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Research Article

Can Soil Compaction Alter Morphophysiological Responses and Soybean Yield under Application of Selective Herbicides?

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Compacted soils may be negatively affecting the selectivity of herbicides applied in preemergence in the soybean crop. Therefore, the present work aimed to investigate possible negative effects on the morphophysiological characters of soybean plants, as well as on the agronomic and yield performances of this crop. For this purpose, two trials were carried out, one in a greenhouse and the other under field conditions. In a greenhouse, the study was carried out in a completely randomized design in a 2×8 factorial, with five replications, while in the field, the design used was randomized blocks, with the treatments arranged in split-plot (2×8), with six repetitions. The first factor/plot corresponded to the physical condition of the soil: compacted or not compacted, while the second factor/subplot was constituted by the application of preemergence herbicides: clomazone, diclosulam, flumioxazin, S-metolachlor, [imazethapyr + flumioxazin], [pyroxasulfone + flumioxazin], and [sulfentrazone + diuron], plus a control without herbicide. In the greenhouse study, there was a significant interaction between soil compaction and herbicides applied in preemergence for the relative index of chlorophyll *b* and root dry mass. Furthermore, the isolated herbicide factor did not promote significant changes in any of the morphophysiological variables evaluated. Compaction alone had a negative impact on the variables relative index of chlorophyll *a* and carbon assimilation rate, with reductions in the values of these variables when the soybean was submitted to growth in compacted soil. For the field experiment, there were no significant interactions between the factors for any of the analyzed variables, nor the effect of herbicides alone. The isolated soil compaction factor negatively impacted the plant stand and the thousand-grain mass of soybean, showing reductions in the values of this parameter when the soybean was grown in compacted soil.

1. Introduction

Brazilian agriculture plays a key role in national economic sustainability, with the country listed among the largest food producers in the world and routinely appointed as the world's breadbasket for food production for the next generation. For the country to leave the status of a major food importer in the mid-20th century and become one of the world's largest exporters in the 21st century, investment in science, through the creation of national research companies and the strengthening of universities, was fundamental.

Proof of this refers to the level reached for the soybean crop in the 2021/2022 harvest, obtaining a production greater than 125 million tons of oilseed [1]. This deserves attention, especially when considering the center of origin of the species, which is located on the Asian continent, and in less than half a century, Brazil has become one of the world's exponents of soybean production. This whole discussion reinforces the need for continuous investment in research in the area of Agricultural Sciences, for which the country has great potential.

In this sense, in the last soybean harvests, some factors have been commonly identified as limiting the achievement

of higher yields for this crop, emphasizing the occurrence of compacted soils and the interference of weeds with this crop. Compaction is the result of a decrease in the volume of soil solids when external pressure is applied, which causes a reduction in total porosity and soil aeration, in addition to an increase in soil density [2]. Consequently, there is a physical limitation to the growth of the root system, a decrease in the water infiltration rate in the soil, less oxygen availability for the roots, and a reduction in the accessibility of plants to water and nutrients, which trigger physiological restrictions to their growth [3].

Losses of agricultural crops in compacted soils are estimated between 12 and 37% of soybean yield [2]. These losses are related to the water deficit and the mechanical impediment to the growth of the root system of the plants, as well as the period of water excess, a fact that causes a reduction in the availability of oxygen for the plants due to a lower rate of water infiltration into compacted soil [4, 5].

Similarly, due to the damage caused by soil compaction, weeds have been causing a series of damages in soybean production systems, especially biotypes with resistance to herbicides. Currently, considering only the soybean production system, estimates indicate that the average annual cost of plant resistance in Brazil is around R$4,918,820,000.00, and this value can reach a total of R$9 billion per year if the losses caused to crop yield due to the interference of the weed community are added [6].

Regarding the level of yield loss in the soybean crop caused by weed interference, two of the main species in Brazil are considered, which are horseweed (*Conyza* sp.) and sourgrass (*Digitaria insularis*), and the reductions can reach 63 and 80%, respectively [7, 8]. This becomes even more problematic when considering that both horseweed and sourgrass are already widespread in all geographic regions of the country, with the common occurrence of simultaneous infestations of both with biotypes resistant to glyphosate [9, 10].

Faced with all problems related to the interference of weeds with soybean, the need to adopt integrated weed management to ensure the productive potential of the crop becomes evident [11]. In this sense, the chemical method is widely adopted for weed control in soybean, given its characteristics of fast implementation, low dependence on labor, and good cost-benefit ratio [12]. In the chemical control of weeds in soybean, herbicides can be used in three application modalities in relation to the crop cycle, namely, presowing burndown (management), preemergence, and postemergence [13].

In recent years, due to the intensification of records about weed resistance, the use of preemergence herbicides in soybean has again become widely disseminated, since in this modality, plants are more susceptible to the toxicity of active ingredients [14]. The herbicides applied in preemergence are characterized by showing residual activity in the soil, and this is influenced by physical and chemical properties, both herbicide molecules and those of the soil [15].

Furthermore, the dynamics of herbicides used in preemergence may also vary, depending on the physical condition of the soil, since the behavior of water processes will directly influence the persistence of the molecule in the soil environment [16]. The knowledge of the characteristics and dynamics of the products applied to the soil, aiming at the elimination of weeds, is of paramount importance for successful chemical control of weeds, especially about the availability or retention of the product in the soil, and this is associated with the understanding of how compaction can interfere with existing processes in the product x soil x plant relationship and substantially in the assertiveness of weed control in different production environments.

