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Herbicides weed management in changing environmental conditions

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Abstract: Elevate CO_2 levels in the atmosphere might have prominent effects on weed phenology, consequently changing herbicide performance on weeds. Increased atmospheric CO_2 concentration increase leaf thickness and reduce stomatal number and conductance potentially reducing the absorption of POST–emergence applied herbicides. From the other side, higher temperature stimulates stomata conductance, reduce the viscosity of epicuticle waxes, thus increasing the penetration and diffusion of herbicides as a result of changes in the composition and the permeability of the cuticle. However, in some circumstances higher temperatures might cause hastened metabolism, which consequently decreases herbicide activity on target plants. In conditions of higher RH, cuticle hydration and stomatal conductance increases, consequently increases the permeability and translocation particularly of hydrophilic herbicides into the leaves. Similar, under higher irradiance, stomata stay open, photosynthetic rate increases consequently increasing absorption, penetration and subsequent phloem translocation of POST–em systemic herbicides in weed tissue. Drought might cause increased cuticle thickness and increased leaf pubescence, with consequent reductions in herbicide absorption into the leaves. Rainfall after POST–emergence herbicides application might reduce their efficiency through washing out. Increased frequency and intensity of precipitation will have a negative effect on absorption, translocation, and activity of PRE–emergence herbicides.

Key words: environmental conditions, weeds, control, herbicides

Uravnavanje plevelov s herbicidi v razmerah spreminajočega se okolja

Izvleček: Povečane koncentracije CO_2 v ozračju bi lahko imele znatne učinke na fenologijo plevelov kar bi posledično lahko spremenilo učinkovanje herbicidov nanje. Povečane koncentracije CO_2 v ozračju povečujejo debelino listov in zmanjšujejo število rež, kar potencialno zmanšuje njihovo prevodnost in potencialno zmanjšuje absorbcijo POST–em nanešenih herbicidov. Po drugi strani višje temperature pospešujejo prevodnost rež in zmanjšujejo viskoznost epikutikularnih voskov in s tem povečujejo penetracijo in difuzijo herbicidov kot posledico sprememb v sestavi in prevodnosti kutikule. V nekaterih razmerah lahko višje temperature pospešijo presnovo, ki posledično lahko zmanjša aktivnost herbicidov na tarčnih rastlinah. V razmerah večje relativne zračne vlažnosti se povečata hidratacija kutikule in stomatarna prevodnost kar posledično poveča permeabilnost in translokacijo, še posebej hidrofilnih herbicidov v liste. Podobno v razmerah večjega obsevanja ostajajo reže dalj časa odprte, povečana fotosinteza posledično poveča absorbcijo, penetracijo in translokacijo sistemskih POST-em herbicidov po floemu v tkiva plevelov. Suša lahko povzroči povečanje debeline kutikule in dlakavosti listov kar posledično zmanjša absorbcijo herbicidov vanje. Dež lahko po nanosu POST–em herbicidov zmanjša njihovo učinkovitost zaradi izpiranja. Povečana pogostost in jakost padavin imata negativni učinek na absorbcijo, translokacijo in aktivnost PRE–em herbicidov.

