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Glyphosate Resistance of *Chloris virgata* Weed in Australia and Glyphosate Mobility Are Connected Problems

Aman D. Sharma

Abstract

The purpose of this review paper is to address two major aspects of glyphosate application on farmers' fields. The first aspect is the development of glyphosate resistance in weeds like *Chloris virgata*, and the second aspect is glyphosate mobility, which is directly controlled by soil sorption processes and indirectly by molecule degradation processes. This is a global problem, as excessive glyphosate residues in groundwater, drinking water, and urine of subsistence farmers from intensive agricultural localities have been reported, which can pose a risk to human health. Approaches like biochar as a possible strategy to control glyphosate leaching and crop competition as a cultural method to control glyphosate-resistant weed like *Chloris virgata* can be the potential solutions of the glyphosate resistance and glyphosate mobility.

Keywords: resistance, glyphosate, mobility, biochar, crop competition

1. Introduction

1.1 Chemistry of glyphosate

Glyphosate (N-(phosphonomethyl) glycine) is a non-selective post-emergence herbicide widely used in field crops, vegetable crops, and orchards. Glyphosate is absorbed by plants via leaves and shoots and is transported throughout the whole plant. Its usual formulation is salt of a deprotonated acid of glyphosate and a cation, e.g. isopropylamine or trimethylsulfonium. Its chemical structure has three groups (amine, carboxylate, and phosphonate) that form strong coordination bonds with metal ions to form bidentate and tridentate complexes (**Figure 1**). Hence it is a strong chelating herbicide [1].

Chemically, glyphosate is a phosphonate. It is mainly the phosphonate group via which glyphosate is bonded to iron and aluminum oxides by ligand exchange with the formation of mononuclear, monodentate, and/or binuclear, bidentate surface complexes [2].

1.2 Glyphosate degradation

Among the microorganisms, bacteria represent the majority of the glyphosate-degrading organisms [3]. Bacteria degrade glyphosate by cleaving the C-N bond and

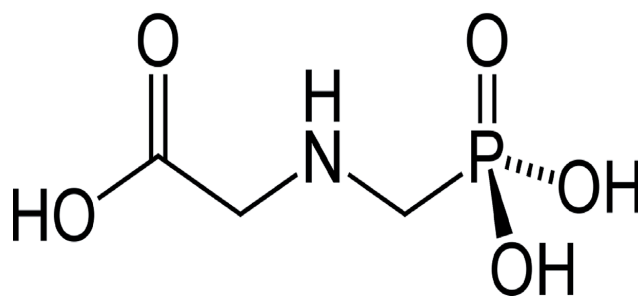


Figure 1.
Chemical structure of glyphosate [1].

converting glyphosate to AMPA (amino-methyl phosphonic acid) which is further decomposed and finally excreted to the environment. Glyphosate degradation can also occur via C-P lyase pathway to sarcosine, rather than AMPA. A bacterial strain *Bacillus subtilis* Bs-15 degraded 18% (12 h) to 67% (96 h) of glyphosate in sterile soil and 19% (12 h) to 72% (96 h) in unsterilized soil. It indicates that Bs-15 can significantly enhance glyphosate degradation.

1.3 Mobility of glyphosate

The binding mechanisms of clay minerals and organic colloids result in non-occurrence of free glyphosate, but leaching of glyphosate complexes via preferential flow paths through the soil and transfer to waterways can occur, which could be a concern from the environmental pollution point of view [4]. In another study related to the desorption rate of glyphosate from goethite mineral surfaces, the rate of glyphosate desorption is mainly controlled by the breaking of the Fe-glyphosate bond through a dissociative or a dissociative interchange mechanism [5]. Soil redox condition is also an important factor controlling the mobility of glyphosate. Microbial degradation and mineralization of glyphosate were slow in anoxic environments compared with oxic environments [6].

In US soils, glyphosate and AMPA have been detected together and found widely in the environment. The occurrence was more frequent in soils and sediments, ditches and drains, and rivers and streams and less in lakes, ponds, wetlands, soil water, and groundwater [7]. In western Switzerland, the surface runoff has been suggested as the major reason for the occurrence of glyphosate and AMPA in surface waters [8]; however, in a study related to Danish soils, limited leaching of glyphosate was reported in non-structured sandy soils, while subsurface leaching to drainage systems was observed in a structured soil when high rainfall followed glyphosate application [9].