Thus, in the present study, the objective was to evaluate the interaction between soil compaction and the selectivity of herbicides applied in preemergence of soybean, assessing the effects on physiological and agronomic traits of this crop.

2. Materials and Methods

Two experiments were carried out, one in a greenhouse and the other in the field, both in the municipality of Rio Verde, state of Goiás, in areas located at the geographical coordinates 17°47′14.11″ S and 50°57′53.81″ W. The experiment conducted in greenhouse was carried out from 11/09/2021 to 01/04/2022, while the one installed in the field was carried out during the 2021/2022 harvest, in the period between 11/19/2021 (sowing) and 03/04/2022 (harvest). The climate of the municipality of Rio Verde is Aw, which is called "tropical with dry season," characterized by more intense rainfall in summer compared to the winter [17].

2.1. Greenhouse Experiment. For the composition of the experimental units, rigid plastic pots made of high-density propylene with a volume equivalent to 4.0 dm^3 were filled with soil collected in arable areas. After collection, a sample was sent for physical-chemical analysis, which showed the following values for the analyzed properties: pH ($CaCl_2$) = 5.30; O.M. = 19.84 $g \cdot dm^{-3}$; $P = 20.42$ $mg \cdot dm^{-3}$; $K = 365.00$ $mg \cdot dm^{-3}$; effective CEC = 7.01 $cmolc \cdot dm^{-3}$; clay = 48.7%; silt = 7.4%; and sand = 43.9% (clayey texture).

This was a 2×8 factorial completely randomized experimental design, with 16 treatments and five replications. The levels of the first factor were related to the physical condition of the soil: compacted and noncompacted. The levels of the second factor consisted of herbicides applied in soybean preemergence, plus a control without application (Table 1). All doses of the evaluated herbicides were within the range recommended for soybean according to the package leaflet of each commercial product.

To prepare the treatments with the physical condition of soil compaction, after filling, the pots were taken to the laboratory where the soil contained in the experimental units was compressed until a compaction contrast was obtained between the two physical conditions proposed for the experiment. In experimental units without compaction, the amount of soil necessary to reach a soil density of 1.28 $Mg \cdot m^{-3}$ was used, while in experimental units with compaction, the amount of soil necessary to reach a density equivalent to 1.65 $Mg \cdot m^{-3}$. Thus, for all pots whose

Table 1: List of herbicides, doses, and mode of action evaluated in preemergence application in soybean crops.

Treatments	Dose ($g \cdot ha^{-1}$)	Mode of action
Control	—	—
Clomazone	800	DOXP inhibitor
Diclosulam	29.4	ALS inhibitor
Flumioxazin	60	PPO inhibitor
S-metolachlor	1,440	VLCFA inhibitor
[Imazethapyr + flumioxazin]	[106 + 50]	ALS inhibitor + PPO inhibitor
[Pyroxasulfone + flumioxazin]	[90 + 60]	VLCFA inhibitor + PPO inhibitor
[Sulfentrazone + diuron]	[210 + 420]	PPO inhibitor + PSII inhibitor

condition was compaction, the soil was moistened to field capacity. These values were selected from the study developed by Guimarães et al. [18], who carried out a study with soil from the experimental area to build the curves for obtaining the maximum soil density. To compact the soil, an automatic press was used (Model Instron Emic 23-300) and the compaction force applied to the pot was 5.8 kN, equivalent to 2 $kgf \cdot cm^{-2}$.

On November 9, 2021, four seeds of the Credenz CZ36B86 I2X® soybean cultivar were sown per experimental unit. This cultivar is characterized by an indeterminate growth habit and an early cycle, with a maturity group of 6.9 [19]. After the emergence of soybean seedlings, thinning was performed to maintain two plants per experimental unit. Upon sowing, fertilization was not carried out, since the fertility levels were satisfactory considering the total duration of the study. Soybean seeds were inoculated before sowing to ensure the success of biological nitrogen fixation. For this purpose, a liquid inoculant (*Bradyrhizobium elkanii*; concentration of 5×10^9 viable cells mL^{-1}) was applied in 0.15 L c.p. 100 kg^{-1} of seeds.

The application of herbicide treatments in preemergence was carried out in the plant-and-apply modality, and applications were carried out immediately after soybean sowing and the soil of the experimental units was moist. For that, a CO_2 backpack sprayer was equipped with 4 XR110.02 nozzles, spaced at 0.50 m, at a pressure of 38 lb in^{-2}. These application conditions provided the equivalent of 200 $L \cdot ha^{-1}$ spray solution.

Throughout the experiment, pots were kept in a greenhouse with irrigation volumes and shifts programmed according to the development requirements of soybean plants. In addition, insecticides and fungicides were not necessary since the plants were in a protected environment, and there was no incidence of pests and pathogens on soybean plants.