Ključne besede: okoljske razmere, pleveli, nadzor, herbicidi

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1 INTRODUCTION

Agriculture production in terms of quantity and quality, as well as agronomic practices, including weed management, may be affected significantly in conditions of climate change (Varanasi et al., 2016). Elevating CO_2 levels associated with changes in temperature and precipitation are important concerns for upcoming weed management and crop production. Taking into account the greater physiological flexibility (Ziska et al., 2010; Davidson et al., 2011; Billore, 2019) and their greater intra specific genetic variation (Dukes & Mooney, 1999), weeds are expected to show greater competitiveness and better accommodation regarding increasing CO_2 concentrations and temperature in comparison with crops (Singh et al., 2011; Varanasi et al., 2016). Considering its positive effect on weed growth, shifting environmental conditions will impact directly or indirectly on the weed control methods by reducing their effectiveness on weeds and making them a considerable issue for sustainable agriculture production as well as costlier in same time (Ziska et al., 1999; Karl et al., 2009). Climatic variation factors are estimated to have significant effects on the growth and physiological processes of weedy plants, like growing rate, stomatal conductance, and photosynthetic efficiency (Fuhrer, 2003; Manisankar & Ramesh, 2019). Elevate CO_2 and temperature, sunlight intensity, relative humidity, rainfall, and drought influence the coverage, penetration, translocation, persistence and activity of herbicides (Muzik, 1976; Hatzios & Penner, 1982; Bailey, 2003; Bailey, 2004; Malarkodi et al., 2017). Additionally, interactions among these environmental factors may have uncertain consequences on herbicide efficacy (Sutherland et al., 2017). Numerous studies confirmed that shifting climate conditions might also decrease the susceptibility of weeds to some herbicides (Varanasi et al., 2016; Ziska, 2016; Fernando et al., 2016; Matzrafi et al., 2018). For example, elevated CO_2 reduced the efficacy of glyphosate and glufosinate against *Cirsium arvense* (L.) Scop., and *Elytrigia repens* (L.) Desv.ex Nevski (Ziska & Teasdale, 2000). Similarly, Manea et al. (2011) reported that glyphosate efficacy at increased CO_2 concentrations is diminished in C_4 weeds such as *Eragostis curvula* (Schrad.) Nees, *Paspalum dilatatum* Poir., and *Chloris gayana* Kunth, as a result of increased leaf area and total plant biomass. Higher temperatures may worse the consistency of cuticular lipids, thereby increasing the absorptivity and penetration of herbicides through the cuticle (Price, 1983; Patterson et al., 1999); for example, uptake and translocation of ^{14}C-glyphosate was found to be higher at 22 °C than at 16 °C in *Desmodium tortuosum* (Sv.) DC. (Sharma & Singh, 2001). Although tendency of elevated air temperatures is to increase absorption and translocation of most POST-em applied herbicides (Patterson et al., 1999), in some cases higher temperatures also might encourage rapid metabolism, which consequently decreases herbicide efficacy on target plants (Kells et al., 1984; Madafiglio et al., 2000; Medd et al., 2001; Johnson & Young, 2002). Increased CO_2 and temperature might change weed growth phenology, with shortened the period spent in the seedling stage, i.e. the stage of greatest POST-em herbicide efficacy (Ziska et al., 1999). Also, changes in these factors caused alteration in leaf morphology, leaf surface characteristics or variation in root-to-shoot ratio which affect herbicide absorption, distribution and efficacy (Olesen & Bindi, 2002; Poorter & Navas, 2003; Ziska et al., 2004; Dukes et al., 2009). Additionally, enhance in tuber and rhizome growth, joined with enhance in biomass, particular in perennial weeds (Oechel & Strain, 1985), would induce a dilution effect on any herbicide treatment (Patterson, 1995), making their control more complicated (Patterson et al., 1999). Modifications in environmental factors, such as drought spells or prolonged rainy periods, might restrict the field conditions necessary for optimal herbicide applications (Amare, 2016). Generally, dry soil conditions decrease the activityof PRE-em herbicides, affect their behavior in the soil and the herbicide effectiveness “windows” due to strong herbicide adsorption (Bailey, 2004; Howden et al., 2007), whereas severe or frequent rainfall after the application may cause herbicide leaching (Soukup et al., 2004; Pacanoski & Mehmeti, 2021) and dilution (Kanampiu et al., 2003).

