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Sustainable Control of *Galinsoga parviflora* with Oxyfluorfen, Flumioxazin, and Linuron Application in Two Soils Cultivated with Garlic

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Abstract: Herbicides applied in PRE-emergence enables sustainable weed control. The objective of this study was to evaluate the control of gallant soldier *(Galinsoga parviflora)* with the residual herbicides oxyfluorfen, flumioxazin, and linuron in soils cultivated with garlic from two regions of Brazil: Rio Paranaíba-MG (Oxisol) and Curitibanos-SC (Ultisol). The efficiency of the herbicides was evaluated at the following doses: oxyfluorfen (0, 3, 6, 12, 24, 48, 96, 192, 384, and 768 g a.i. ha^{-1}), flumioxazin (0, 2, 4, 6, 8, 15, 30, 40, 60, and 120 g a.i. ha^{-1}), and linuron (0, 30, 40, 50, 100, 200, 400, 800, 1600, and 2430 g a.i. ha^{-1}). The degree of damage on the 7th, 14th, and 21st day after emergence (DAE) and dry matter on the 21st day after emergence (DAE) were determined to evaluate the control (C_{80}) and the growth reduction (GR_{80}) of 80% of the plant, respectively, compared to the treatment without herbicide. Three herbicides were effective at the control of *G. parviflora*, with the C_{80} at 21 DAE on Ultisol being 81.82, 4.59, and 141.26 g a.i. ha^{-1}, and a GR_{80} of 61, 8.3, and 151.3 g a.i. ha^{-1} for oxyfluorfen, flumioxazin, and linuron, respectively. On the other hand, on Oxisol (lower clay content and soil organic matter), the doses were lower, with the C_{80} at 21 DAE at 20.85, 3.50, and 118 g a.i. ha^{-1}, and a GR_{80} of 54, 4.03, and 101.23 g a.i. ha^{-1}, respectively. This weed showed higher control under flumioxazin compared to the other herbicides in both soils. The use of low doses of residual herbicides contributes to sustainable weed control in garlic growing in the field.

Keywords: dose-response curve; weed; low doses; clay; soil organic matter

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1. Introduction

Gallant soldier (*Galinsoga parviflora*) is an annual weed of the Asteraceae family, which usually grows ≤60 cm tall [1]. This weed is considered cosmopolitan and is common in over 32 crops in 38 countries [2]. In a survey of increasing weed problems in Europe, it was reported that this species has become increasingly common, especially in Eastern Europe, and has heavily infested cereals, legumes, tubers, vegetables, ornamentals, and orchards [2].

The species has a very short reproductive cycle of less than 50 days, and produces an average of 65 million non-dormant seeds per hectare with a high potential for seed bank formation in the soil [3]. In Brazil, the major problems with this weed occur mainly in vegetable fields, such as garlic (*Allium sativum* L.) [1].

When studying the relationship between *G. parviflora* and garlic crop, Coutinho et al. [4] found that this species competes with garlic for potassium. This nutrient is essential for an increase in bulb production, and its scarcity in the soil reduces productivity [5]. Furthermore, according to Marcuzzo and Santos [6], *G. parviflora* is a host of the bacterium *Pseudomonas marginalis* pv. marginalis, which causes bacterial late blight of garlic. As such, there is a need for the sustainable management of this species.

The importance of garlic in the economy is mainly due to its culinary and medicinal properties [7]. Currently, the subspecies *Allium sativum* var. *sativum* is the most cultivated and consumed garlic [8]. In the world, 30.7 million tons of garlic are produced per year, and China is the largest producer (23.25 million tons), followed by India (2.91 million tons) [9]. In Brazil, there was an increase in production in the years 2020-2021 from 132 thousand tons of garlic to 168.1 thousand tons, and this increase in productivity was related to pest management, with an emphasis on weed control [10]. Garlic is vulnerable to weed interference with reductions of up to 80% in productivity [11]. Among weed control strategies in garlic cultivation, chemical control is the most used due to its effectiveness and lower cost [12]. The application of herbicides in the PRE-emergence of *G. parviflora* enables the control of the species before it causes economic damage to the crop. In addition, the residual effect of herbicides in the soil allows control of the weed over a longer period, reducing the need for multiple applications and reducing costs and environmental impact [13].

Some PRE herbicides are recommended for the control of *G. parviflora* in Brazilian garlic crops, such as linuron and flumiozaxin [14]. Although oxyfluorfen is not approved for use in garlic crops, it is recommended for the control of *G. parviflora* control, and due to the few weed management strategies in garlic crop, it showed good results in PRE control with reduced doses [15,16].

Linuron is a broad-spectrum systemic herbicide that acts in the PRE and POST-emergence of weeds by inhibiting photosystem II (PSII), in the photochemical step of photosynthesis [17]. Regarding oxyfluorfen and flumiozaxin, both herbicides act by contact and control monocotyledonous and dicotyledonous weeds, with the mechanism of action being inhibition of the enzyme protoporphyrinogen oxidase (PPO) [18,19]. All these molecules are very important for the control of *G. parviflora* at the early stages of development.

By relating the herbicides behavior to the type of soil and weed species present in the field, it is possible to select the best control molecules and reduce product doses. Some authors have shown that satisfactory weed control can be achieved even if herbicides are used at a lower dosage than recommended on the label [20–22]. This can help to reduce production costs and environmental impacts, and increase agronomic efficiency. The use of residual herbicides is a sustainable alternative, because it is performed at early stages of weed development (soon after germination), and the control is maintained for a longer time, reducing the need for sequential applications of herbicides, as well as preventing weeds from producing seeds that infest agricultural areas [18]. However, studies with such herbicides are still scarce, being of great importance for researchers and famers.

Therefore, the objective of this study was to evaluate the control of *G. parviflora* by the application of the residual herbicides oxyfluorfen, flumioxazin, and linuron in soils cultivated with garlic from two regions of Brazil. Investigating the agronomic efficiency of herbicides at lower doses than recommended in the package is important both from an economic point of view for producers and from an ecological point of view.

2. Materials and Methods

Soil samples were collected at a depth of 0–10 cm in the region of Rio Paranaíba-MG (1.073 m altitude, latitude: 19°11′39″ S, longitude: 46°14′37″ W), classified as Oxisol (clay), and Curitibanos-SC (987 m altitude, latitude: 27°16′58″ S, longitude: 50°35′04″ W), classified as Ultisol (clay). These soils of the Rio Paranaíba and Curitibanos regions are of great importance in Brazil and the most cultivated with garlic each year. The physicochemical attributes of the two soils are listed in Table 1.

Source: Laboratory of Soil Analysis of the Federal University of Viçosa, Viçosa, MG, Brazil.

Soil pH was measured in water at a 1:2.5 ratio. The extraction of Ca^{2+}, Mg^{2+}, and Al^{3+} was by KCl (mol/L). H + Al was determined by calcium acetate (0.5 mol/L) at pH 7.0. OM content was determined by the Walkey–Black method. CEC at pH 7.0 was determined by the sum of the basic cations (Ca^{2+}, Mg^{2+}, K^+, and H^+ and Al^{3+}). K was determined by Mehlich-1 extractor. The mineralogical analysis of the clay and silt fractions was determined by X-ray diffractometry and by thermoanalytical techniques.

Table 1. Physicochemical attributes of the soils of Curitibanos [Ultisol (clay)] and Rio Paranaíba [Oxisol (clay)] from the regions of Santa Catarina and Minas Gerais, Brazil, respectively.