To measure the effects of treatments on soybean, evaluations were made for phytotoxicity, plant height, relative chlorophyll *a* and *b* indices, carbon assimilation rate, and transpiration rate, in addition to shoot and root dry mass. In the assessment of phytotoxicity, a qualitative visual scale proposed by the EWRC [20] was used, with scores ranging from 1 to 9, where 1 means no symptoms and 9 means plant death. These evaluations were carried out at 7, 14, and 28 days after soybean emergence (DAE). Plant height was evaluated at 15 DAE when the soybean was in the phenological stage V2 [21]. For this purpose, the distance from the soil surface to the apical meristem of the plant was measured using a graduated ruler.

The relative chlorophyll *a* and *b* indices were determined using the ClorofiLOG® 1030 chlorophyll meter (Falker, Brazil). Values of chlorophyll *a* and *b* were evaluated on the second fully expanded trifoliate leaf from the apex to the base of soybean plants; the measurement was taken on the central leaflet. Carbon assimilation rate (A) and transpiration rate (E) were also measured in the morning (between 9 and 12 h), taking measurements on the third fully expanded leaf, with a photosynthetically active photon flux density of 1,000 $\mu mol \cdot m^{-2} \cdot s^{-1}$, with a portable infrared gas analyzer, model CI-340 [22]. Additionally, the instantaneous efficiency of water use was determined from the A/E ratio. Evaluations of relative chlorophyll indices and those related to plant gas exchange were performed at 28 DAE.

Finally, to determine the dry mass of shoots and roots, at 50 DAE, the plants were carefully taken from the pots, and the shoots separated from the root system, and later the collected material was packed in kraft paper bags and dried in a forced air oven, in which the samples remained for 72 hours, at an average temperature of 65°C. After this period, the material was weighed on a precision analytical balance.

2.2. Study Carried Out under Field Conditions. The soil of the experimental area was classified as Rhodic Ferralsol according to the WRB [23]; or *Latossolo Vermelho distrófico* according to Brazilian classification [24], and subjected to a no-till system with soybean as a previous crop. A soil sample was taken from a depth of 0–20 cm. On this occasion, the soil in the experimental area had a pH of 5.5 in $CaCl_2$; 25.85 $mg \cdot dm^{-3}$ of P; 425.82 $mg \cdot dm^{-3}$ of K; 21.70 $g \cdot dm^{-3}$ O.M.; 580 $g \cdot kg^{-1}$ clay, 80 $g \cdot kg^{-1}$ silt, and 340 $g \cdot kg^{-1}$ sand (clayey texture).

Figure 1 shows the climatological data related to maximum and minimum air temperature and rainfall during the period of the field experiment. During this period, there was an accumulated rainfall of 760.40 mm. At mechanized sowing (11/19/2021), the same cultivar used in the greenhouse experiment (CZ36B86 I2X) was used, adopting 0.5 m row spacing, planting depth of 3 cm, and seed density to obtain a final population equivalent to 18 plants per meter. The soybean seeds were inoculated using the same dose and product as in the greenhouse experiment. Fertilization was carried out according to soil analysis and crop needs, adding 400 $kg \cdot ha^{-1}$ at presowing of formulation 02-20-18.

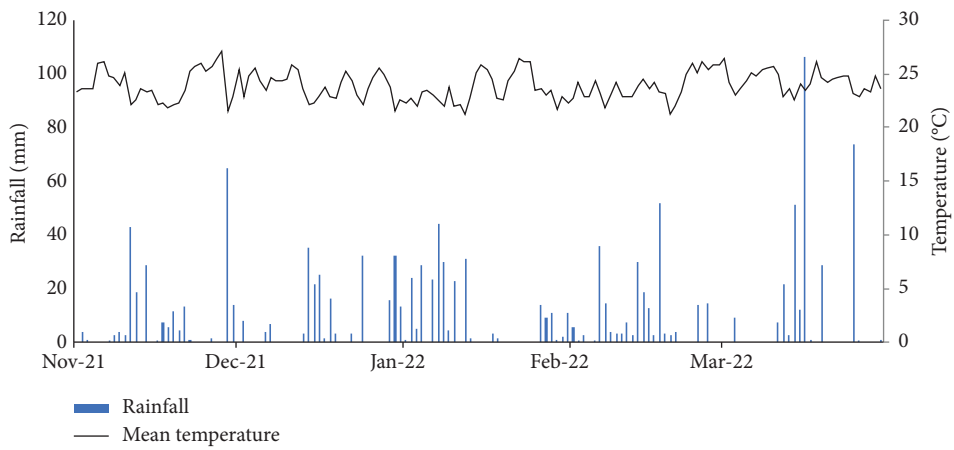

Figure 1: Mean temperature and rainfall observed during the period of the field experiment with soybean planted in compacted soil and applied with herbicides in preemergence.

This was a split-plot (2 × 8) randomized block experimental design, totaling 16 treatments with six replications. Similar to the experiment carried out in a greenhouse, the factor assigned to the main plot was related to the physical condition of the soil, and in the subplots, the herbicides applied in the preemergence of soybean. Each subplot consisting of 10 soybean sowing lines, 5 m long, totaling an area of 25 m^2. For useful area, 0.5 m was eliminated from each edge of the experimental unit (16 m^2).