2 INTERACTION CO_2 – HERBICIDE EFFICACY

The importance of interaction CO_2 concentration - herbicide efficacy has occupied research attention in recent decades as a result of the constant increase in concentrations of atmospheric CO_2. Elevate CO_2 levels in the atmosphere might have prominent effects on weed phenology (Anwar et al., 2021), consequently altering herbicide effectiveness on weeds (Ziska, et al., 1999; Ziska & Teasdale, 2000; Ziska et al., 2004; Ziska & Runion, 2007). One of the most pronounced effects of increased CO_2 concentrations is the minimizing of stomatal conductance, which could increase up to 50 % in some weeds (Bunce, 1993). Minimized number and stomatal conductance with increasing CO_2 could decrease transpiration resulting in decreased herbicide absorption and efficacy, particularly of POST-em applied herbicides (Bunce & Ziska, 2000; Ziska & McClung, 2008; Ziska, 2008). Additionally, Nowak et al. (2004) and Ainsworth & Long (2005) indicated that C_3 and C_4 weeds grown in condition of increased CO_2 concentrations have increased leaf pubescence and developed thicker cuticle. Apart from increasing leaf thickness, increased CO_2 concentrations might also generate partially stomatal closure (Ziska, 2008; Jackson et al., 2011). These characteristics might minimize up take and efficacy of POST-em applied herbicides. Manea et al. (2011) found that in three of four C_4 grass species tolerance to glyphosate in conditions of raised CO_2 is significantly increased. Similar results were obtained by Ziska & Goins (2006). The explanations for the minimized efficacy of the herbicides could be that elevating CO_2 increase leaf consistency and reduce stomatal number and their conductivity potentially reducing the absorption of POST-em applied herbicides. Furthermore, an increase in the apparent photosynthesis rates as a result of increased CO_2 concentrations, mainly in C_3 weeds, might cause rapid seedling growth, the most susceptible stage for optimal weed control, which could modify the efficacy of POST-em herbicides. For example, *Chenopodium album* L., a C_3 weed, demonstrated higher tolerance to glyphosate as a result of increased growth and plant biomass at raised CO_2 concentration (Ziska et al., 1999). In addition, perennial weeds may become even more troublesome, if vegetative growth is stimulated as a result of increased photosynthesis in relation to elevated CO_2. This could be due to less herbicide translocation as the root system becomes more vigorous. In this context, *Elymus repens (L.) Gould* (Ziska & Teasdale, 2000) and *Cirsium arvense* (Ziska et al., 2004) showed prominent tolerance to glyphosate due to elevated CO_2 levels, which caused large stimulation of belowground growth. Elevate CO_2 levels increases concentration of starch in leaf tissue (Patterson, 1995), particularly in C_3 weeds (Wong, 1990), but reduce protein concentration (Bowes, 1996; Taub et al., 2008; Loladze, 2014). Reduction of protein content results to diminished demand for aromatic and branched-chain amino acids synthesis, which may reduce the efficacy of many herbicides, including ALS and EPSPS inhibitors (Patterson et al., 1999; Varanasi et al., 2016). Changed environmental conditions, particularly rising of CO_2 concentration and temperatures, stimulate weed growth through modification of photosynthesis, pigment production, as well as overall metabolic activity. Because of that, herbicides photosystem I and II and pigment inhibitors may become more effective. However, the effects of rising CO_2 on herbicide efficacy is species determined. Namely, at double atmospheric CO_2 concentrations, efficacy of metsulfuron on *Amaranthus retroflexus* L. decreased by 4.6 %, efficacy of imazethapyr in control of *Stellaria media* (L.) Vill. was unchanged, whereas efficacy of imazamethabenz-methyl over *Avena fatua* L. improved by 15.7 % (Archambault et al., 2001). According same authors, in the same conditions, efficacy of linuron in control of *Polygonum convolvulus* L. was reduced by 15 %, whereas status quo in the efficacy was reported for metribuzin on *Chenopodium album* L. and bromoxynil on *Kochia scoparia* (L.) Schrad., respectively. The effects of rising CO_2 on ACCase inhibitors varied and depend on weed species. At double–environment CO_2 concentrations clodinafop efficacy in control of *Avena fatua* increased by 8.6 %, while *Avena fatua* L. control was not affected by sethoxydim. No change in the efficacy was reported for control of *Avena fatua* and *Setaria viridis* (L.) P.Beauv.by fluazifop (Archambault et al., 2001). Further, decreasing of clopyralid efficacy for 8.9 % was noted in control of *Senecio vulgaris* L., whereas increasing of efficacy of 2,4-D for 26.9 % was obtained in control of *Polygonum convolvulus* L. (Archambault et al., 2001). Increased frequency of herbicide applications might exceed CO_2 caused declines in efficacy, but might bring additional risks for human and animal health because it might increase the occurrence and concentration of these chemicals in the environment (Ziska et al., 2004).