In a study related to ^{14}C glyphosate transport in undisturbed topsoil columns, the amounts of glyphosate leached from the macroporous sandy loam were 50–150 times larger than that from the sandy soil [10].

1.4 Glyphosate residues

Glyphosate and its decomposition product AMPA have been reported in stream water samples in areas of Zurich, Switzerland, with median concentrations of 0.11 and 0.20 $\mu\text{g/l}$; however, these compounds were not detected in groundwater [11].

In a Canadian study, glyphosate residues were observed in both upland and wetland settings; however, the concentrations were well below the Canadian guidelines for drinking water quality. Many other studies have reported glyphosate residues in streams and groundwater systems [8].

An enzyme-linked immunosorbent assay (ELISA) was used to determine glyphosate presence levels in Hungarian water samples. Few samples showed exceedingly high concentration levels of glyphosate with this method [12]. Liquid chromatography is another method that can be used for the detection of glyphosate residues in cereal, oilseed, and pulse crops [13].

1.5 Soil properties and glyphosate mobility

Data from sorption studies indicated that sorption coefficients are the most sensitive parameters for environmental risk assessment and soil properties like pH and clay content govern the glyphosate adsorption in Argentinian soils. In a related study in Argentina, high glyphosate sorption with low desorption in mollisols and ultisols indicated a low risk of groundwater contamination [14].

In another study on glyphosate mineralization in different agricultural soils, exchangeable acidity (H^+ and Al^{3+}), exchangeable Ca^{2+} ions, and ammonium lactate extractable K were the key soil parameters governing mineralization [15]. In a study related to glyphosate sorption with high soil phosphate levels, glyphosate sorption distribution constant K_d in soils ranged from 173 to 939 l Kg⁻¹ under very strong to strongly acidic conditions, but the K_d was always <100 l Kg⁻¹ under moderately acidic to slightly alkaline conditions suggesting that glyphosate may become mobile by water in soils with high phosphate levels [16]. This is important concerning the application of phosphatic fertilizers, as the phosphate ion would desorb glyphosate from adsorption sites resulting in the mobility of glyphosate towards aquatic environments [17].

Generally, iron and aluminum oxides adsorb a greater amount of glyphosate and phosphates in comparison to layer silicates [18] supporting the role of soil mineralogy concerning glyphosate sorption. As high phosphorus application can desorb glyphosate from sorption sites, application of char can be effective in these scenarios concerning sorption of glyphosate. The rapid degradation of glyphosate in surface waters and its practically irreversible sorption indicated a low potential environmental risk [19].

An investigation on adsorption of the herbicide glyphosate and its main metabolite AMPA found that $pH_{(CaCl_2)}$ values, available phosphate, and amorphous iron and aluminum contents were the major parameters to predict the adsorption constants for these molecules [20]. In a similar study, while examining the effect of humic acid (HA) on the adsorption/desorption behaviour of glyphosate on goethite minerals, the herbicide was desorbed by two parallel processes: (i) a direct detachment from the surface, which is first order in adsorbed glyphosate, and (ii) a ligand exchange with HA molecules, which is first order in adsorbed glyphosate and first order in dissolved humic acid [21]. Glyphosate is adsorbed by humic acids via hydrogen bonding [22].

A laboratory study related to the fate of glyphosate and degradation in cover crop residues and underlying soil indicated that the differences in sorption and degradation levels were due to differences in the composition of the crop residues and availability to microorganisms [23]. In a related study of adsorption and mobility of glyphosate in different soils under no-till and conventional tillage, adsorption of glyphosate was influenced by the soil clay content and cation exchange capacity (CEC) and negatively related to pH and phosphorus. High Freundlich parameter (K_F) values obtained in isotherm studies were the dominant factor influencing glyphosate mobility. K_F values indicate the adsorption capacity of the soil [24].