Soil compaction in the treatments under this condition occurred after a long period of rainfall, which would ensure the saturation of the soil profile, and on 11/18/2021, a backhoe loader (model CASE 580N, 7,858 kg operational weight) coupled with the ballast, resulting in a total load of 8.5 t, was driven in a repeated and continued path 10 times, over the plots, resulting in a contrast of compaction between the plots. To characterize the physical condition of the soil before soybean sowing, an evaluation of resistance to penetration in the field was carried out using a penetrometer PLG 1020 (Falker, Brazil), in which penetration resistance data were obtained every 0.01 m up to 0.40 m deep. Measurements were taken two days after the occurrence of rain so that the soil water content was close to the field capacity. The soil compaction operation before sowing and the gradient resulting from the process are illustrated in Figure 2.

All experimental units were weeded throughout the soybean development cycle to eliminate the effect of weed interference with the crop, leaving the plants exposed only to the effect of treatments (soil physical condition and herbicides applied in preemergence). During soybean development, all treatments were carried out in accordance with the recommendations, controlling pests and diseases and preventing their influence on crop development [25]. All maintenance applications were carried out using an electric backpack sprayer, adopting a spray volume equivalent to 150 $L \cdot ha^{-1}$.

The first of the evaluations to determine the sensitivity aspects of the cultivar was phytotoxicity, evaluated by percentage score [20] at 7, 14, and 28 DAE, which coincided with the moment when the soybean plants were at the phenological stages V1, V2, and V5 [21]. At the time of harvest, on 03/04/2022 (R8 phenological stage), plant height was measured using a graduated ruler, considering the distance from the ground to the apical meristem of the plants, in five plants per experimental unit. On the same date, the final stand was evaluated by counting the number of plants present in 3 m, whose results are presented in percentage of emerged plants, relative to the sowing density adopted per meter.

Moreover, at the time of soybean harvest, the number of pods per plant and the weight of a thousand grains were evaluated. For the evaluation of the number of pods per plant, pods per plant were counted in five plants per experimental unit. In the evaluation of the thousand-grain mass, a thousand grains were counted, which were weighed on a precision scale, correcting the moisture to 13%. To determine grain yield, all plants present in the useful area of each experimental unit were harvested by hand; this material was subsequently subjected to threshing, packaging, identification, and weighing, and the grain moisture was corrected to 13% in all treatments.

2.3. Statistical Analysis. Statistical analysis was not performed for data from phytointoxication evaluation because a scale with scores based on qualitative parameters was used, opting to present only the mean values of repetitions for each treatment. After the end of the experiments, data were analyzed using the SISVAR software [26]. First, data were tested by analysis of variance by the F-test ($p \leq 0.05$), and when significant effects were detected between the tested factors (soil physical condition and preemergence herbicides) or between the levels of each factor, the LSD-Fisher test was applied ($p \leq 0.05$).

3. Results and Discussion

3.1. Greenhouse Experiment. Table 2 lists the results of the soybean phytotoxicity evaluations as a function of the preemergence application of different herbicide treatments.

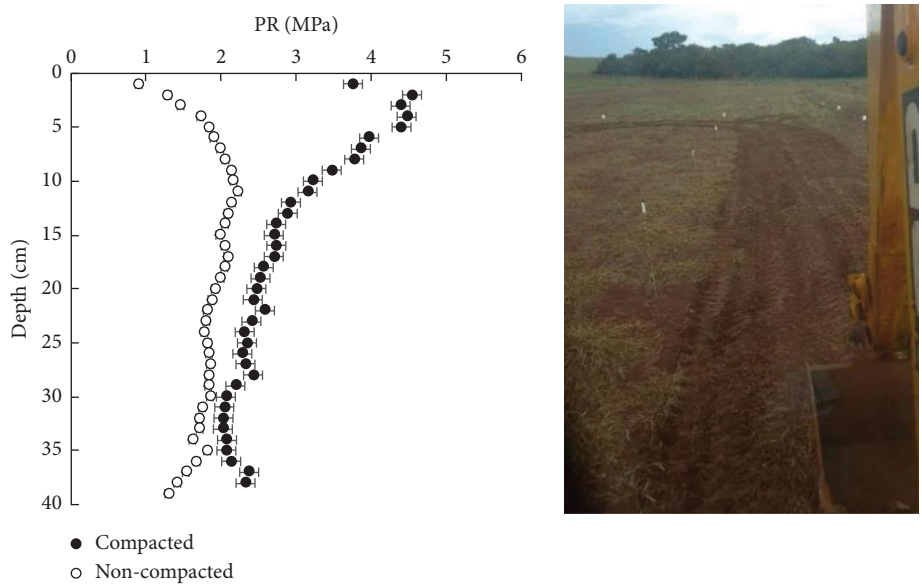

Figure 2: Penetration resistance (PR) values after the soil compaction process by repeated and continued heavy machine traffic and recording of machine traffic during the compaction process.

Table 2: Phytotoxicity scores at 7, 14, and 28 DAE of soybean plants as a function of soil physical condition and preemergence herbicide application.

