* in the water channels, lowlands, undisturbed fields and field
101 bunds as an annual/ perennial was reported by [52].

102 In C4 plants with (Hatch and Slack) pathway, the first stable compound formed in
103 the mesophyll cell is Oxaloacetic acid (OAA, 4C) in the presence of the enzyme, Phospho
104 Enol Pyruvate (PEP) Carboxylase. OAA produces malate or aspartate, which undergo
105 decarboxylation inside the bundle sheath cells thereby enhancing the CO₂ concentration in
106 the area surrounding RuBisCO thus avoiding the photorespiration process. [16] reported
107 that under high temperatures, C4 pathway is more efficient due the absence of
108 photorespiration.

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

118

119 **2.2. Response of weeds to elevated carbon dioxide**

120 **a. Response of crops and weeds with C₃ pathway**

121 [40] observed that potentially fast-growing wild species and plants with nitrogen
122 fixing roots gained more biomass than slow-growing species (54% vs. 23%) with increase
123 in CO₂ from 300 to 720 ppm. Elevation in CO₂ concentration enhances the efficiency of
124 C₃ pathway by increasing the CO₂: O₂ ratio around RuBisCO, thus favouring
125 carboxylation and reducing photorespiration. C₄ plants are unaffected or the least affected
126 by the elevation in atmospheric CO₂ concentration since they have an internal CO₂
127 concentrating mechanism.

128 [64] studied the response of rice (C₃ crop) and red rice (*Oryza sativa fsp.spontanea*,
129 C₃ weed) in ambient (300 ppm) and elevated concentrations (400 and 500 ppm) of CO₂.
130 He observed that the tiller number, panicle number, tiller weight, leaf weight, panicle
131 weight and 50 seed weight of cultivated rice increased at 400 ppm but reduced at 500 ppm.

132 Beyond 500 ppm rice showed no response. While, its C₃ weed counterpart- red rice had a
133 linear increase in both biomass and seed yield with elevation in CO₂ from 300 ppm to 500
134 ppm. All the yield attributes were double for red rice at 300 ppm and four to five-fold
135 more at 400 and 500 ppm when compared with cultivated rice. The difference in response
136 is due to physiological plasticity and genetic diversity of red rice compared to cultivated
137 rice. [11] reported a strong response of weedy rice to elevated CO₂ as evident from a
138 higher tiller production and plant height of weedy rice compared to two popular rice
139 varieties in Kerala: Uma and Jyothi when grown in open top chamber. Weedy rice grown
140 in an atmosphere with enriched CO₂ produced taller plants with high anthocyanin
141 pigmentation compared those grown under open conditions with ambient concentration of
142 CO₂.

143 **b. Response of crops and weeds with C₄ pathway**

144 [60] conducted a study in four C₄ crops viz. grain amaranth (*Amaranthus*
145 *hypochondriacus*), sugarcane(*Saccharum officinarum*), sorghum (*Sorghum bicolor*)and
146 maize (*Zea mays*)and six weed species namely *Amaranthus retroflexus*, *Echinochloa crus-*
147 *galli*, *Panicumdichotomiflorum*, *Setaria faberi*, *Setaria viridis*and *Sorghum halapense*.
148 Both crops and weeds were grown at ambient (385 ppm) and elevated (680 ppm)
149 concentrations of CO₂ up to 60 days after sowing (DAS). Photosynthesis of weeds
150 increased by 19 percent, which was nearly double that of crops (10 %). Among the
151 selected plants redroot pig weed (*Amaranthus retroflexus*) showed the maximum increase
152 in photosynthesis (+30 percent) and the least photosynthetic stimulation was observed in
153 maize (*Zea mays*) ie., +5 percent with elevation in CO₂ concentration.*Fimbristylismiliacea*
154 with C₃- C₄ intermediate photosynthetic mechanism dominated in the double-cropped
155 wetlands as reported by [45].Barnyard grass (*Echinochloa crus-galli*) a troublesome
156 graminaceous weed infesting rice fields having C₄ photosynthetic pathway reduced rice
157 grain yields by 58 per cent when it was planted at a density of 8 plants per square metre.
158 Results revealed that barnyard grass reduced the Rubisco activity, leaf photosynthetic
159 capacity, and energy conversion efficiency in rice [54].

160 **c. Response of C₃ crop with C₄ weeds and C₄ crop with C₃ weeds**

161 Generally, plants respond to elevated CO₂ by partial closure of stomata
162 which reduces the transpiration loss. Hence, water requirement decreases and water use

163 efficiency (WUE) increases with increase in the level of CO₂. [28] opined that, if the WUE
164 of C₃ and C₄ plants triggered to 70- 100 percent, there will be a threat of C₃ weed invasion
165 into drier habitats.