1.6 Methods to understand glyphosate mobility

Sorption coefficients provide accurate information needed for reliable risk assessments of groundwater contaminants by pesticides [25]. In a study related to sorption

and leaching of ^{14}C -glyphosate in agricultural soils, non-extractable glyphosate residues become available eventually and take part in biodegradation and leaching. Empirical constants (K_F) of Freundlich sorption isotherm were 16.6 for the clay loam, 33.6 for the silty clay loam, and 34.5 for the sandy clay loam indicating that it is the soil structure which dictates the glyphosate sorption behaviour [26]. Leaching of glyphosate was dependent on hydrodynamic and biodegradation properties of soils [26]. Application of char can be used as a strategy to increase the sorption of glyphosate [27].

Movement of pesticides and their bioavailability and biotransformation are controlled by adsorption/desorption mechanisms operating at the interface between organic and inorganic soil colloids. High-resolution magic angle spinning and nuclear magnetic resonance techniques can distinguish mobile and immobile phases of pesticides like glyphosate [28]. Another study on glyphosate transport parameters suggested that glyphosate sorption is a kinetic process that depends on pore-water velocities and residence time of soil solution [29].

1.7 Why is glyphosate application on field sites a concern?

The International Agency for Research on Cancer (IARC) has reclassified that glyphosate is “probably carcinogenic to humans” [30]; however, the United States Environment Protection Agency (US EPA) concluded that there is no convincing evidence that “glyphosate induces mutations” [31]. The US EPA relied mostly on unpublished regulatory studies, 99% of which were negative, while IARC relied mostly on peer-reviewed studies, 70% of which were positive [31]. Glyphosate-based herbicides often contaminate drinking water sources, air, and precipitation in agricultural regions [30]. As the usage of glyphosate-based herbicides continues to increase, investment in epidemiological studies, biomonitoring, and toxicology studies based on the principles of endocrinology should be done [30]. Apart from cancer, glyphosate has been found to be a potential factor causing chronic kidney disease due to drinking water faced by Sri Lankan farmers [32]. The role of drinking water has also been reported in another study which caused ill health in Indian farmers [33].

1.8 Biochar’s potential role as a sorbent for organic pollutants like glyphosate

Biochar can be defined as “the porous carbonaceous solid produced by the thermochemical conversion of organic materials in an oxygen-depleted atmosphere that has physicochemical properties suitable for safe and long-term storage of carbon in the environment” [34]. Biochar and activated charcoal are similar concerning production via pyrolysis, with medium to high surface areas [35]; however, biochar is not activated or treated like activated charcoal [35, 36]. Crop residues are pyrolyzed at high temperature ($>500^\circ\text{C}$) in the absence of oxygen, followed by various activation processes to form activated charcoal [35]. In comparison to activated charcoal, biochar has a non-carbonized fraction that interacts with soil contaminants like glyphosate. Soil minerals can increase the surface area and pore size of biochar, which in turn increase the adsorption capacity of biochars for organic pollutants like glyphosate [37]. Biochar application can reduce the bioavailability and leachability of organic pollutants in soils through adsorption and other physicochemical reactions [38]. An increase in the surface area of biochars has been observed to increase the biochar’s ability to adsorb organic contaminants [39, 40]. The addition of phosphorus fertilizer to biochar-amended soils can, however, remobilize glyphosate and damage non-target plants; therefore, improved understanding of this risk is important (Figure 2) [41].

The soil environment is a three-dimensional structure of water-filled pores, gas-filled pores, and soil particulates (organic matter, sand, silt, and clay) [42]. Biochar can be used as a sorbent for organic pollutants due to its highly aromatic