Treatments	Dose (g·ha^{-1})	*Phytotoxicity*					
		Compacted			Noncompacted		
		7 DAE	14 DAE	28 DAE	7 DAE	14 DAE	28 DAE
Control		1	1	1	1	1	1
Clomazone	800	2	2	1	2	2	1
Diclosulam	29.4	2	2	1	2	2	1
Flumioxazin	60	2	1	1	2	1	1
S-metolachlor	1,440	2	1	1	2	1	1
[Imazethapyr + flumioxazin]	[106 + 50]	2	2	1	2	2	1
[Pyroxasulfone + flumioxazin]	[90 + 60]	2	1	1	2	1	1
[Sulfentrazone + diuron]	[210 + 420]	2	2	1	2	2	1

In general, the symptoms observed as a result of damage caused by herbicides were classified as mild in intensity, not exceeding a score of two in any of the evaluations, regardless of the physical condition of the soil. The injuries in soybean plants as a result of preemergence herbicide application were characterized by slight chlorosis and/or slight reduction in plant size.

Our results do not corroborate the literature, in which pronounced symptoms of injuries were found due to the preemergence herbicide application in soybean, both in compacted soil, as in soils without this physical restriction in the soil environment [27, 28]. Possibly, the absence of more pronounced injuries in soybean plants in the present experiment is related to differences in the physical-chemical properties of the soil compared to soils of the aforementioned studies, since it was already mentioned that these characteristics of the soil environment govern the processes of sorption and desorption of herbicides, making them more available in the soil solution. Another possibility refers to the differential tolerance of the soybean cultivars used in this experiment compared to those tested in other studies, for the herbicides applied in preemergence, since there are soybean materials that are less sensitive to the phytotoxic action of herbicide molecules [29].

The summary of the analysis of variance of the response variables measured is presented in Table 3. For plant height (PH), transpiration rate (E), and shoot dry mass (SDM), no significant effect was detected for the interaction between the studied factors (soil physical condition and herbicides), nor these isolated factors. On the other hand, the effect of the interaction between the factors on the relative index of chlorophyll b (RICb) and root dry mass (RDM) was observed. For the isolated factors, there was a significant effect of soil physical condition influencing the relative index of chlorophyll a (RICa) and b and the carbon assimilation rate (A), and root dry mass.

Possibly, this lack of effect of treatment on plant height may be related to the time of evaluation since during the first weeks after emergence, soybeans have a smaller root system [30], which favors low growth in depth; and these seedlings are highly dependent on the reserves contained in the cotyledons. Under these conditions, the effect of compaction

Table 3: ANOVA summary ($F_{Calculated}$ + CV) for plant height (PH), relative index of chlorophyll *a* (RIC*a*) and *b* (RIC*b*), carbon assimilation rate (*A*), transpiration rate (*E*), shoot dry mass (SDM), and root dry mass (RDM), as well as ratios of carbon assimilation rate to transpiration rate (*A*/*E*) and shoot dry mass to root dry mass (SDM/RDM), between the soybean as a function of soil physical condition and preemergence herbicide application.

Source of variation	DF	$F_{Calculated}$								
		PH	RIC*a*	RIC*b*	*A*	*E*	SDM	RDM	*A*/*E*	SDM/RDM
Soil physical condition (C)	1	1.23^{ns}	6.48^{*}	3.88^{*}	6.04^{*}	1.03^{ns}	0.13^{ns}	54.96^{*}	5.81^{*}	21.81^{*}
Herbicide (H)	7	0.60^{ns}	0.52^{ns}	0.75^{ns}	0.44^{ns}	0.31^{ns}	0.83^{ns}	1.86^{ns}	0.85^{ns}	1.39^{ns}
C *versus* H	7	0.91^{ns}	1.31^{ns}	2.69^{*}	0.44^{ns}	0.74^{ns}	1.18^{ns}	3.44^{*}	1.19^{ns}	0.63^{ns}
Mean	—	7.52	28.84	6.5	21.37	2.99	11.53	2.74	7.13	9.47
CV (%)	—	21.88	19.16	17.64	23.75	23.5	12.55	60.46	15.86	88.21

DF: degree of freedom. $^{ns\ and *}$Nonsignificant and significant by *F*-test ($p \leq 0.05$), respectively.

may be reduced as a result of the root growth zone not having reached the compacted layer in the soil. In addition, as all herbicides evaluated were registered for the crop, the effect on plant height in the early development of soybean is inferred to be reduced, as observed herein.

For the evaluation of the relative index of chlorophyll *a*, higher values of this variable were observed for plants that grew in noncompacted soil (Table 4). This increase in the relative values of chlorophyll *a* may be associated with a more favorable soil condition for plant development. Similarly, for the relative index of chlorophyll *b*, soybean plants also obtained a higher value in noncompacted soil, which also shows a higher photosynthetic capacity of plants developed in soil without physical restriction due to the presence of higher values of this photosynthetic pigment.

Regarding the effect of herbicides on the production of chlorophyll by soybean plants, in noncompacted soil, no differences were observed between the active ingredients applied in soybean preemergence for the relative index of chlorophyll *b* (Table 4). However, in the physical condition of compacted soil, the control without herbicide, and the treatments with application of flumioxazin, clomazone, and [pyroxasulfone + flumioxazin], showed higher values of the relative index of chlorophyll *b* compared to S-metolachlor. Although S-metolachlor does not act directly on the chlorophyll biosynthesis pathway, S-metolachlor-induced ROS production in compacted soil may have damaged chloroplasts and cell membranes, subsequently reducing chlorophyll content and impairing cell membrane integrity [31].