166 Sorghum (*Sorghum bicolor*) and common cocklebur (*Xanthium strumarium*) were
167 provided with a higher concentration of CO₂. On taking observation 41 DAS, a higher leaf
168 area and biomass production was obtained for cockle bur with C₃ pathway than the C₄ crop
169 sorghum. Thus, [57] opined that in the presence of C₃ weeds the vegetative growth,
170 competitiveness and yield of economically important C₄ crops gets reduced.

171 **d. Response of C₃/ C₄ crop in a C₃-C₄ weed association**

172 Under field conditions, crop experiences competition from both C₃ and C₄ weeds.
173 [56] conducted an experiment to study the response of a C₃ crop, soybean (*Glycine max*) to
174 elevated CO₂, when grown in combination with a C₃ weed, *Chenopodium album* and a C₄
175 weed, *Amaranthus retroflexus*. Sole cropping of soybean increased the biomass and yield
176 by 32 and 23 percent. Soybean, when grown along with *Chenopodium album*, the biomass
177 reduction increased from 23 to 34 percent and consequently seed yield reduction increased
178 from 28 to 39 percent. Soybean, grown in combination with C₄ weed *Amaranthus*
179 *retroflexus* showed a decrease in yield reduction from 45 to 30 percent. C₃ crop get the
180 benefit of elevated CO₂ when grown in isolation and C₃ weed have a greater competitive
181 advantage over the crop, while C₄ weed competition decreased but not nil.

182 A study conducted by [58] revealed that sorghum when grown in a weed free
183 environment with increased CO₂ had significant difference leaf weight and leaf area but
184 there is no significant difference in terms of yield related to ambient CO₂ condition. In the
185 presence of C₃ weed - at ambient CO₂ condition, there is no significant loss in biomass or
186 yield in sorghum but at elevated CO₂, sorghum yield was reduced by 16 percent and
187 biomass by 14 percent. But in the presence of C₄ weed – at ambient and elevated
188 CO₂ concentrations, there is significant biomass and yield loss in sorghum. At elevated
189 CO₂ condition, sorghum yield and biomass were reduced by 23 percent and 20 percent
190 relative to elevated CO₂ weed-free condition.

191 **e. Changes in weed biology**

192 All the aspects of weed biology can be influenced by increased carbon dioxide
193 concentration, temperature and precipitation [38]. Canada thistle (*Cirsium arvense*), a C₃

194 weed showed 70 percent increase in growth when exposed to elevated atmospheric CO₂
195 [59]. [31] observed higher growth and biomass accumulation by a C₄ weed, *Amaranthus*
196 *viridis* with increase in CO₂. This observation can be explained by the result of [33], in
197 which they found out that developing leaves of C₄ plants use C₃ pathway until the
198 complete differentiation of Kranz anatomy. Hence, all C₄ plants are C₃ during their early
199 development and access all the benefits of elevated CO₂ as C₃ plants.

200 Alterations in weed biology give rise to tall and large sized plants. [41] opined that
201 increase in plant height and size help the wind dispersed invasive species such as *Cirsium*
202 *arvense*, *Sonchus arvensis* and *Carduus nutans*. [61] analyzed the pollen production of
203 common rag weed (*Ambrosia artemisiifolia*) in three concentrations (280, 370 and 600
204 ppm) of atmospheric CO₂. Pollen production shot up from 131 percent at 280 ppm to 320
205 percent at 600 ppm due to increase in the number and size of floral spikes. Floral weight
206 decreased from 21 to 13 percent but the weight of total pollen increased from 3.6 to 6
207 percent between 280 and 600 ppm.

208 [32] conducted an experiment in the Directorate of Weed Science Research at
209 Jabalpur, to study the response wild oats (*Avena fatua*) to change in the CO₂ concentration.
210 Ambient CO₂ concentration was 370 ± 20 ppm and the elevated CO₂ concentration was
211 550 ± 30 ppm. Wild oats showed early maturation (13 days prior to that under ambient
212 CO₂ concentration) and seed shattering thus enriching the weed seed bank. Drought
213 conditions prolong the viability of weed seed bank in the soil.

214 A study conducted by [24] in three weed species namely *Bromus tectorum*,
215 *Hordeum murinum*, and *Lactuca serriola* indicated that leaf area consistently responded to
216 higher CO₂ concentration than a combination of high CO₂ concentration and elevated
217 temperature. Growth and productivity of *Parthenium hysteroporous* observed under
218 elevated CO₂ conditions and results revealed that under ambient CO₂ concentration,
219 parthenium grew taller with a greater number of leaves, flowers, and dry biomass
220 compared to the ambient CO₂ concentration.