Soil Classification [1] (Textural Class)	OM	pH	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	CEC	Sand	Silt	Clay
	%	(H_2O)	mg dm^{-3}	cmol$_c$ dm^{-3}						%	
Ultisol (clay)	4.61	6.20	9.3	203	6.70	2.98	0.00	14.10	3.4	17.3	79.3
Oxisol (clay)	3.76	6.71	217.6	68.0	5.16	2.46	0.00	8.49	9.0	38.5	52.5

OM = organic matter, P = phosphorous, K^+ = potassium, Ca^{2+} = calcium, Mg^{2+} = magnesium, Al^{3+} = aluminum, H + Al = potential acidity, CEC = cation exchange capacity. [1] Soils classified by the Brazilian Soil Classification System and Soil Taxonomy [23]. Source: Department of Soil, Federal University of Viçosa, Viçosa, MG, Brazil.

The studies were performed in the greenhouse of the Agronomy Department (DAA) of the Federal University of Viçosa (UFV), in Viçosa-MG, Brazil. The experimental design was completely randomized, in a factorial 2 × 9 + 2 scheme, for each herbicide, corresponding to two soil types, nine herbicide doses, and two non-herbicide treatments (one for each soil), with four replicates.

Each experimental unit consisted of pots with a capacity of 0.3 dm^3, filled with soil and weighed on a balance to standardize the volume of soil in each pot. Subsequently, linuron, flumioxazin, and oxyfluorfen were applied to the surface of the soils at the following doses: linuron (Afalon 450SC®, Adama, Ashdod, Israel, 450 g L^{-1}) (0, 30, 40, 50, 100, 200, 400, 800, 1600, and 2430 g a.i. ha^{-1}) (0, 0.0045, 0.006, 0.0075, 0.015, 0.03, 0.06, 0.12, 0.24, and 0.3645 mg Kg^{-1} of soil), flumioxazin (Flumioxazin 500SC®, Sumitomo Chemicals, Mumbai, India, 500 g L^{-1}) (0, 2, 4, 6, 8, 15, 30, 40, 60, and 120 g a.i. ha^{-1}) (0, 0.0003, 0.0006, 0.0009, 0.0012, 0.00025, 0.0045, 0.006, 0.009, and 0.018 mg kg^{-1} of soil), and oxyfluorfen (Goal BR®, Dow Shangyu Nutrichem®, Shaoxing, China, 240 g L^{-1}) (0, 3, 6, 12, 24, 48, 96, 192, 384, and 768 g a.i. ha^{-1}) (0, 0.00045, 0.0009, 0.0018, 0.0036, 0.0072, 0.0144, 0.0288, 0.0576, and 0.1152 mg kg^{-1} of soil). The herbicide was applied immediately after sowing 80 seeds of the gallant soldier (*Galinsoga parviflora*) weed species in each treatment. A pressurized CO_2 sprayer with two TT110.02 tips was used for the application, maintained at a distance of 0.5 m and at a pressure of 0.2 MPa. The application was made at a height of 0.5 m above the pots; syrup volume was 160 L ha^{-1}. The pots were irrigated daily.

Emerging plants were counted, and the control was assessed by calculating the percentage of weed emergence in the treated soils compared to soils not treated with the herbicides.

On the 7th, 14th, and 21st days after weed emergence (DAE), the injury level in the plants was assessed, by visual assessment, assigning grades from 0 (no injury) to 100% (death of the plant). After 21 DAE, the weed area was collected and placed in paper bags, which were then placed in a forced-circulation air oven at 70 °C for 48 h. Afterwards, the dry matter of the weed was determined using an analytical precision balance (0.0001 g).

To calculate the herbicide dose that provides 80% control (C_{80}) and 80% dry matter grown reduction (GR_{80}), the equation proposed by [24] was used. Thus, by means of Equation 1, it was possible to determine the C_{80} and GR_{80}, substituting y by the value 80:

$$x = b * \sqrt[c]{\frac{a}{y} - 1} \quad (1)$$

In the equation, y is the percentage of dry matter or injury level; x is the dose of herbicide; a is the lower limit of the curve; b is the difference between the maximum and minimum points of the curve; c is the intermediate point between the lower (a) and upper (b) limits; and d is the slope of the curve. Using the values of C_{80} and GR_{80} obtained in the control efficiency studies, it was possible to determine the dose required to control *G. parviflora* in the two soils cultivated with garlic.

In the studies on the dose-response curve of the herbicides, the statistical analysis of the data was performed using the F-test of the analysis of variance (ANOVA), where the data on aerial dry matter were run in the statistical environmental R Core Team (version

4.1. R Foundation for Statistical Computing, Vienna, Austria) [25], in order to verify the significance of the factor interaction. When there are significant ($p \leq 0.05$) interactions, non-linear regressions of the log-logistic type will be plotted using SigmaPlot® software (version 13.0 for Windows, Systat Software Inc., Point Richmond, CA, USA).

The C_{80} values at 21 DAE and the GR_{80} of linuron, oxyfluorfen, and flumioxazin on Ultisol and Oxisol were compared by ANOVA by F-test, and when significant, the means were compared by Tukey test ($p < 0.05$). The R software (version 4.1.0) was used for statistical analysis and the figures were plotted in SigmaPlot ® software.

3. Results

3.1. Oxyfluorfen

Higher doses of oxyfluorfen resulted in more damage to *G. parviflora* and reduction in aerial dry matter in both soils. In addition, the application of PRE herbicides to weeds at low doses resulted in control of these weeds, as can be seen in the evaluation at 21 DAE (Figure 1).

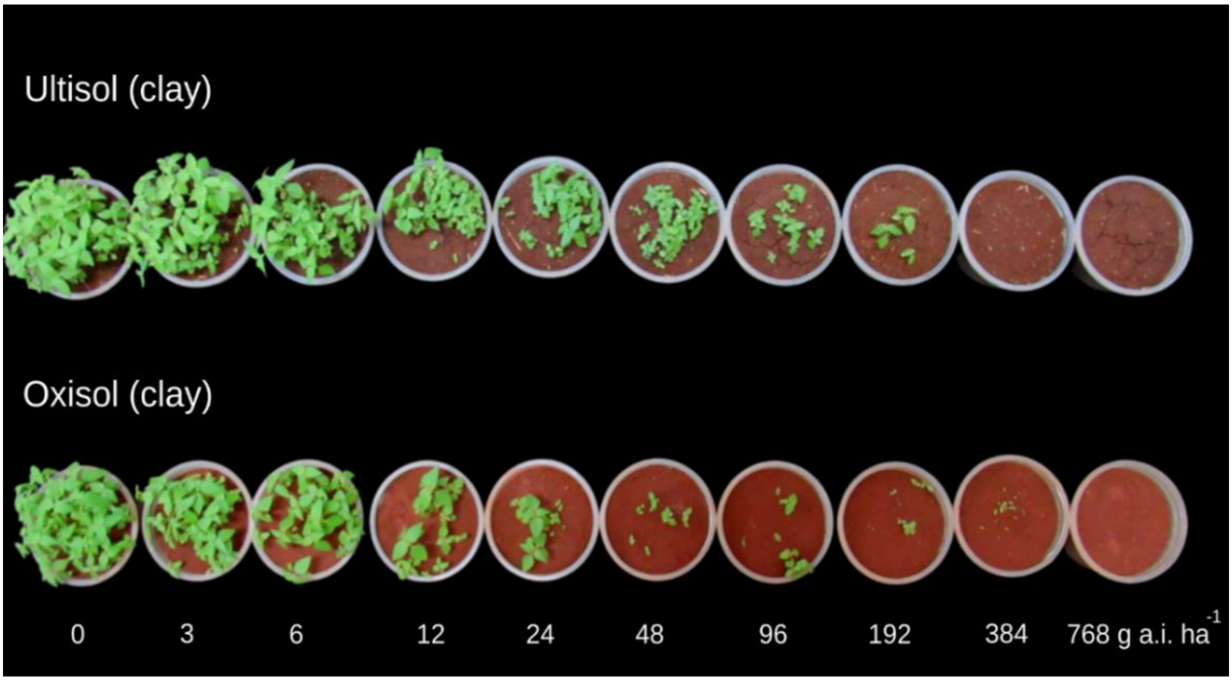


Figure 1. Control of gallant soldier (*Galinsoga parviflora*) under oxyfluorfen doses (0, 3, 6, 12, 24, 48, 96, 192, 384, and 768 g a.i. ha^{-1}) applied PRE-emergence on Ultisol (clay) and Oxisol (clay) at 21 days after emergence (DAE).