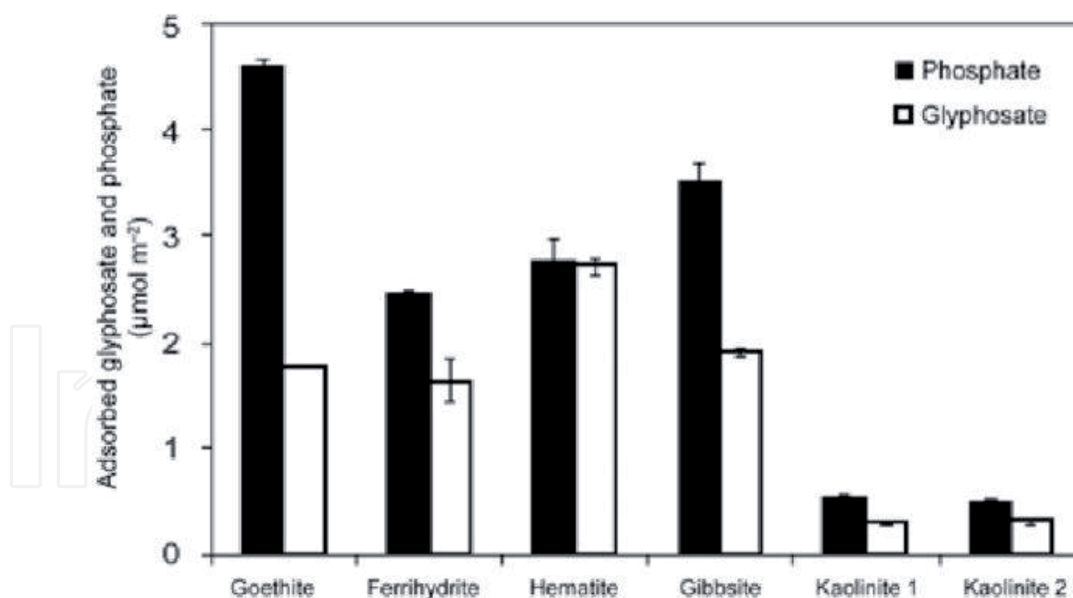


Figure 2.
 Phosphate and glyphosate adsorption by minerals [5].

nature, high surface area, micropore volume, and abundance of polar functional groups [43]. Factors affecting biochar's performance for adsorption include pyrolysis temperature and surface area. Pyrolysis temperature is one of the factors directly affecting biochar's performance. An increase in pyrolysis temperature of biochar generally increases the degree of carbonization and consequently surface area.

Even with the increase in surface area of biochars, sorption sites can be blocked by organic matter, and this is the likely cause for the diminished capability of aged biochars to adsorb organic contaminants [44]. The behaviour of biochar changes with time after its application to soil, and this process is known as "aging". Aging can alter the behaviour of biochar. To increase the remediation efficiency of biochar concerning herbicides, more detailed research to explore the aspect of aging is warranted.

1.9 Behaviour of herbicides in a soil-biochar system

In a study related to herbicide terbutylazine-biochar-soil interaction, there was higher adsorption of herbicide in soil with low organic matter than in soil with the high organic matter. The reason for this result was attributed to a high concentration of organic molecules competing with herbicide for sorption sites in the soil having a high amount of organic matter [40]. Availability of herbicides can be greatly reduced with the application of biochar [45]. Even a low application rate (0.1%) of biochar in the soil can appreciably reduce the availability of herbicides like diuron [44].

In a comparative study [46], 42 times higher hexachlorobenzene sorption by biochar than that by control soil was observed, resulting in the reduction of volatilization and earthworm (*Eisenia foetida*) uptake of hexachlorobenzene from the soil. The extent of sorption of pesticides generally depends on the aromaticity of soil organic carbon. Properties that make biochars effective against herbicides are a high specific surface area, high microporosity, and high aromatic carbon.

1.10 The behaviour of glyphosate in a soil-biochar system

Plant uptake of pesticides decreases markedly with increasing biochar content of the soil despite the greater persistence of the pesticide residues in biochar-amended soils [47]. In a similar study related to the effects of biochar, wood vinegar, and plants on glyphosate leaching and degradation, the addition of biochar to the soil

decreased the leaching of glyphosate irrespective of plants. Hence, it was concluded that biochar can be used as an effective strategy to reduce the potential environmental risk to aquatic environments caused by glyphosate [27].

In a study related to the effects of wood-based biochar on the leaching of pesticides chlorpyrifos, diuron, and glyphosate, it was concluded that biochar can be used as an adsorptive layer directly on or close to the soil surface to prevent losses of pesticides [48]. In another study, biochar was found to limit glyphosate transport in soil systems; however, the addition of phosphatic fertilizer remobilized the glyphosate from biochar-amended soils. This phosphate-induced glyphosate desorption phenomenon is important to consider in soils having biochar amendment [41]. The type of biochar also plays an important role, as hardwood biochars were ineffective sorbents of glyphosate in high-phosphate soils [41]. Biochars produced at high temperature were effective sorbents of glyphosate [41]. Reduced glyphosate sorption on biochars was observed with the increase in pH from 6 to 9 [41, 49, 50].