Regarding the carbon assimilation rate (net photosynthesis), there was a difference only between noncompacted and compacted soil, with the former showing greater photosynthesis and better plant development (Table 4). This greater photosynthesis may be related to the greater relative indices of chlorophylls *a* and *b* present in plants, which developed in soil without physical restriction (noncompacted). Our findings corroborate Grzesiak et al. [32] who also found a significant reduction in photosynthesis in corn and triticale grown in compacted soil.

The decrease in the photosynthesis rate is the result of a decline in stomatal conductance attributed to a chemical message, mainly abscisic acid (ABA), produced in stressed roots and transported to shoots by xylem [33]. Although the transpiration rate did not vary as a function of soil physical condition and/or herbicide application, the instantaneous water use efficiency (*A*/*E*) was 8.2% lower in plants in compacted soil (Table 4). In this case, the reductions in the instantaneous water use efficiency were due to the gradual decrease in stomatal conductance with increasing soil compaction, without maintaining the photosynthetic rate [34]. Even in plants tolerant or resistant to the application of a certain molecule, oxidative stress can be expected, due to the action of the so-called reactive oxygen species (ROS) leading to alteration of the enzymatic system, harming the entire physiological apparatus, especially photosynthesis, by bringing the plant to a certain level of intoxication [35].

Shoot dry mass was not influenced by the different treatments, while root dry mass was about 3 times higher in soybean grown in noncompacted soil compared to compacted soil (Table 4). This is because, in compacted soil conditions, the first effect on the plant is on the root system, which in turn induces morphophysiological changes throughout the plant [36]. This is supported by the results of the shoot/root dry mass ratio, plants that developed in compacted soil had an increase of ≈64.00% compared to those grown in noncompacted soil, without physical limitation to root growth.

As to the effect of treatment on root dry mass, except for the treatment composed of the combination [pyroxasulfone + flumioxazin], in all others, there was a greater increase in dry mass in the root system of soybean plants grown in noncompacted soil (Figure 3). In addition, in noncompacted soil, the treatment composed of the control without herbicide was the one with the highest accumulation of root dry mass, not differing only from the treatment with diclosulam (Table 4).

Because the present experiment was conducted in a protected environment, the water supply was continuous, not subjecting plants to stress due to excess or lack of water. Under these conditions, the soybean plant seeks to maintain shoot growth to ensure that the photosynthetic process remains at adequate levels to continue the vegetative/reproductive cycle in a normal way [37].

The results obtained here, carried out under controlled conditions, showed evidence of possible morphophysiological changes in the plants or the reduced selectivity of herbicides, without, however, inferring effects, in the plant population or grain yield of the crop. Given such evidence, there is a need for assertive answers about the behavior of these changes, either in plants or in the selectivity of

Table 4: Mean values for the relative index of chlorophyll *a* and *b*, carbon assimilation rate (*A*), transpiration rate (*E*), shoot and root dry mass, instantaneous water use efficiency (EiUA), and shoot/root dry mass ratio in soybean plants as a function of soil physical condition and preemergence herbicide application.

Treatments	Dose ($g \cdot ha^{-1}$)	Relative index of chlorophyll *a*		Relative index of chlorophyll *b*	
		Compacted	Noncompacted	Compacted	Noncompacted
Control	—	28.20	32.46	6.60 Aa	6.56 Aa
Clomazone	800	30.42	29.08	6.62 Aa	6.58 Aa
Diclosulam	29.4	27.96	30.54	6.02 Aab	6.66 Aa
Flumioxazin	60	26.54	29.26	6.66 Aa	6.32 Aa
S-metolachlor	1,440	21.40	32.10	5.16 Bb	6.94 Aa
[Imazethapyr + flumioxazin]	[106 + 50]	28.02	31.30	6.46 Aab	7.60 Aa
[Pyroxasulfone + flumioxazin]	[90 + 60]	28.58	26.74	6.98 Aa	6.70 Aa
[Sulfentrazone + diuron]	[210 + 420]	29.06	31.86	5.98 Aab	6.66 Aa
Mean		27.27 B	30.41 A	6.25	6.75
		A (μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$)		*E* (mmol H_2O $m^{-2} \cdot s^{-1}$)^{ns}	
Control	—	21.74	22.18	3.10	2.84
Clomazone	800	17.22	23.04	2.72	2.94
Diclosulam	29.4	19.04	24.14	2.76	2.96
Flumioxazin	60	21.90	23.92	2.86	3.26
S-metolachlor	1,440	20.46	20.02	3.22	2.88
[Imazethapyr + flumioxazin]	[106 + 50]	20.70	24.48	3.00	3.34
[Pyroxasulfone + flumioxazin]	[90 + 60]	19.08	21.74	2.50	3.32
[Sulfentrazone + diuron]	[210 + 420]	19.70	22.64	3.18	3.08
Mean		19.98 B	22.77 A	2.91	3.08
		Shoot dry mass (g)^{ns}		Root dry mass (g)	
Control	—	11.75	11.85	2.59 Ba	6.19 Aa
Clomazone	800	11.43	11.82	1.15 Ba	3.70 Ab
Diclosulam	29.4	11.74	11.68	1.48 Ba	4.42 Aab
Flumioxazin	60	11.86	9.34	1.20 Ba	3.97 Ab
S-metolachlor	1,440	11.19	11.67	1.57 Ba	3.81 Ab
[Imazethapyr + flumioxazin]	[106 + 50]	11.38	11.50	0.91 Ba	4.07 Ab
[Pyroxasulfone + flumioxazin]	[90 + 60]	11.77	12.21	1.30 Aa	2.81 Ab
[Sulfentrazone + diuron]	[210 + 420]	11.54	11.66	0.73 Ba	3.95 Ab
Mean		11.59	11.50	1.37	4.12
		EiUA		Shoot/root dry mass ratio	
Control	—	7.10	7.91	4.66	2.06
Clomazone	800	6.08	7.71	11.01	7.75
Diclosulam	29.4	6.81	8.27	14.72	3.53
Flumioxazin	60	7.50	7.34	11.27	3.76
S-metolachlor	1,440	6.40	6.87	17.15	4.85
[Imazethapyr + flumioxazin]	[106 + 50]	6.87	7.33	15.49	5.13
[Pyroxasulfone + flumioxazin]	[90 + 60]	7.37	6.66	18.17	9.99
[Sulfentrazone + diuron]	[210 + 420]	6.44	7.36	18.18	3.81
Mean		6.82 B	7.43 A	13.83 B	5.11 A