The behavior of the injury level curve of *G. parviflora* caused by oxyfluorfen was similar at 7, 14, and 21 DAE on Ultisol, with an increase in oxyfluorfen dose resulting in an increase in the injury level on *G. parviflora*. Up to the dose of 24 g a.i. ha^{-1}, no satisfactory control was observed in any epoch of evaluation, with species control less than or equal to 60%. However, when the dose was increased to 96 g a.i. ha^{-1}, the control was higher than 80% in all time evaluations. In Oxisol, the herbicide behavior was similar at 7, 14, and 21 DAE, where only 12 g a.i. ha^{-1} caused 60% injury to *G. parviflora* and 24 g a.i. ha^{-1} caused >80% injury to this weed (Figure 2).

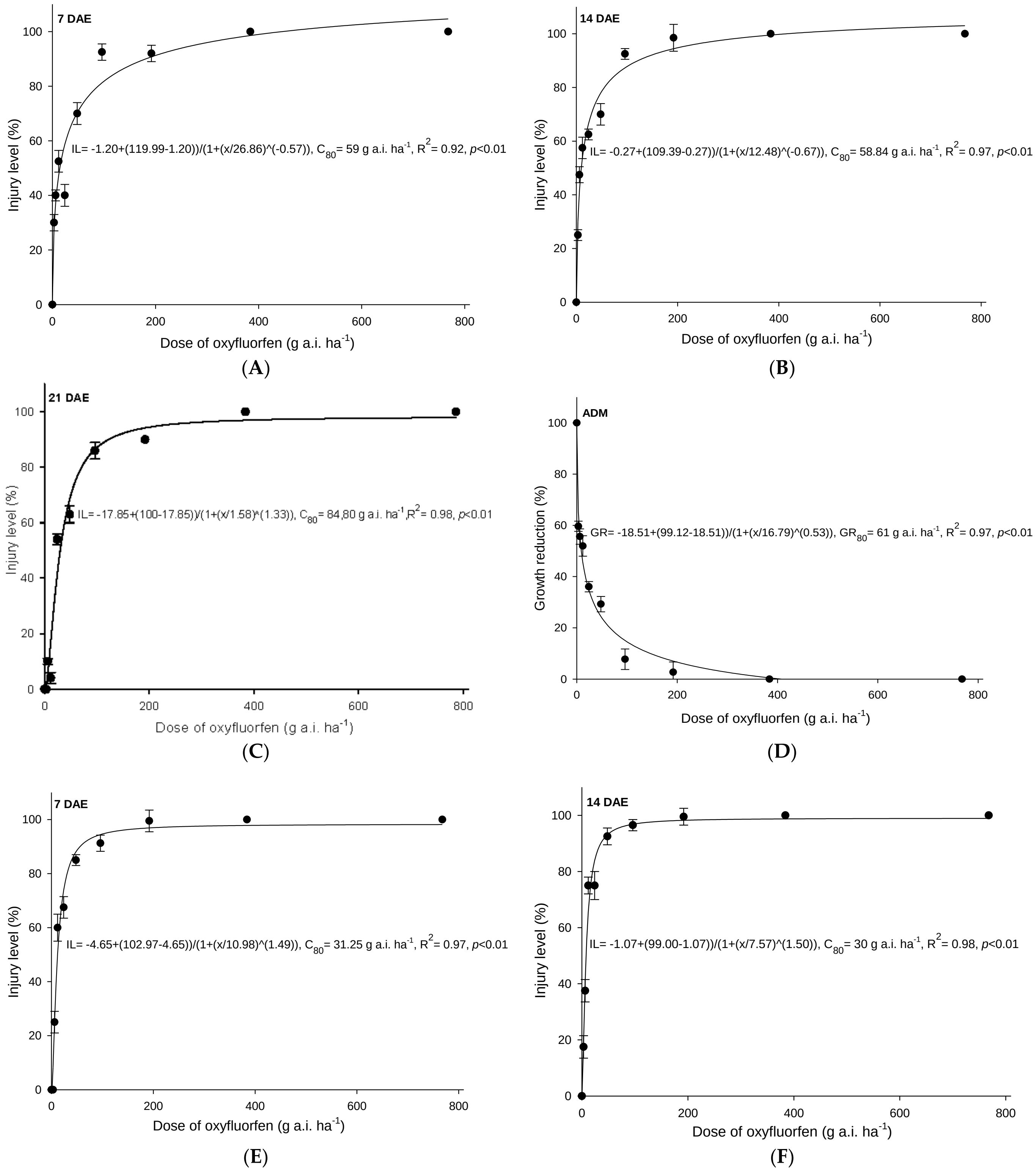
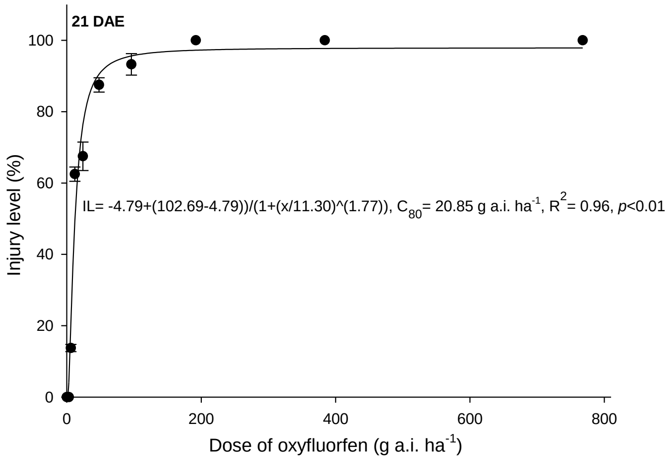
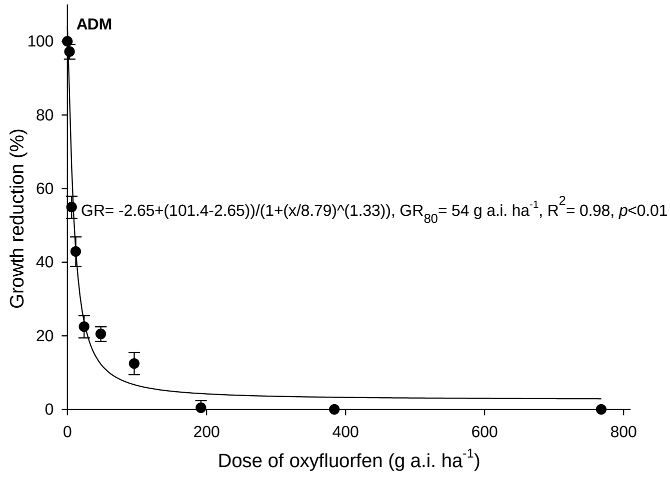


Figure 2. *Cont.*



(**G**)



(**H**)

Figure 2. Injury level of gallant soldier (*Galinsoga parviflora*) at 7, 14, and 21 days after emergence (DAE) and grown reduction in aerial dry matter (ADM) in Ultisol (clay), (**A**–**D**) and Oxisol (clay) (**E**–**H**) under the oxyfluorfen doses (0, 3, 6, 12, 24, 48, 96, 192, 384, and 768 g a.i. ha^{-1}). The vertical bars of each symbol correspond to the standard error of the mean (n = 4).