2. Glyphosate-resistant weeds

The second major aspect in this review paper is the evolution of glyphosate resistance in weeds due to heavy reliance on glyphosate. Glyphosate toxicity and glyphosate resistance are not different but connected problems, as glyphosate is applied to control weeds and its application results in movement of glyphosate to water bodies via soil systems affecting human health. When glyphosate-contaminated drinking water is used for human consumption, it may potentially result in diseases like cancer or chronic kidney disease; however, frequent application of glyphosate not only results in its downward movement via soil systems but also results in the development of glyphosate resistance in weeds. Hence these problems are interconnected.

While assessing the weeds at risk of evolving glyphosate resistance in Australian subtropical glyphosate-resistant cotton systems, species with the highest risk to glyphosate resistance were *Brachiaria eruciformis*, *Conyza bonariensis*, *Urochloa panicoides*, *Chloris virgata*, *Sonchus oleraceus*, and *Echinochloa colona* [51]. Thirty-eight weeds in total distributed over 37 countries have shown resistance to glyphosate [52]. These weeds represent the greatest threat to sustainable weed control practices [52]. Weed surveys in the cotton-growing areas of New South Wales (NSW) and Queensland, Australia, indicated the dominance of *Conyza bonariensis*, *Echinochloa colona*, and *Chloris virgata* [53].

Chloris virgata is a high-risk species to glyphosate resistance in summer fallow [51]. Glyphosate resistance in *Chloris virgata* populations in Australia has emerged due to transformation in Australian cropping systems, particularly unirrigated cotton systems, from regular tillage and use of residual herbicides to minimum or no-tillage systems with a heavy reliance on glyphosate [54]. This lack of tillage is the major reason for the emergence of weeds like *Chloris virgata* that are small-seeded and emerge at or close to the surface [54]. A weed management system depending on only one tactic, for example, application of glyphosate, is the main driver for this species shift. With repeated use of glyphosate, *Chloris virgata* populations have become less susceptible to glyphosate formulations, especially after the early tillering stage [54].

Mechanisms involved in providing resistance to glyphosate in weeds include (i) target-site alterations (target site mutation, target site gene amplification) [55, 56] and (ii) non-target site mechanisms involving reduced glyphosate uptake and/or reduced translocation of glyphosate [57–59]. The alterations inhibit glyphosate binding or increase the effective dose needed for enzyme inhibition. Target site EPSPS mutations are the primary mechanism conferring glyphosate resistance in populations of *Chloris virgata* [55].

2.1 *Chloris virgata* (feathertop Rhodes grass)

Chloris virgata as a glyphosate-resistant weed [51] has also been identified as a host for barley yellow dwarf and cereal yellow dwarf viruses [60]. As *Chloris virgata* can tolerate high-salinity and high-alkalinity soil environments, *Chloris virgata* can form a dominant community in these environments [61, 62]. *Chloris virgata* is tolerant to drought stress [63]. Many studies on *Chloris virgata* seed biology have been completed in China, India, Qatar, and Honduras [63], while very few studies have been conducted in Australia [64, 65].

Chloris virgata grass seed biology includes the study on dormancy, germination conditions, seed bank dynamics, growth, and development [66]. Dormancy mechanisms enable the seed to sense the optimum environmental conditions for the establishment of seedlings and hence play a pivotal role in control strategies for weedy grasses [67]. There are two types of seed dormancy mechanisms, those based in the tissues surrounding the embryo (seed coat based) or those found within the embryo [67]. The role of smoke in breaking the dormancy of plump windmill grass (*Chloris ventricosa*), a related species to *Chloris virgata* grass [68], has been reported; but no study related to dormancy breakdown of *Chloris virgata* grass by smoke has been reported. The seeds of *Chloris virgata* are triangular in shape and light in weight and hence shed easily from the heads making them good wind (anemochory) and water (hydrochory) dispersers [64].