^{ns}Nonsignificant by *F*-test ($p \leq 0.05$). Mean values followed by different uppercase letters, in the same row, and lowercase letters, in the same column, are significantly different by the LSD-Fisher test ($p \leq 0.05$).

chemical molecules, under field cultivation conditions, in which the effects on the plant population or the soybean yield components are known under the mentioned conditions.

3.2. Study Carried Out under Field Conditions. For the sensitivity of the soybean crop, visually analyzed by the phytotoxicity of the products in soil without compaction, the herbicides S-metolachlor and flumioxazin proved to be selective throughout the period evaluated, without visual symptoms of intoxication in plants until 28 DAE (Table 5). Under this same physical condition of the soil, no symptoms of phytotoxicity beyond small visual changes were recorded in some plants (score 2), up to 14 DAE of the plants, for the other products evaluated. In this scenario, the applications of the combinations [sulfentrazone + diuron] and [imazethapyr + flumioxazin], in addition to the isolated application of diclosulam, presented visual symptoms up to 14 DAE, while the isolated application of clomazone promoted a phytotoxic effect only at 7 DAE. At 28 DAE, no visual symptoms of damage caused by herbicides applied in preemergence were recorded.

Under no soil compaction, preemergence applications of [sulfentrazone + diuron], [imazethapyr + flumioxazin], and diclosulam pointed to similar behavior in terms of

Figure 3: Visual aspect of the root system of soybean plants at 50 DAE as a function of soil physical condition and preemergence herbicide application. Treatments in order from left to right: control, clomazone (800 g·ha^{-1}), diclosulam (29,4 g·ha^{-1}), flumioxazin (60 g·ha^{-1}), S-metolachlor (1.440 g·ha^{-1}), [imazethapyr + flumioxazin] ([106 + 50] g·ha^{-1}), [pyroxasulfone + flumioxazin] ([90 + 60] g·ha^{-1}), and [sulfentrazone + diuron] ([210 + 420] g·ha^{-1}).

Table 5: Phytotoxicity scores at 7, 14, and 28 DAE of soybean as a function of soil physical condition and herbicide application in preemergence.

Treatments	Dose (g·ha^{-1})	*Phytotoxicity*					
		Compacted			Noncompacted		
		7 DAE	14 DAE	28 DAE	7 DAE	14 DAE	28 DAE
Control		1	1	1	1	1	1
Clomazone	800	2	1	1	2	1	1
Diclosulam	29.4	3	2	1	2	2	1
Flumioxazin	60	1	1	1	1	1	1
S-metolachlor	1,440	1	1	1	1	1	1
[Imazethapyr + flumioxazin]	[106 + 50]	2	2	1	2	2	1
[Pyroxasulfone + flumioxazin]	[90 + 60]	2	1	1	1	1	1
[Sulfentrazone + diuron]	[210 + 420]	3	2	1	2	2	1

phytotoxicity, in which the visual symptoms are classified as small alterations, for which metabolic recovery of the plant is expected, reducing yield losses. Under compaction conditions, the application of [sulfentrazone + diuron] as well as diclosulam showed higher levels of injury at 7 DAE. For the combination [sulfentrazone + diuron], Zobiole et al. [16] stated that this active ingredient can reduce leaf area, as well as nodulation, reducing nitrogen inputs in the crop cycle. As observed in soil without compaction, the scores observed for other applications were considered only as small changes in a few plants subjected to a compacted environment.

Due to their characteristics, the herbicides evaluated here show good solubility and mobility in the soil profile. For these products with higher solubility, symptoms of intoxication tend to be more severe in sandy soils with low organic matter content [38], a contrary condition observed in the experimental area of this study, according to the soil analysis previously presented. Studies show that production environments with low content of organic matter and high content of sand have a lower sorption capacity of soil particles and consequently greater availability of herbicide molecules in the soil solution, which will be readily absorbed by plants [39]. This behavior may indicate that the good solubilization and mobilization of the molecules, in any of the physical conditions studied, reduced the scores of phytotoxicity observed here.