G. parviflora required 59, 58.84, and 84.82 g a.i. ha^{-1} of oxyfluorfen to reach C_{80} at 7, 14, and 21 DAE, respectively, in Ultisol, and 31.25, 30, and 20.85 g a.i. ha^{-1} in Oxisol (Figure 2). Higher doses were required to reach C_{80} in Ultisol compared to Oxisol, at all assessment points.

According to ANOVA, there was a significant difference (F = 5.943000; p = 0.000006) between the soils and the oxyfluorfen dose for reducing the aerial dry matter of *G. parviflora* (Figure 2). GR_{80} in Ultisol occurred at a dose of 61 and at 54 g a.i. ha^{-1} in Oxisol (Figure 2).

Higher doses were required at 21 DAE to cause C_{80} in Ultisol compared to 7 and 14 DAE in this soil. This factor could be related to greater sorption of the herbicide over time, decreasing bioavailability in the soil solution.

3.2. Linuron

Linuron showed satisfactory control of >80% of *G. parviflora* at a ~4-fold lower dose compared to that recommended on the label for this species (810 g a.i. ha^{-1}) in both soils. Figure 3 shows the control of weeds at 21 DAE with the application of different doses in PRE.

The behavior of the injury curve caused by linuron to *G. parviflora* was similar in both soils at 7, 14, and 21 DAE (Figure 4). The dose of 100 g a.i. ha^{-1} was able to cause injury of 60% or close to this value. When the herbicide dose was doubled (200 g i.a. ha^{-1}), control increased to above 80%, and with doses >400 g a.i. ha^{-1}, weeds were controlled to levels close to 100%. Slightly higher doses were required on Ultisol than on Oxisol at 21 DAE to achieve the same level of injury, as observed in C_{80} (Figure 4).

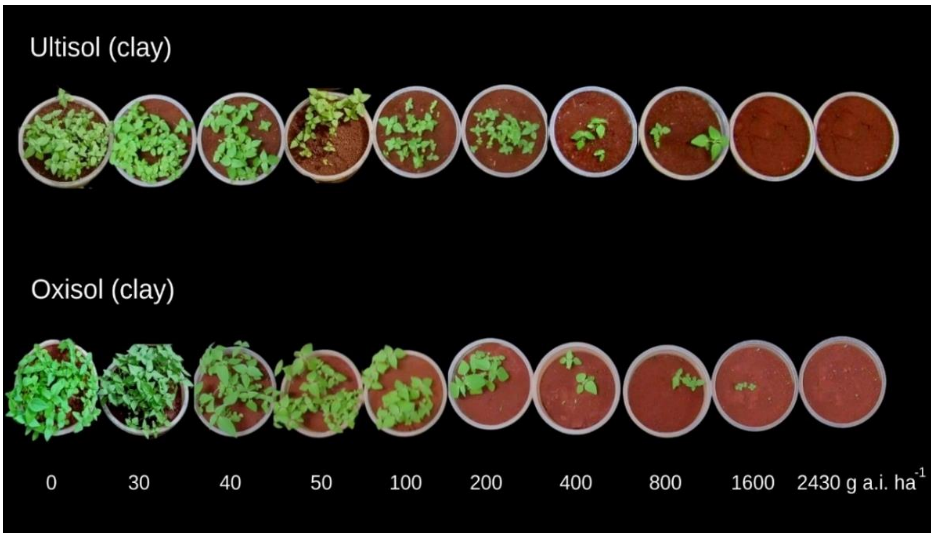
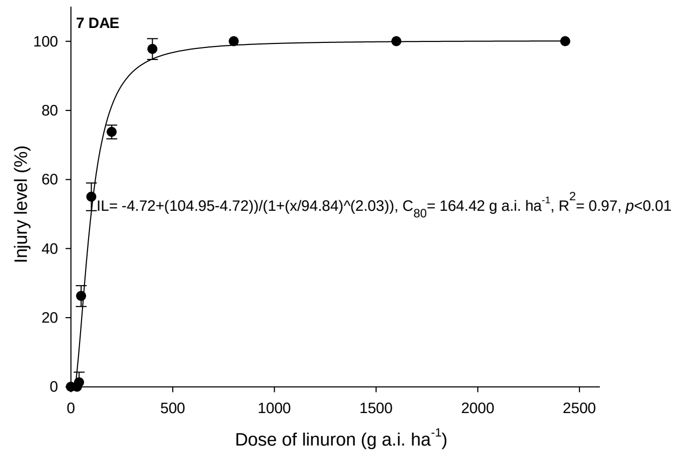
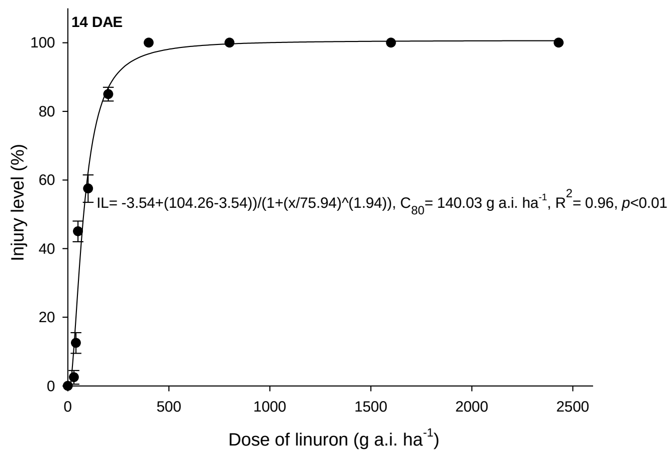


Figure 3. Control of gallant soldier (*Galinsoga parviflora*) under linuron doses (0, 30, 40, 50, 100, 200, 400, 800, 1600, and 2430 g a.i. ha^{-1}) applied PRE-emergence to Ultisol (clay) and Oxisol (clay) at 21 days after emergence (DAE).



(**A**)



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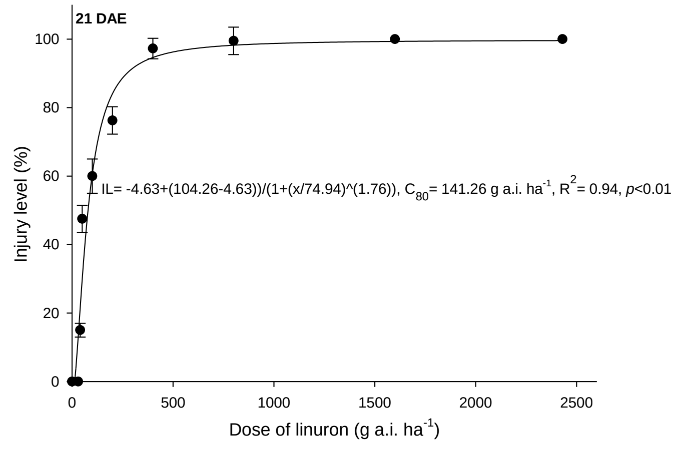

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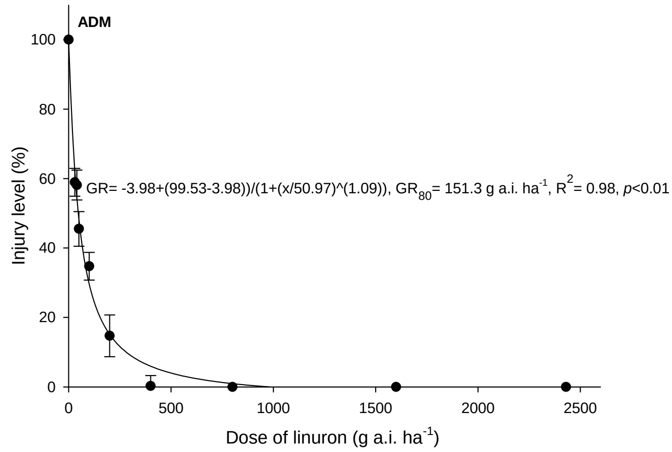


(**D**)

Figure 4. *Cont*.