Seed germination is a key event in the growth of annual plants like *Chloris virgata* grass which is regulated by several environmental factors such as temperature and water potential [69–71]. High rainfall has been associated with *Chloris virgata* population outbreaks [72], suggesting that water plays an important role in the germination process. *Chloris virgata* grass possesses the C_4 photosynthesis mechanism and has better water use efficiency than grasses having the C_3 photosynthesis mechanism. Among all the potential factors for *Chloris virgata* germination; light, salinity, and osmotic potential are the most critical factors [64]. A light requirement for germination has been observed among many small-seeded species and warm-season grasses [67, 73]. In a study related to germination responses of *Chloris virgata* to temperature and reduced water potential, maximum germination percentages of *Chloris virgata* seeds were found at 15–25°C [74]. Germination of *Chloris virgata* seeds is affected by several factors; however, temperature and light play a significant role in the germination of *Chloris virgata* seeds. More studies on factors affecting *Chloris virgata* growth are needed due to the paucity of information.

In a study related to growth, development, and seed biology of *Chloris virgata* in South Australia, *Chloris virgata* seedlings emerging after summer rainfall events under field conditions needed 1200 growing degree days from emergence to mature seed production [65]. Harvested seeds of *Chloris virgata* were dormant for a period of about 2 months and took 5 months of after-ripening to reach 50% germination [75]. Seedling emergence of *Chloris virgata* was highest (76%) for seeds present on the soil surface and seedling emergence was significantly reduced by burial at 1 (57%), 2 (49%), and 5 cm (9%) soil depth. Furthermore, *Chloris virgata* seeds buried in the soil persisted longer than those left on the soil surface [75].

The thermal time to panicle emergence of *Chloris virgata* is similar to shattercane (*Sorghum bicolor*) [76]. A related species of *Chloris virgata*, windmill grass (*Chloris truncata*) under irrigated field requires 21–23, 43–45, and 74–75 days from seedling emergence to reach tillering, panicle emergence, and mature seed stage [75]. Maximum plant density and biomass in case of windmill grass have been found to be 4.2–28.2 plants m^{-2} and 8.3–146.1 g dry biomass m^{-2} depending on location [77].

Water stress due to extremely low rainfall over the summer months was the reason for the delayed growth of *Chloris virgata* under rainfed conditions when

compared to irrigated conditions [75]. Under irrigated conditions, 619 to 730 g of dry biomass m^{-2} of *Chloris virgata* (89 days after sowing) was observed; however, this value was much higher than one of its related species, windmill grass (*Chloris truncata*) (146 g m^{-2}) [75].

Chloris virgata has several characteristics like rapid germination and low base temperature (2.1 to 3.0°C) for seed germination enabling it to survive rainfall events in spring, summer, and autumn in South Australia [75].

2.2 Evolution of glyphosate resistance in *Chloris virgata*

On national ranking basis in Australia, *Chloris virgata*, as an herbicide-resistant weed, ranks ninth, resulting in herbicide-resistant weed cost of \$2.6 million [78]. In the northern region of Australia, it is the top fourth herbicide-resistant weed after ryegrass (*Lolium rigidum*), wild turnip (*Brassica rapa*), and barnyard grass (*Echinochloa crus-galli*) [78].

Minimum tillage due to its benefits like reduced soil erosion and improvement in moisture conservation has resulted in the reduction of soil disturbance in grain cropping fields. The factors that aided the adoption of minimum tillage systems in Australian cropping systems include machinery modifications that allow greater flexibility in the cropping systems, precision agriculture and refinement of controlled traffic farming, improved crop resistance or tolerance to plant diseases associated with stubble retention, availability of more crop options and rotations, development of a broader spectrum of effective herbicides, and the use of genetic modification technologies to breed herbicide-resistant crops [79].

Minimum tillage has increased the use of herbicides and consequently increased the rapid appearance of herbicide resistance in weeds [75]. Another reason for evolution is the introduction of glyphosate-resistant crops in the mid-1990s that has resulted in a sharp increase in the populations of *Chloris virgata* [80].