221 2.3 RESPONSE OF WEEDS TO RISING TEMPERATURE

222 Soil and above ground temperature are important, in governing the reproduction
223 and establishment of weeds. Weed species distribution in a geographical area was
224 indicated by atmospheric temperature [37]. As most of the physiological processes such as

225 photosynthesis, respiration and transpiration are highly temperature dependent, any
226 changes in temperature might affect plant growth. [29] opined that phenological
227 development of plant was more influenced by increased temperature than elevated CO₂.
228 Increased temperature alters the weed proliferation and competitive advantage in crop
229 stands.

230 Under normal warm conditions, [19] explained the presence of a temporal non-
231 synchrony between the C₄ weed – green foxtail (*Setaria viridis*) and C₄ crop - maize (*Zea*
232 *mays*) during seedling emergence, such that *Setaria* emerges only after the establishment
233 of maize crop. [38] observed that higher temperature result in synchronous emergence of
234 *Setaria viridis* and maize, leading to competition at the emergence stage. High temperature
235 triggers the germination and subsequent emergence of *Setaria* seeds. Hence, at higher
236 atmospheric temperature minor weeds may pose threat to the crop. [41] observed that a 4°C
237 rise in temperature, caused early emergence of *Chenopodium album* and *Setaria viridis* by
238 26 and 35 days and flowering advanced by 50 and 31.5 days, respectively.

239 [49] analyzed the variations in the root: shoot ratio of soybean, prickly sida (*Sida*
240 *spinosa*) and sickle pod (*Cassia obustifolia*) with rise in temperature. A higher
241 photosynthate translocation to the plant roots was observed in *Cassia obustifolia* at 36°C
242 (day temperature) and 31°C (night temperature). Root:shoot ratio of *Sida spinosa* and *C.*
243 *obustifolia* was 1.3 and 1.6 respectively, and that of soybean was 0.8. Thus, it is evident
244 that under high atmospheric temperature, weed has advantage over the crop, since the
245 underground propagules remain viable and helps in the regeneration of the plant after the
246 high temperature stress, while the crop has very low re-growth potential. The resilience of
247 *C. rotundus* under various pressures originates from its strong underground tuber system,
248 where each tuber produces multiple active buds, enabling continuous growth in
249 conjunction with its allelopathic impact [7].

250 **2.4. RESPONSE OF WEEDS TO CHANGES IN RAINFALL**

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

256 [55] analyzed the floristic diversity of the basin and observed two alien weed
257 species in the rice fields, which eradicated the native *Echinochloa* sp. It was inferred that
258 the amphibious adaptation (survival both under flood and residual moisture) of the two
259 alien species: *Marsiliaquadrifolia* and *Leptochloa chinensis* resulted in the weed shift. [44]
260 opined that under excess rainfall, *Rhamphicarpa fistulosa* - a parasitic weed in cereals
261 would pose a serious threat to the crop.

262 [36] reported that *Anoda cristata* and *Abutilon theophrasti* are two common C₃
263 weeds in cotton. Prevalence of drought leads to severe competition of these two weeds
264 with cotton, causing a yield reduction in cotton. [44] predicted the infestation of the
265 parasitic weed, *Striga hermonthica* under conditions of prolonged drought. Past research
266 gave thrust in the manipulation of species response to CO₂ enrichment and not on
267 associated increase in temperature or drought [20]. [23] forecasted the changes in
268 temperature and moisture, and explained that changes will have implications on
269 germination, spatial and temporal emergence of weed seeds and seedlings. In reality, crops
270 and weeds get exposed to a multitude of climatic changes. Hence, considering a
271 combination of climate change consequences is of significance.

272 2.5. RESPONSE OF WEED TO CHANGE IN CARBON DIOXIDE AND TEMPERATURE

273 [22] opined that at low and high temperatures, growth enhancement due to
274 elevated CO₂ decreases. On the contrary, [15] observed that CO₂ enriched atmosphere
275 provided extreme temperature tolerance to plants. [48] reported the amelioration of high
276 temperature-induced stress in quack grass (*Agropyron repens*) in an atmosphere with
277 elevated CO₂ concentration.