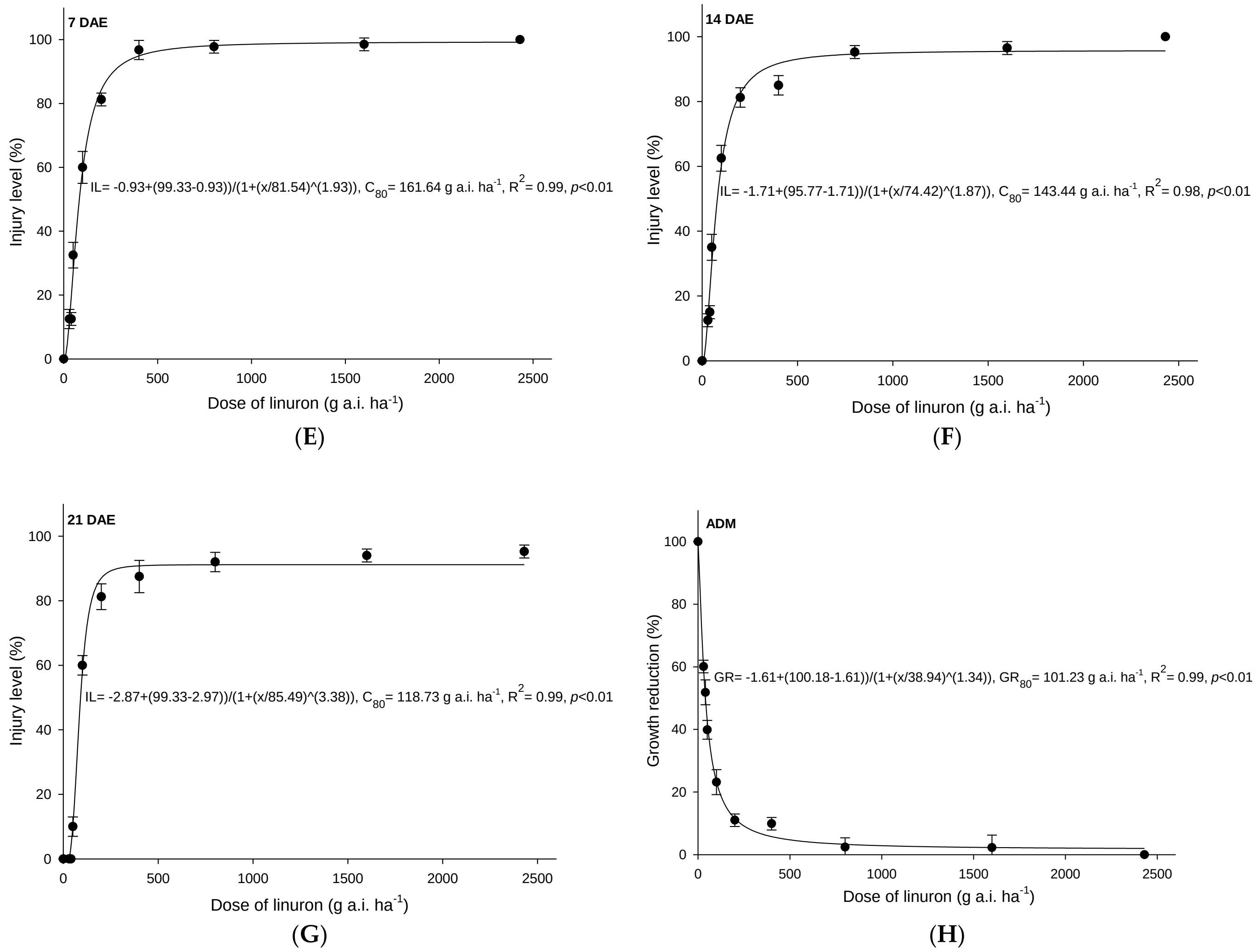


Figure 4. Injury level of gallant soldier (*Galinsoga parviflora*) at 7, 14, and 21 days after emergence (DAE) and grown reduction in aerial dry matter (ADM) in Ultisol (clay), (**A**–**D**) and Oxisol (clay) (**E**–**H**) under the linuron doses (0, 30, 40, 50, 100, 200, 400, 800, 1600, and 2430 g a.i. ha^{-1}). The vertical bars of each symbol equal the standard error of the mean (n = 4).

According to ANOVA, there was a significant interaction (F = 2.52600; p = 0.01583) between the soil and linuron dose for aerial dry matter. Ultisol showed GR_{80} of 151.3 g a.i. ha^{-1} and Oxisol GR_{80} of 101.23 g a.i. ha^{-1}.

3.3. Flumioxazin

G. parviflora was more sensitive to flumioxazin than linuron and oxyfluorfen. Control was satisfactory at a dose about ~10-times lower than the dose recommended in the package insert for control of the species (90 g a.i. ha^{-1}). Excellent weed control was observed at 21 DAE at reduced doses (Figure 5).