3 INTERACTION TEMPERATURE − HERBICIDE EFFICACY

Temperature has multiple impacts on weed growth and development as well as herbicide efficacy. Alterations in the apparent photosynthesis rate, respiration, phloem translocation, and protoplasmic flux, as well as rate of water up take and transpiration, leaves formation, cuticle compactness and hydration, number and aperture of stomata will affect uptake, diffusion, and metabolism of herbicides (Bailey, 2004; Zanatta et al., 2008; Rodenburg, et al., 2011). Higher temperature encouraged stomata conductivity, reduced the viscosity of cuticle waxes, thus increasing the uptake and diffusion of herbicides as a result of modifications in the structure and the permeability of the cuticle (Price, 1983; Chandrasena, 2009). *Abutilon theophrasti* Medik. plants treated with acifluorfen at lower (20/15 °C) day/night temperature regime showed 70 % higher production of epicuticular wax on the leaf surface than plants in condition of higher (32/22 °C) day/night temperature. Decreasing of the wax production was connected with better efficacy of herbicides when temperature increased, corroborating the assumption of higher herbicide efficiency as cuticle structure altered. This study also confirmed that when temperature increased from 20/15 °C to 32/22 °C, there was a 25 % increase in the acifluorfen absorption applied alone and 99 % increase in acifluorfen absorption applied with oil–based surfactant (Hatterman-Valenti et al., 2011). Ganie et al. (2017) noted that the efficacy of 2,4-D and glyphosate in control of *Ambrosia artemisiifolia* L. and *Ambrosia* *trifida* L. might be enhanced if applied at higher (29/17 °C) day/night temperature regime, because of improved absorption and translocation compared with applications during lower (20/11 °C) day/night temperatures. Study in greenhouse conditions using different night/day temperatures (5/10 °C, 15/20 °C, and 20/25 °C) demonstrated that *Raphanus raphanistrum* L. grown in conditions of lower (5/10 °C) temperatures was poorly controlled with 1,200 g ai ha^{-1} of glufosinate. Contrary, 100 % mortality was achieved under higher temperatures15/20 °C and 20/25 °C, respectively for the same dose (Kumaratilake & Preston, 2005), indicating increased efficacy of glufosinate under increased air temperature. Flumiclorac exhibited higher activity on *Amaranthus retroflexus* (threefold) and *Chenopodium album* (sevenfold) with increasing of temperatures from 10 °C to 40 °C (Fausey & Renner, 2001). Johnson & Young (2002) reported for threefold increase in mesotrione efficacy in control of *Abutilon theophrasti* and *Xanthium strumarium* L. with increasing of temperatures from 18 °C to 32 °C. Similarly, at higher temperature, fluthiacet was twice and three times more effective in control of *Amaranthus retroflexus* and *Chenopodium album*, respectively, compared to the efficacy observed at 10 °C (Fausey & Renner, 2001). Atrazine applied at 15:00 h, when the air temperature was the highest, provided the greatest control of *Ambrosia artemisiifolia* L. and *Abutilon theophrasti* (Stewart et al., 2009). Stopps et al. (2013) confirmed that glyphosate efficacy in control of *Ambrosia artemisiifolia* L. and *Abutilon theophrasti*, *Amaranthus* spp., increased when herbicide was applied between noon and 6 pm, which coincides to the higher air temperatures during the day. Contrary, the efficacy of bromoxynil on *Abutilon theophrasti* declined by up to 45 % when applied at 24:00 h, when the air temperature was the lowest (Stewart et al., 2009). Irrespective of temperature increase, dicamba/diflufenzopyr provided > 95 % control of *Amaranthus retroflexus,* and *Ambrosia artemisiifolia*, *Chenopodium album*. On the other hand, lower temperatures reduced control of *Abutilon theophrasti* by 7 % to 15 % (Stewart et al., 2009). Similar, in research of Ziska et al. (1999) glyphosate efficacy was reduced in control *Ambrosia trifida* and *Ambrosia artemisiifolia* at low temperatures.