Glyphosate resistance was first reported in broadleaf *Conyza* (horseweed) species. The mechanism suggested for resistance was an altered subcellular distribution resulting in sequestration of the glyphosate molecule away from the enzyme target site in the chloroplast [81]. Weeds receiving repeated exposure to a single mode of action of herbicide are the most likely candidates to develop resistance [82].

From the evolution point of view, minimum tillage along with reliance on glyphosate has contributed the most towards glyphosate resistance in *Chloris virgata*. The evolution of the glyphosate resistance in *Chloris virgata* highlights the need for diversity in weed management strategies for successful control of *Chloris virgata* and other *Chloris* species [82].

2.3 Crop competition as a strategy to control *Chloris virgata*

Crop competition can be used as an effective strategy against *Chloris virgata*, especially when herbicides like glyphosate fail or underperform [83]. Crop competition to control weeds has proven to be one of the most effective cultural strategies in Australian cropping systems, aiming at suppression of weed biomass and fecundity resulting in crop yield gains [84]. Three major weed variables that affect crop-weed competition are:

- Time of emergence of the weed relative to the crop and weeds that emerge later than the crop are much less competitive than the weeds that emerge before the crop.

- Weed seedling density is the second most important factor influencing weed-crop competition.
- Differences in the competitive ability of weeds due to rapid leaf area development, high-density root systems, and plant heights [85].

Crop and weed plants compete for limited resources like water, nutrients, and light. Competition for nutrient uptake is dependent on intrinsic nutrient requirements and uptake efficiencies. Uptake efficiencies are further dependent on root length densities and nutrient membrane transporters. Species with a low nutrient requirement, extensive root systems, and effective membrane transporters will have a competitive advantage in a nutrient-limited system [85].

Crop and weed plants compete for water, as water is required for plant growth. In the absence of water, a reduction in photosynthesis, wilting, and nutrient deficiencies can occur. The length, magnitude, and timing of the drought periods as well as soil attributes (water holding capacity, texture, structure, and hydraulic conductivity), plant traits (root structure and density, drought tolerance, and water use efficiency) are the major factors that influence the competition for water availability between crop and weed plants [85].

Light as a third major factor affects the growth of crop and weed plants [86]. Different phenophases of both crop and weed plants are affected by light. Morphological changes in both crop and weed plants due to competition for light include an increase in stem elongation and reduction in stem diameter, the rate of leaf appearance, and root and shoot biomass [87, 88].

Crop competition studies under field conditions are mainly influenced by the environment, soil type, plant density, spatial arrangement, the proportion of each species, and design of experiment [89]. The design of the crop competition experiment depends on the objective, as different objectives require different techniques [90].

Crop species may outcompete weed species depending on factors such as crop density, crop planting pattern, crop vigor, and weed vigor. Crop density or the number of plants per unit of area is important for competition studies considering the relationship among plant yield and the number of individuals and resources present in the area [91]. The competitiveness of a crop can be enhanced using competitive cultivars, higher plant densities, narrow row spacings, and different row orientation [92].

Weed growth can be substantially reduced by shading weeds in the inter-row space by physical orientation of the crop rows [92]. Competitive ability of the crops can also be increased by increasing plant density [84]. The significant interaction between sorghum cultivars and planting densities in suppressing weed biomass has been observed [93]. A high-density crop can limit water and nutrients available to weeds more effectively than a low-density crop, and high-density crops can result in the reduction of light available to weeds [92].

3. Summary

In summary, the review paper covered two major problems associated with single reliance on glyphosate application for controlling weeds. The first one is glyphosate mobility via soil systems, a potential risk for aquatic environments, and there is no information on the fate of glyphosate on Australian soils from the last 22 years apart from a single study in Western Australia. This research gap prompted an investigation into glyphosate sorption behaviour in Australian soils of the different mineral composition due to increased usage of glyphosate as a single strategy to

control weeds. The second major problem is the evolution of glyphosate-resistant weeds like *Chloris virgata* in New South Wales and Queensland, Australia, a major threat to sustainable weed control strategies, and due to paucity of information on the management of *Chloris virgata*, we hypothesized that cultural methods like crop competition can be used as a strategy to control glyphosate-resistant *Chloris virgata*.

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