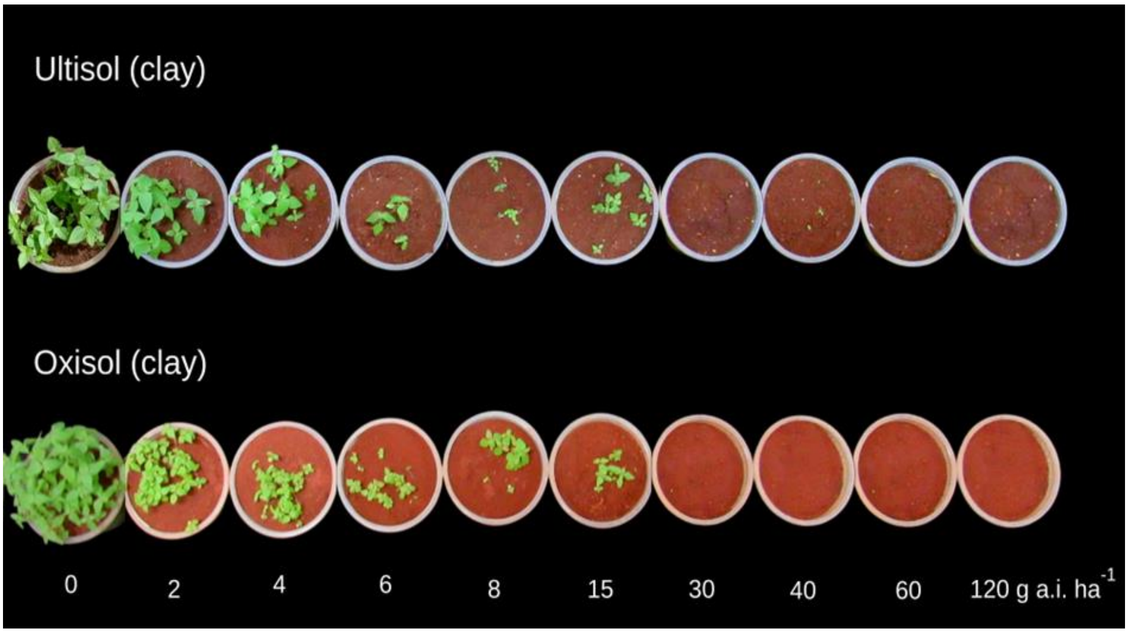
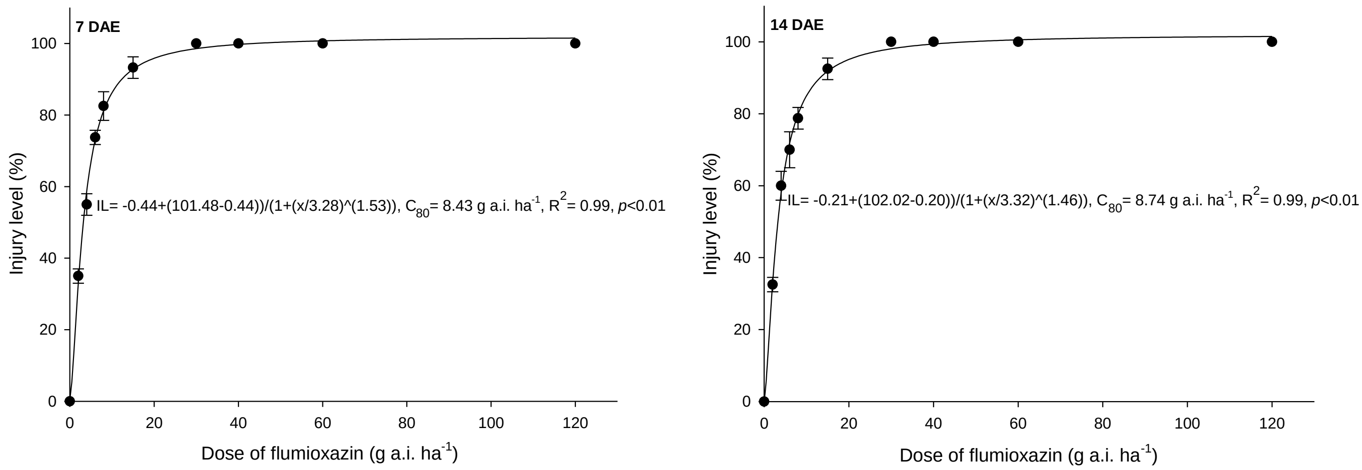


Figure 5. Control of gallant soldier (*Galinsoga parviflora*) under flumioxazin doses (0, 2, 4, 6, 8, 15, 30, 40, 60, and 120 g a.i. ha^{-1}) applied PRE-emergence on Ultisol (clay) and Oxisol (clay) at 21 days after emergence (DAE).

Excellent weed control was observed at 21 DAE at reduced doses (Figure 5). The behavior of the injury curve in *G. parviflora* by flumioxazin in Ultisol showed similar behavior at 7, 14, and 21 DAE. Up to the dose of 4 g a.i. ha^{-1} on Ultisol, a satisfactory control did not occur, at only approximately 60%. Only 8 g a.i. ha^{-1} was effective in causing more than injury above 80% on *G. parviflora*. In Oxisol, the behavior of the injury curve of *G. parviflora* by flumioxazin was differen; lower doses caused the effective control of the species. The dose of 4 g a.i. ha^{-1} caused more than 70% injury, and 8 g a.i. ha^{-1} caused almost 100% injury in this species (Figure 6).



(**A**) (**B**)

Figure 6. *Cont.*

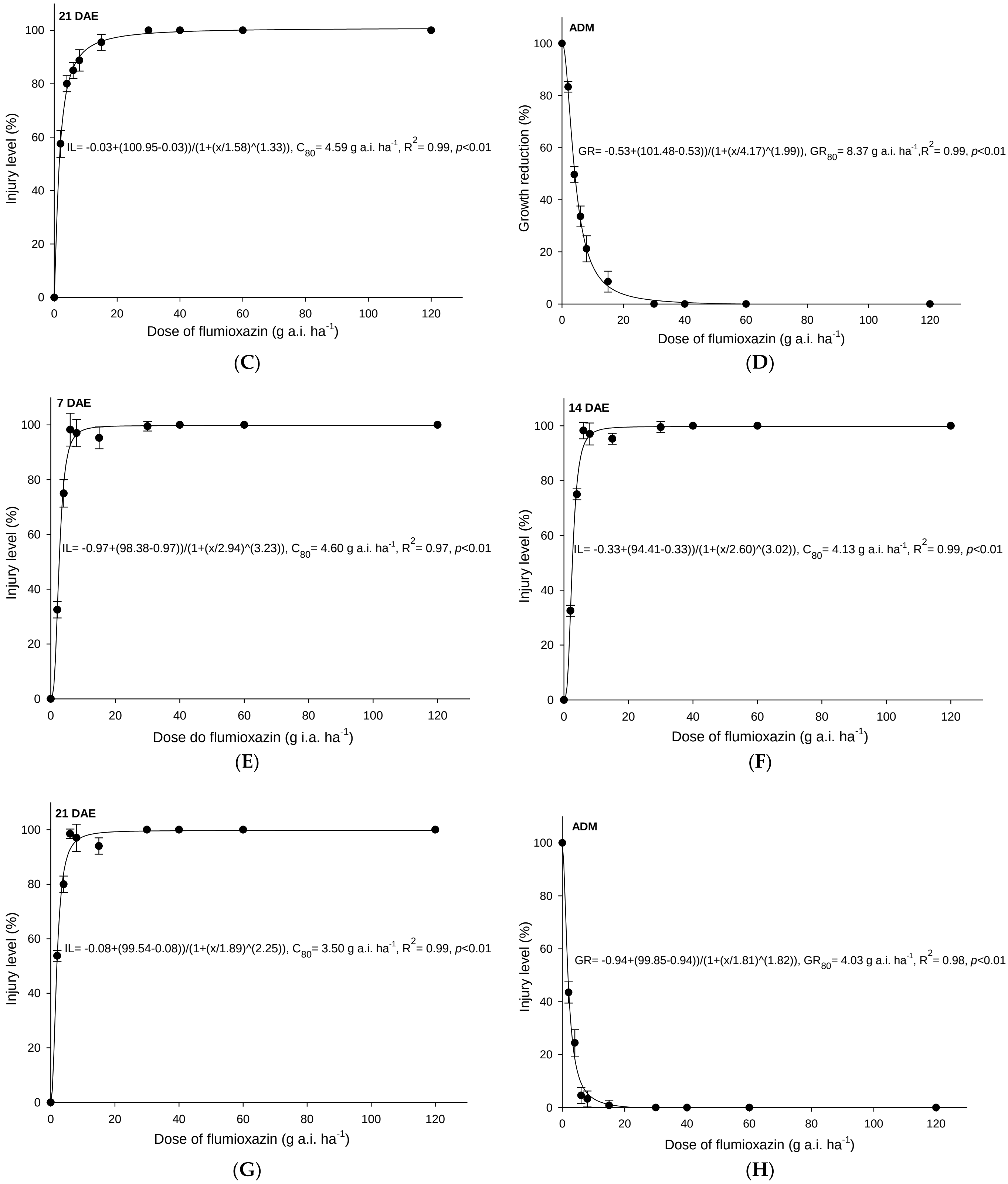


Figure 6. Injury level of gallant soldier (*Galinsoga parviflora*) at 7, 14, and 21 days after emergence (DAE) and grown reduction in aerial dry matter (ADM) in Ultisol (clay), (**A**–**D**) and Oxisol (clay) (**E**–**H**) under the flumioxazin doses (0, 2, 4, 6, 8, 15, 30, 40, 60, and 120 g a.i. ha^{-1}). The vertical bars of each symbol equal the standard error of the mean (n = 4).