Although the tendency of higher atmospheric temperatures is to enhance absorption and translocation of most POST-em applied herbicides, in some circumstances higher temperatures might cause hastened metabolism, which consequently decreases herbicide activity on target weeds (Johnson & Young, 2002). Enhanced metabolism rate was the reason for reduction of pinoxaden efficacy on *Brachypodium hybridum* (L.) P. Beauv. control and other grasses in conditions of higher temperature (Matzrafi et al., 2016). Ou et al. (2018) tested effects of temperature on *Kochia scoparia* (L.) Schrad. growth treated with glyphosate and dicamba under three day/night temperatures: 17.5/7.5 °C; 25/15 °C; and 32.5/22.5 °C. Visual above-ground dry biomass, injury and mortality data indicated greater sensitivity to both glyphosate and dicamba when *Kochia scoparia* was grown in conditions the two cooler day/night temperature regimes. Similar trend was noted in investigation of Kleinman et al. (2016) when *Conyza bonariensis* (L.) Cronq., *Conyza canadensis* (L.) Cronq., and *Kochia scoparia* were treated with glyphosate. A significant variation in control of *Amaranthus palmeri* S. Watson with mesotrione was obtained when the weed was grown in conditions of low and high day/night temperature regimes (25/15 °C and 40/30 °C, respectively) compared to optimum day/night temperature (32.5/22.5 °C). Related to weed height, injury, and mortality, *Amaranthus palmeri* S. Watson was more susceptible to mesotrione at 25/15 °C and less susceptible at 40/30 °C compared to 32.5/22.5 °C (Godar et al., 2015). Pyrithiobac provided higher efficacy in control of *Amaranthus palmeri* at 18 °C (25 % dry mass accumulation) than at 40 °C (70 % dry mass accumulation), although the highest efficacy was recorded at 27 °C (only 2.5 % dry weight accumulation) (Mahan et al., 2004). Mesotrione efficacy in control of *Digitaria sanguinalis* (L.) Scop. and *Amaranthus rudis* J.D.Sauer decreased by six and seven times when temperature increased from 18 °C to 32 °C (Johnson & Young, 2002). Increased temperatures as well as increased metabolic activity of the weeds nullify increased herbicide translocation, because herbicide metabolisation increases at higher temperature, as well (Martini et al., 2015; Matzrafi et al., 2016). Higher temperatures also might generate diminishing of herbicide absorption due to quick drying of spray droplets to solid deposits (Devine et al., 1993) and volatility of some herbicides, such as growth regulators herbicides causing in vapor drift and possible injury on non target broadleaf crops (van Rensburg & Breeze, 1990; Strachan et al., 2010).

Further, soil temperature has an effect on the absorption and translocation of PRE-em herbicides within the weed plant, as well as their persistence in the soil (Rodenburg et al., 2011). Warmer soil temperatures might reduce efficacy of PRE-em herbicides through rising volatility and degradation by soil microorganisms. For example, higher temperature had a great impact on the volatilization of the triallate from the soils. According Atienza et al. (2001) triallate losses increased from 7 % to 41 % in loamy soil and 14 % to 60 % in sandy soil, respectively with rising temperatures from 5 °C to 25 °C. Opposite, in the controlled trial conditions, low soil temperatures (around 10 °C) decreased the efficacy of alachlor and EPTC (Mulder & Nalewaja, 1978).