278 [35] observed that at high temperature of 23°C day temperature and 19°C of night
279 temperature, wild oats (*Avena fatua*) completed its development faster. Since maturation is
280 faster, more seeds get deposited in soil seed bank thereby increasing the plant number. At
281 480 ppm CO₂, 44 percent more seeds were produced, compared to 397 ppm. At high
282 temperature and light intensity during midday C₄ weeds like redroot pigweed (*Amaranthus*
283 *retroflexus*) and Johnson grass (*Sorghum halapense*) efficiently fix CO₂ than C₃ crops like
284 soybean and cotton. [17] reported that high temperature increases the evaporative
285 demand. Since C₄ plants have high water use efficiency and CO₂ compensation point they
286 are best adapted to an atmosphere with high CO₂, temperature and light intensity.

287 [32] reported that infestation of *Phalaris minor* in wheat, aggravate with increase
288 in CO₂ due to climate change and the condition may worsen with water scarcity. With CO₂
289 enrichment, wheat gain biomass against *P. minor*. Under water stress conditions, *P.*
290 *minor* survived better and had an advantage over wheat. [53] assessed the response of
291 tomato (*Solanum lycopersicum*) and *Amaranthus retroflexus* at three different levels of
292 CO₂ viz. 400, 600 and 800 ppm, with and without water stress. Without water stress, leaf
293 photosynthetic rates, plant height, leaf area and biomass increased with elevation in
294 CO₂ concentration for tomato. The plant height and biomass of *Amaranthus retroflexus*
295 increased even under water stress.

296 [30] conducted a study to know the response of *Cynodon dactylon* growth
297 under elevated temperature and moisture conditions with three temperature levels ambient
298 (0°C), +2°C and +4°C increase over the ambient and with two moisture levels viz., supply
299 of moisture at 100 percent of evaporation and 60 percent of evaporation occurred previous
300 day. The results inferred that, because of its high acclimatization capacity *C. dactylon*
301 produced more growth under elevated temperature of +4°C with sufficient moisture. C₄
302 photosynthetic pathway might have helped the weed to utilize moisture and temperature
303 more efficiently even under stress conditions.

304 3. WEED MANAGEMENT IN CHANGING CLIMATE

305 The growth of underground parts such as roots and rhizomes are highly stimulated
306 than that of shoots under elevated CO₂, which makes mechanical tillage less efficient
307 since, it helps in the dispersal of weed propagules [62]. [9] observed significant differences
308 in morphometric characteristics of weedy and cultivated rice during early growth stages.
309 Variations were noted in culm thickness and ligule length and the most notable distinction
310 was found in tiller count, with 87% of weedy rice variants exhibiting a higher number of
311 tillers per plant (ranging from 11 to 20) compared to cultivated rice varieties (Jyothi (Ptb-
312 39) and Uma-MO-16 had 10 and 9 tillers, respectively). Weedy rice plants were observed
313 to be taller and lankier (ranging from 105 to 115.67 cm) with predominantly round culms,
314 sometimes displaying anthocyanin pigmentation at the nodal regions. They also tended to
315 have shorter ligules, early flowering times compared to cultivated rice, a greater number of
316 tillers per plant, and predominantly awned grains. The study concluded that morphological
317 adaptations displayed by these morphotypes in response to the changing climatic

318 conditions strongly suggested the potential for weedy rice to pose a persistent threat to rice
319 cultivation.

320 **3.1 Herbicide efficacy in changing climate**

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

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

343 **3.2 Mechanisms of herbicide resistance**

344 Gene mutations in the target site leads to a modified target site such that the
345 herbicide molecule would not recognize the actual site of action. This leads to target site
346 resistance. Any hindrance in the herbicide's translocation path leads to non-target site
347 resistance. Non-target site resistance occurs due to several reasons: (a) Fast metabolism of
348 toxic herbicide molecules into safe, non-toxic forms (b) decreased translocation of the

349 applied herbicide due to drought or high temperature (c) reduced leaf uptake due to certain
350 modifications in the leaf structure and (d) sequestration of the herbicide molecule in the
351 vacuole.

352 [21] observed a new mechanism of herbicide resistance called 'gene
353 amplification' in *Amaranthus palmeri* where, 5-enol pyruvyl shikimate 3-phosphate
354 synthase (epsps), the target site of glyphosate undergo amplification by increasing the copy
355 number of epsps, to 160-fold. The combined post-emergent herbicide penoxsulam +
356 cyhalofopbutyl exhibited significantly higher efficacy in terms of weed dry weights,
357 effectively controlling grasses, sedges, and broadleaf weeds in wet-seeded rice [42].