As with oxyfluorfen and linuron, higher doses were required for flumioxazin to reach C_{80} on Ultisol compared to Oxisol, with a difference of approximately twice the dose at 14 DAE, and this difference decreased at 21 DAE (Figure 6). According to ANOVA, there was significant interaction (F = 4.10000; p = 0.00038) between soil and flumioxazin dose. Ultisol required twice the dose to reach GR_{80} (8.37 g a.i. ha^{-1}), while Oxisol reached GR_{80} at lower doses (4.13 g a.i. ha^{-1}).

3.4. Comparison of *Galinsoga parviflora* Control with Linuron, Oxyfluorfen, and Flumiozaxin in the Two Soils

There were significant differences in the C_{80} and GR_{80} values of *G. parviflora* on Oxisol with the application of the three herbicides (Figure 7). Flumioxazin doses provided lower C_{80} and GR_{80} compared to oxyfluorfen and linuron, indicating greater sensitivity of the weed to this herbicide. The application of oxyfluorfen resulted in intermediate values of C_{80} and GR_{80} on Oxisol. The application of linuron, among the three herbicides, at reduced doses, was the one that resulted in higher C_{80} and GR_{80} in both soils.

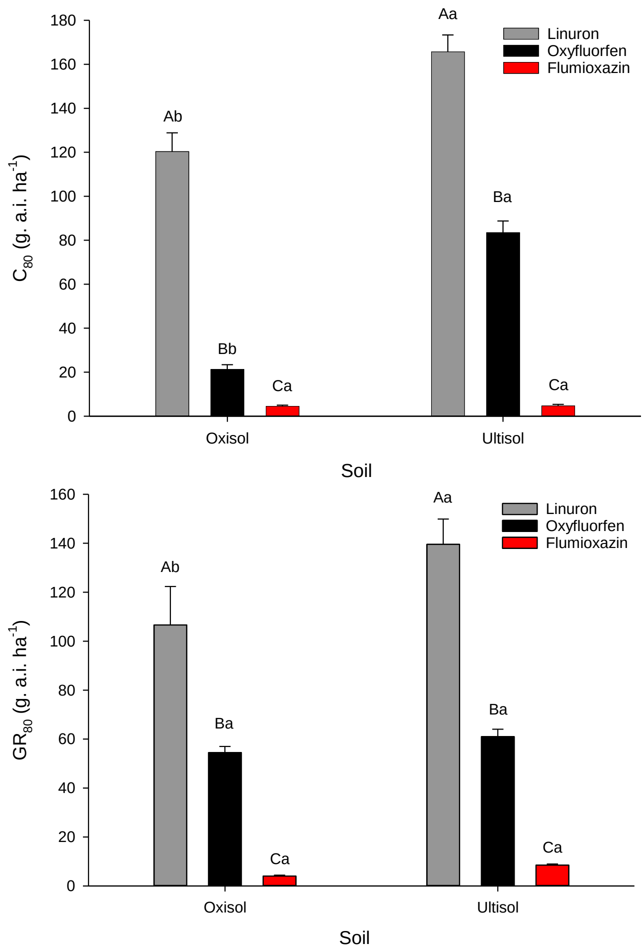


Figure 7. Doses to control 80% (C_{80}) of gallant soldier (*Galinsoga parviflora*) at 21 days after emergence (DAE) and growth reduction (GR_{80}) with linuron, oxyfluorfen, and flumioxazind in Ultisol (clay) and Oxisol (clay). Different capitalized letters indicate significant differences ($p < 0.05$) between different soils and herbicides, while the same letter indicates no significant difference ($n = 4$).

When comparing the same herbicide in both soils, significant differences were observed between the C_{80} values provided by linuron and oxyfluorfen (Figure 7). These two herbicides required higher doses on Ultisol compared to Oxisol. Flumiozaxin had no significant differences on C_{80} value in the two soil types, with very low doses enough to achieve C_{80}.

Soil type interfered with the GR_{80} resultant from the application of linuron, with higher doses needed on Ultisol compared to Oxisol. As for oxyfluorfen and flumiozaxin, at reduced doses, the GR_{80} values were equal, independent of soil type.

4. Discussion

4.1. Oxyfluofen

Some characteristics of oxyfluorfen were low water solubility (0.116 mg L^{-1} at 20 °C), and high K_{oc} (3.46–4.13 L Kg^{-1}) and K_{ow} (log K_{ow} = 4.86) [26]. Due to these properties, oxyfluorfen is sorbed in most soils and has strong binding to OM, clay, and CEC, and is considered to have low mobility to immobility in soil [26]. Since oxyfluorfen is almost insoluble in water and tends to sorb in soil, it is sorbed on suspended particles or sediments [27]. Aspects related to the physicochemical attributes of these soils could explain the difference in control dose. Ultisol has a clay content of 26.8%, an OM value 0.8% higher, and a CEC value 1.66 times higher than Oxisol (Table 1).

Oxyfluorfen is a non-ionizable (neutral) herbicide that remains in molecular form in solution and is not influenced by pH [28]. However, OM and clay are closely related to sorption of herbicides in soil. The OM is not only the main site where bound residues are formed, but also, similar to the clay, it has a high specific surface area that can strongly retain the herbicides, so the bioavailability of the product in the soil solution is lower, resulting in lower weed control efficiency [29].

Some studies have been carried out to determine the doses that are effective in controlling weeds with oxyfluorfen. Doses of 170 g a.i. ha^{-1} were efficient in the complete control of *Amaranthus hybridus* and *G. parviflora*. Another study conducted in clayey soil condition with 5.2% OM showed that 115 g a.i. ha^{-1} gave satisfactory weed control, and 173 g a.i. ha^{-1} was sufficient to control 90% of the species present in the field [30].

Oxyfluorfen is poorly soluble in water (0.116 mg L^{-1} at 20 °C) [31] and is strongly sorbed to soil colloids. Therefore, the control efficiency of the herbicide, even at low doses, depends on the moisture content of the soil. As a result, this herbicide has shown good control in irrigated crops [16]. The same author points out that when the soil is dry, weeds can germinate, but as soon as it rains or is irrigated, they die or are controlled.

Oxyfluorfen has great potential for use in garlic cultivation, due to its broad-spectrum herbicidal activity, with the ability to control a wide range of weed species. The study with the application of oxyfluorfen + quizalofop-ethyl (150 + 50 g a.i. ha^{-1}) resulted in minimal weed density at the growth stages of the garlic crop. Maximum weed control efficiency (84.17%) was observed in this herbicide treatment, resulting in a higher yield of garlic bulbs [15].

However, the control efficiency of oxyfluorfen and the dose depend on the sensitivity of the weed species present on the plot, the OM and clay content of the soils, and the soil moisture. The use of low doses of oxyfluorfen is important in the control of weeds in garlic crops as this herbicide is not recommended for cultivation and can cause carry-over effects to sensitive succeeding crops at high doses.