4 INTERACTION RELATIVE HUMIDITY – HERBICIDE EFFICACY

Relative humidity (RH) is mainly important for the activity of POST-em herbicides through its effects on herbicide absorption, including interactions between the herbicide droplets, leaf cuticle, and accessibility of water in or round droplets (Devine et al., 1993). In conditions of higher RH, cuticle hydrating and stomatal conductivity increases, consequently increases the penetrability and translocation particularly of hydrophilic herbicides into the leaf surface (Kudsk et al., 1990; Wichert et al., 1992; Shaw et al., 2000; Hatterman-Valenti et al., 2011). Penetration as well as efficacy of most POST-em herbicides is usually higher when weeds were exposed to higher RH after spraying than before, concluding that slowly droplets drying might be the reason for higher efficacy at higher RH levels rather than cuticle hydrating (Ramsey et al., 2002). The susceptability of *Digitaria sanguinalis* and *Amaranthus rudis* to mesotrione was two and four–times higher at 85 % RH compared with 30 %, respectively (Johnson & Young, 2002). Glufosinate ammonium efficacy in control of *Avena fatua* significantly increased (> 95 %) at higher RH compared with its efficacy at lower (40 %) RH. Additionally, penetration of glufosinate ammonium was higher when *Avena fatua* plants were exposed to higher RH for 30 min before and after application compared with those left at constantly lower RH (Ramsey et al., 2002). Efficacy of acifluorfen on *Ambrosia artemisiifolia* and *Xanthium strumarium* was 30 % higher when it was applied at 85 % RH compared with its efficacy at 50 % RH (Ritter & Coble, 1981). Likewise, acifluorfen, fomesafen, and lactofen provided higher efficacy in control of *Ipomoea lacunosa* L., *Ipomoea hederacea* Jacq. var. *integriuscula, Sida spinosa* L., and *Xanthium strumarium* at 85 % RH, compared to the condition of 50 % RH (Wichert et al., 1992). Similarly, when the efficacy of acifluorfen was estimated on trials carried–out for two consecutive years, it was concluded that there was higher control of *Xanthium strumarium* obtained in the year of higher RH condition (Shaw et al., 2000). Casley & Coupland (1985) stated that higher RH increased glyphosate performance due to slower evaporation from the plant surface, while Mathiessen & Kudsk (1996) claimed that higher RH had no significant influence on glyphosate efficacy.

5 INTERACTION SUNLIGHT INTENSITY – HERBICIDE EFFICACY

Alterations in sunlight intensities influence on the plants anatomy, morphology, and physiology, which consequently have an effect on herbicide performance in the plants. Stomatal conductivity and formation of leaf cuticle are positively correlated with sunlight intensity (Hull et al., 1975; Raschke et al., 1978). Under conditions of higher irradiation, stomata stay open, photosynthetic rate increases consequently increasing uptake, penetration and subsequent phloem translocation of POST-em applied herbicides in weed plant tissue (Fausey & Renner, 2001; Hwang et al., 2004; Camargo et al., 2012). Efficacy of clethodim, talkoxydim and bentazon proportionally increased with increasing of sunlight intensity (McMullan, 1996, Hatterman-Valenti et al., 2011). In study of Fausey & Renner (2001) flumiclorac provided nine times higher control of *Chenopodium album* at light intensity of 1,000 µmol m^{-2} s^{-2} than at 4 µmol m^{-2} s^{-2}. Control of *Amaranthus retroflexus* was 15 times more effective with the same herbicide under higher light intensity compared to the lower one. In same study, fluthiacet was also more effective in control of these two species at irradiance condition of 1000 µmol m^{-2} s^{-2}, as compared to the efficacy obtained at 4 µmol m^{-2} s^{-2}. Similar, oxadiazon and oxadiargyl reduced the growth of *Echinochloa crus–galli* (L.) P.Beauv. in the presence of light, but were completely ineffective in the dark (Hwang et al., 2004). UV light reduced the efficacy of tralkoxydim and clethodim, which indicates that application of these graminicides when sunlight intensity is higher during the day might increase their efficacy. Filtering UV light for 4 h after application improved efficacy of these herbicides between 13 and 55 % (McMullan, 1996). UV light is obviously significant to cyclohexanedione herbicide efficacy because these herbicides are unstable in UV light (Campbell & Penner, 1985; Falb at al., 1990; McInnes et al., 1992). Similar, ^{14}C-paraquat penetration and efficacy in control of *Abutilon theophrasti*, *Chloris virgata* Sw. and *Digitaria sanguinalis* was reduced during the UV-B treatment because of increasing leaf epicuticular wax deposition (Wang et al., 2006). On the other hand, in lower irradiance conditions, tendency of plants is to form thinner leaves with greater specific leaf surface and plant height to catch accessible sunlight required for photosynthesis. These adjustments in weed growth and leaf mofphology determinate the herbicide amount that is received and retained by the weed (Upasani & Barla, 2018). For example, surface coverage as well as absorption of POST-em herbicides is enhanced in weed with higher branching, whereas leaves with thicker structure retard herbicides penetration causing decreased herbicide efficacy (Riederer & Schonherr, 1985).