358 3.3 Changes in leaf under elevated carbon dioxide and herbicide resistance

359 [14] observed depolarisation of guard cells, stomatal closure and reduced
360 stomatal conductance under elevated CO₂. [1] observed the changes in outer cuticle
361 as increased cuticle thickness and leaf pubescence. In wet-seeded rice, bensulfuron-methyl
362 + pretilachlor demonstrated the highest weed control efficiency and was comparable to
363 pyrazosulfuron-ethyl, effectively controlling grasses, sedges, and broadleaf weeds [43].

364 3.4 Causes for reduction in glyphosate efficiency

365 Glyphosate, popularly known by its trade name- Roundup is a non-selective, post-
366 emergent, systemic herbicide used worldwide for general weed control. Advent of roundup
367 ready crops has enabled the use of glyphosate in cropped fields also, since the crops are
368 modified genetically for showing resistance to roundup. Glyphosate, either alone or in
369 combination with 2,4-D, has exhibited potential in managing *C. rotundus* growth due to its
370 rapid translocation to the tubers [3]. Glyphosate has lost its efficiency as a total weed killer
371 due to various adaptations in the weeds to cope up with climate change. Seedling stage is
372 the herbicide sensitive stage of weeds, hence shortening of this stage results in reduced
373 efficacy of herbicides. Eg. *Chenopodium album* spent 5 days less on seedling stage
374 [63]. Closure of stomata, reduced stomatal number and stomatal conductance during dry
375 conditions affect the entry and translocation of glyphosate, thereby reducing its efficacy, as
376 it is post emergent (foliage applied). Increased cuticular thickness and starch deposition
377 affects the penetration and entry of herbicide. [13] found that regardless of whether
378 herbicides were applied before or after plant emergence, they persisted in the active
379 surface soil, causing fluctuations in soil enzyme activities across different post-treatment
380 days in semi-dry rice. Profuse underground growth help weeds to re-grow and produce

381 new flushes after the destruction of above ground portion by the herbicide. This leads to
382 herbicide dilution, since the recommended dose of the herbicide is not sufficient to control
383 the weeds. [4]documented a decrease in tuber viability (20-23.3%) and regeneration (6-8
384 sprouts per m²) when using a stale seedbed in combination with pre-plant application,
385 followed by directed post-emergence glyphosate application for *C. rotundus*
386 management.Heavy rains after herbicide spray would wash off the herbicide from foliage.
387 Unpredictable rains reduce rain safe period that is required after herbicide application.
388 Roundup Ready crops facilitate the use of glyphosate in cropped fields for selective killing
389 of weeds. But, [39] inferred that Roundup Ready Soybean translocated more C₁₄-
390 glyphosate to meristematic tissues at 35°C than at 15°C, indicating a potentially higher
391 glyphosateinjury at higher temperatures.

392 **4.FUTURE WEED THREATS**

393 **4.1 *Sphagneticolatrilobata***

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

400 **4.2 *Datura stramonium***

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

403 **4.3 *Lantana camara***

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

410 **4.4 *Parthenium hysterophorus***

411 *Parthenium hysterophorus* is an invasive weed species introduced to India. It
412 possesses a C₃-C₄ intermediary pathway of photosynthesis. [34]observed an increased
413 growth and seed output in *P. hysterophorus* at an elevated concentration of CO₂ (550 ppm)
414 and at cooler (30°C day temperature and 15°C night temperature) and wetter conditions.
415 During warm temperature, taller plants with greater biomass, shorter life span, high seed
416 production, seed filling and seed longevity were produced.

417 **4.5 *Eichhornia crassipes***

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

423 **4.6 *Prosopis juliflora***

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

431 **5. CONCLUSION**

432 Ability of weeds to adapt to the changing climate makes them more efficient in
433 competing with the crops. Due to the presence of profuse underground growth, C₄ pathway
434 and C₃-C₄ intermediate pathways, perennial weeds are expected to pose more threat in a
435 changed climate, since they cannot be effectively controlled by herbicides due to dilution
436 effect and several weed adaptations. Modifications in the morphology of leaves and the
437 development of resistance within the weeds result in reduced efficacy of herbicides. Being
438 more efficient in adverse environmental conditions, C₄ pathway plants are benefitted. Rice,
439 being our staple food crop needs to be improved in production. Since it is a C₃ crop, the
440 performance of the crop gets affected with climate change. Hence, development of rice
441 with C₄ mechanism needs a higher thrust. Weeds evolve effectively during stress and

442 climate change is inevitable so weed utilization by bioprospecting helps in managing the
443 weeds in a useful manner. A weed dominated future gives us the opportunity to identify
444 potential crops from weeds.

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