Studies on the behavior of oxyfluorfen are still sparse in the scientific literature; however, as it is a herbicide positioned in PRE and is a PPO inhibitor, it is important to continue studies on this herbicide, as this mechanism of action is essential to avoid the development of resistant weed biotypes. Therefore, herbicides with PPO inhibitors tend to select weeds with resistance much more slowly than other herbicides [18].

4.2. Linuron

Linuron, similar to oxyfluorfen, is a non-ionic herbicide, and herbicide sorption in the soil and weed control are mainly influenced by the clay, OM, and CEC content [32]. This behavior explains the higher doses of Oxisol compared to Ultisol.

In a study conducted by Mantzos et al. [27], the behavior of linuron was investigated when organic wastes were added to the soil (composted sheep manure and beet pulp). As a result, these residues improved the microbial activity in the soil and increased the sorp-tion of the herbicide, which can be attributed to sorption phenomena and chemical reac-tions taking place on the active surfaces of mineral particles and humus [27]. Clay may also act as an important sorbent for linuron [32], indicating the important role of hydro-phobic clay fractions in herbicide retention in soils.

The evaluation of weed control with linuron was carried out in two soils with the same OM content (1.25%) and different clay content (30% and 50%), and showed that weed control was lower in soils with 50% clay content than in soils with 30% when it was PRE-applied (750 g a.i. ha^{-1}) [33]. This study shows the importance of clay in the sorption of linuron. On the other hand, water competes with the soil surface. Under dry conditions (soils without mulch), soils become extremely sorptive to non-polar herbicides, so linuron should be applied when the soil moisture is close to the field capacity to increase control efficiency [34].

Studies by Barbosa [35] demonstrated the control efficiency of linuron at a dose of 720 g a.i. ha^{-1} in POST application in garlic crops and weeds. However, depending on the sensitivity of the weed species, lower doses of linuron can be used for PRE-emergence weed control, so phytosociological screening prior to herbicide positioning and selection is important.

4.3. Flumioxazin

Flumioxazin, similarly to oxyfluorfen and linuron, is a non-ionic herbicide that has low water solubility (0.786 mg L^{-1} at 20 °C) [31]. Sorption–desorption studies showed that the sorption capacity of flumioxazin in soil correlates positively with increasing CEC and OM of the soil. The correlation coefficients between sorption K_d values and CEC and OM content were 0.9909 and 0.8390, respectively [36]. These data are consistent with the present study, where the higher OM and CEC content of Ultisol compared to Oxisol resulted in higher doses to achieve C_{80} and GR_{80}.

The sorption of flumioxazin to soil particles is mainly attributed to the hydrophobic binding. OM and clays provide the necessary conditions for the sorption of flumioxazin due to the hydrophobicity of the particles [36]. However, the bioavailability of flumioxazin in soil solution also depends on the water content of the soil. If soils are kept at field capacity, weed species can be well controlled with low doses [37].

Similar results were obtained in some studies with flumioxazin. Here, weed control varied by species, with control decreasing with increasing soil OM content [38]. Species such as *G. parviflora*, *Alternanthera tenella*, *Digitaria horizontalis*, *Desmodium tortuosum*, and *Nicandra physaloides* were most sensitive to flumioxazin application at doses of 25 and 40 g a.i. ha^{-}1 in sandy and clayey soils, respectively, and these doses were lower than those recommended in the package insert (60 to 90 g a.i. ha^{-1}) [38]. In other sensitive crops, such as onions, flumioxazin is also used in reduced doses for weed control. The results show a control efficiency of *G. parviflora*, *Eleusine indica*, and *Sonchus oleraceus* of more than 90% at a dose of 20 g ha^{-1}, which allows a reduction of 77 to 88% of the commercial dose recommended in the package insert [37].

4.4. Comparison of Galinsoga parviflora Control with Linuron, Oxyfluorfen, and Flumiozaxin in the Two Soils

The control efficiency of *G. parviflora* at reduced doses of flumioxazin, oxyfluorfen, and linuron might be related to the species biology, as the very small seeds usually remain in the surface soil layers, which increases contact with the herbicides. Both soil types have a high clay and OM content, which makes it easier for the seeds to remain in the topsoil layer and come into contact with the herbicides. In addition, the mobility and leaching capacity of all these products are low in clayey soils [30,39,40]. This factor contributes to the control of the seed bank of *G. parviflora*.

Although linuron is more soluble than oxyfluorfen and flumioxazin, larger doses were necessary in the control of *G. parviflora*. This difference is related to the mechanism of action of each herbicide. Oxyfluorfen acts by inhibiting the PPO enzyme, as already described. This product, when applied in PRE, forms a barrier on the soil surface and acts by contac; the seedlings emerge and die after coming into contact with the herbicide [16]. Linuron is a PSII inhibitor, and it is systemic and absorbed mainly by the roots [41]. Therefore, it requires greater development of the weed and accumulation of biomass to absorb the herbicide because it acts in the plant after there is greater photosynthetic activity [42]. They are herbicides with different physicochemical characteristics; the doses recommended in the leaflet for *G. parviflora* control are higher for linuron, followed by oxyfluorfen and flumiozaxin.

In addition, flumioxazin has been recommended for *G. parviflora* control due to its efficiency and control sensitivity of the species to this herbicide. The use of flumioxazin at low doses (40 g a.i. ha^{-1}), as well as oxyfluorfen (96 g a.i. ha^{-1}), were able to control *G. parviflora* and other weed species present in the field [43]. This dose reduction is especially important when relating the control of weeds in vegetables, which, in general, are sensitive to chemical control [44]. Regarding linuron, the *G. parviflora* control is only effective at higher doses.

Although the clay content and OM were higher in Ultisol compared to Oxisol, the differences were small, and then GR_{80} values had no differences between flumioxazin and oxyfluorfen in both soils. Since linuron, among these herbicides, is the most water soluble herbicide, small changes in the clay and OM content of the soils can interfere with the bioavailability of this herbicide in the soil solution, and hence, the differential behavior.

Some authors advocate controlling weeds with lower doses than those recommended in the package insert by studying weed sensitivity, choosing the right molecules, and knowing the soil types [22,45]. This can help to reduce the cost of crop protection and reduce the environmental pollution caused by herbicide use.

5. Conclusions

When using pre-emergence herbicides, it is important to know the physicochemical properties of the soil and the herbicide to achieve efficient weed control at reduced doses. The soil properties that had the greatest effect on the control of gallant soldier (*Galinsoga parviflora*) with non-ionic herbicides such as linuron, oxyfluorfen, and flumioxazin were clay and OM content.

At 21 DAE, applying oxyfluorfen: C_{80} = 84.42 and 20.85 g a.i. ha^{-1}, and GR_{80} = 61 and 54 g a.i. ha^{-1}; linuron: C_{80} = 141.25 and 118.73 g a.i. ha^{-1}, and GR_{80} = 151.3 and 101.23 g a.i. ha^{-1}; and flumioxazin: C_{80} = 4.59 and 3.50 g a.i. ha^{-1} and GR_{50} = 8.37 and 4.03 g a.i. ha^{-1} in Ultisol and Oxisol, respectively. The *G. parviflora* was more sensitive to flumioxazin than oxyfluorfen and linuron.

This study was designed to show the importance of knowing soil types and herbicides for efficient weed control with residual herbicides. Monitoring weeds and knowing the sensitivity of these species to different herbicides is important to reduce dosage and selecting the best molecules. Sustainable weed control can be achieved by using lower herbicide doses than those recommended on the label. This is important from both an economic and an environmental point of view.

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