6 INTERACTION DROUGHT AND RAINFALL PATTERN − HERBICIDE EFFICACY

Herbicides might become less effective because of alteration of the external environment (drier and warmer conditions) or alterations in anatomy, physiology, and phenology of the weed flora (Clements et al., 2014; Chauhan et al., 2014; Ziska & McConnell, 2015). In this context, POST-em herbicide efficacy might be significantly influenced by drought. Drought might cause enlarged cuticle thickness and intensify grow of leaf pubescence, with consequent reductions in herbicide penetration into the leaves (Patterson, 1995). For example, the weed cuticle under arid conditions was 50-80 % thicker relative to optimal available water situations (Hatterman-Valentiet al., 2011). Increasing aridity and drought might reduce herbicide penetration, intensify herbicide volatilization, and consequently reduce its effectiveness. Drought influenced weeds are more challenge for control with POST-em herbicides than weeds that are actively growing in conditions without environmental stress. For example, for systemic POST-em applied herbicides is necessary active weed growth to be effective. In that context, in conditions of drought spells efficacy of glyphosate in control of *Abuthilon theophrasti* was reduced two and eight–fold when it was applied in two and six leaves weed growth stages, respectively (Zhou et al., 2007). Survival of glyphosate-resistant biotype of *Echinochloa colona* (L.) Link treated with double glyphosate rate (1440 g ha^{-1}) in condition of no water deficiency was only 19 %, but under water deficiency this value increased by 62 % (*Mollaee et al., 2020)*. Likewise, under dry soil conditions usually activity of PRE-em herbicides is reduced the due to strong herbicide soil adsorption (Arıkan et al., 2015). These herbicides are highly dependent on accessible water for relocation into the zone of weed seed germination (Olson et al., 2000). Herbicide photodecomposition is common process which takes place on the soil surface, and if optimal moisture does not become accessible in period of few days after application, weed control is often inadequate. Even for considerably persistent herbicides, inability to penetrate into the soil surface because of the moisture shortage give weeds opportunity to germinate without any herbicide injuries. Jursık et al. (2013) claimed a reduced pethoxamid efficacy under dry soil conditions. Contrary, increased soil moisture promotes the efficacy of many, PRE-em herbicides, including PROTOX inhibitors (Hatterman-Valenti et al., 2011).

Rainfall after POST-em herbicides application might reduce their efficiency through washing out. Increased frequency and intensity of precipitation will have a negative effect on penetration, translocation, and activity of PRE-em herbicides (Bailey, 2004; Rodenburg et al., 2011). An unusual increase in precipitation might cause leaching of PRE-em herbicides (Soukup et al., 2004; Pacanoski & Mehmeti, 2021), and consequent crop injury (Pacanoski et al., 2020) and under soil water contamination (Froud-Williams, 1996). From the other side, scarce rainfall amounts during the season might cause water–deficit conditions that impact herbicide efficacy (Zanatta et al., 2008; Keikotlhaile, 2011). For example, situations of water deficit reduced the absorption of acifluorfen (Hatterman-Valenti et al., 2011). Pereira et al. (2011) reported that *Eleusine indica* (L.) Gaertn. grown under water–stress conditions was not effectively controlled by sethoxydim. Similarly, control of *Eleusine indica* with fenoxaprop-p-ethyl, topramezone, foramsulfuron, 2,4-D + dicamba + MCPP + carfentrazone, and thiencarbazone-methyl + foramsulfuron + halosulfuron-methyl at soil moisture contents < 12 % was unsatisfactory (Shekoofa et al., 2020). *Urochloa plantaginea* (Link) R.D.Webster grown under water–deficit stress was less susceptible to ACCase–inhibiting herbicides when applied during the later growth stages (Pereira, 2010).

7 MULTIPLE INTERACTIONS

Atmospheric CO$_2$ and air temperature elevate simultaneously. The result can be completely different when both factors are taken into account together in comparison when only one factor is considering**.** In weeds, alteration in temperatures and CO$_2$ concentrations might modify net photosynthesis rates resulting with modification in carbohydrate accessibility and stability causing in altered weed physiological and biochemical capabilities. Increased CO$_2$ and atmospheric temperature might decrease herbicide efficacy by changing herbicide penetration, translocation and metabolism, subsequently increasing herbicide decomposition in weeds and decreasing herbicide availability for the target weed (Matzrafi, 2019). For example, reduced glyphosate susceptibility was observed in *Chenopodium album* and *Conyza canadensis* in response to elevated temperature, (32/26 °C) combined with raised CO$_2$ (720 ppm). According obtained results by Matzrafi et al. (2019), 61.1

%, 69.0 % and 64.0 %, respectively of the plants tested survived in conditions of mutual effects of higher temperature/elevated CO_2 concentration. Further, the efficacy of cyhalofop-butyl was reduced about 50 % in multiple–resistant *Echinochloa colona* plants grown under higher CO_2 concentration (700 ± 50 ppm) or high (35/23 °C) day/night temperature regime compared to multiple–resistant plants at ambient conditions. Higher CO_2 and temperatures increased the level of resistance to multiple–resistant *E. colona* to cyhalofop–butyl, as well (Refatti et al., 2019). Opposite, mutual effects of ambient CO_2 concentration (400-450 ppm) and day/night temperature (20/10 °C) and increased CO_2 concentrations (400-450 ppm, 800–900 ppm) and day/night temperature (25/15 °C), did not reduce efficacy of glyphosate in control of *Lactuca serriola* L., *Hordeum murinum* L., and *Bromus tectorum* L. (Jabran & Doğan, 2018). Interaction between CO_2 concentrations and water deficiency was studied by *Weller et al. (2019). According their results, e*fficacy of glyphosate in control of glyphosate resistant and susceptible *Chloris truncata* R.Br. biotypes in condition of moisture stress (50 % field capacity) and increased CO_2 level (750 ppm) was significantly reduced. Few studies have examined correlation between temperatures and RH. When higher temperatures are related with higher RH levels, there is increased cuticle hydrating, which consequently increases herbicides penetration and efficacy (Price, 1983). With simultaneous temperature and RH increasing, the efficacy of metribuzin also increased, while at lower temperatures (10 °C and 20 °C) caused no significant decreasing in its efficacy (Gealy & Buman, 1989). Opposite, glufosinate ammonium provided higher efficacy on *Setaria faberi* Herrm. at higher RH as well as higher temperature (Anderson et al., 1993).

8 CONCLUSION

The successfulness of weed management is predicted to change together with the changing of environmental conditions. In conditions of rising CO_2 and air temperature, and unpredictable drought spells and prolonged rainfall forecasts, the possibility of herbicides either to generate crop injure or being ineffective at weed control is expected, as well. Elevated CO_2 and temperatures might cause anatomical, morphological and physiological changes in weeds, their growth and development, all that could impact on absorption, translocation, and metabolism of herbicides and on the entire efficacy of herbicides. Conditions of soil water deficiency decrease the activity of PRE-em herbicides, affect their persistence in the soil and the “windows” for herbicide effectiveness due to strong herbicide adsorption, while severe or frequent rainfall after the application may cause herbicide leaching and dilution. One–sided and repeated herbicide use is estimated to result in appearance of resistant weed biotypes. Changes of environmental conditions might hasten this. In these circumstances, additional herbicide applications at higher rates might be needed to control such weeds, but additional activities increase the cost of control. Modification strategies are existing, but the expenditures of realizing such strategies (e.g. herbicide with new active ingredient, higher herbicide rates) are uncertain. Specific national legislation regulated herbicides use. In case of changing environmental conditions, which encourage weed species spreading out of their geographical boundaries, new herbicidal active ingredient might be essential to control them effectively. Commonly it takes a lot of time to obtain state agreement for a new herbicide active ingredient or an active ingredient that is not been previously used locally.

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