The summary of the analysis of variance ($F_{\text{Calculated}}$ + coefficient of variation) of the response variables analyzed in the experiment is listed in Table 6. Considering the effect of soil physical condition, there was a significant effect on plant stand (PS) and thousand-grain mass (TGM), while for the herbicide factor, no differences were detected for any of the analyzed response variables. As for the effect of the interaction between soil physical condition and herbicide application in soybean preemergence, none of the variables analyzed showed a significant effect.

For the plant stand, there was a lower emergence of soybean plants in compacted soil (Table 6). In general, soils with physical restrictions (compacted) limit the proper development of the root system of plants, which can result in higher soybean mortality during the period of establishment of the crop [2]. The physical condition of noncompacted soil showed a percentage of plant stand about 17% higher than in compacted soil.

In addition to the plant stand, another response variable that also affected the physical condition of the soil was the thousand-grain mass (Table 6). In the comparison between compacted and noncompacted soil, a decrease of

Table 6: ANOVA summary ($F_{calculated}$ + CV) and mean results for evaluations of plant stand (PS), plant height (PH), number of pods per plant (NPP), thousand-grain mass (TGM), and grain yield (GY) of soybean as a function of soil physical condition and herbicide applications in preemergence.

Sources of variation	DF	$F_{calculated}$				
		PS (%)	PH (cm)	NPP (μd)	TGM (g)	GY (kg·ha^{-1})
Block	5	0.23^{ns}	5.37^{*}	2.11^{ns}	1.09^{ns}	0.77^{ns}
Physical condition of the soil (C)	1	10.46^{*}	0.74^{ns}	0.01^{ns}	49.30^{*}	4.91^{ns}
Herbicides (H)	7	1.96^{ns}	1.30^{ns}	0.34^{ns}	0.68^{ns}	1.06^{ns}
C *versus* H	7	0.84^{ns}	1.74^{ns}	1.49^{ns}	0.27^{ns}	0.17^{ns}
CV 1 (%)		30.5	16.9	37.9	6.0	39.5
CV 2 (%)		13.6	9.8	33.0	4.9	14.8
Physical condition of the soil						
Compacted		75.16 b	84.5	36.4	147.4 b	3,240.2
Noncompacted		92.0 a	87.1	36.2	160.7 a	3,876.9
Treatments	Dose (g ha^{-1})					
Control		76.9	87.1	35.8	153.1	3,775.4
Clomazone	800	78.5	86.4	35.3	152.7	3,732.7
Diclosulam	29.4	84.4	88.9	37.2	153.8	3,421.5
Flumioxazin	60	85.3	81.4	33	156.1	3,377.9
S-metolachlor	1,440	89.9	81.7	38.5	156.9	3,653.8
[Imazethapyr + flumioxazin]	[106 + 50]	87.5	87.4	39.4	152	3,564.6
[Pyroxasulfone + flumioxazin]	[90 + 60]	79.8	87.8	36	155.2	3,573.2
[Sulfentrazone + diuron]	[210 + 420]	86.1	85.7	35.2	152.7	3,369.2

DF: degree of freedom. $^{ns\ and *}$Nonsignificant and significant by F-test ($p \leq 0.05$), respectively. Mean values followed by different uppercase letters, in the same row, and lowercase letters, in the same column, are significantly different by the LSD-Fisher test ($p \leq 0.05$).

Table 7: Analysis of soil (depth 0–20 cm) sampled according to the soil physical condition (compacted and noncompacted) after the end of the experiment.

Physical condition of the soil	pH $CaCl_2$ (unit)	Organic matter (g·dm^{-3})	Phosphorus (mg·dm^{-3})	Potassium (mg·dm^{-3})	Effective CEC (cmol·dm^{-3})
Compacted	5.50	20.00	24.04	420.00	7.55
Noncompacted	5.40	20.00	21.88	380.00	6.94

approximately 8.1% in the accumulation of mass in soybean grains was found when the plants were grown in an environment with physical restrictions to root growth. For all other response variables, no treatment effects were observed, regardless of whether they were related to the physical condition of the soil or the herbicides applied in preemergence of the crop.

The results differ from those reported by Biffe [27], in which the authors found lower selectivity of herbicides applied in preemergence for soybean when applied in compacted soil. A fact that may justify the lack of effects of these treatments on soybean development is related to the adequate rainfall observed during the experimental period (Figure 3), which may have contributed to the better development of the crop even with the negative effects provided by compaction and herbicides applied in preemergence. In addition, adequate crop nutrition, through inoculation practices, aiming at supplying nitrogen and fertilization, can contribute to a greater tolerance of soybean to the factors evaluated in the present study.

For contextualization, after the end of the field experiment, soil in the area was collected for analysis to understand the effect of its physical condition on the absorption of nutrients by soybean plants, with the results presented in Table 7. A fact that draws attention is that, although there is no statistical subsidy, in the composite sample taken in the experimental units under the physical condition of compaction, there were higher levels of phosphorus, potassium, and effective CEC. Although it is not possible to draw a scientific conclusion from these results, the experimental compacted soil units are inferred to have lower absorption of nutrients because the root system of soybean plants is more superficial.

Under the conditions of this study, for the most part, there was no direct effect on the crop, as the results generally point to the lack of significant differences between treatments. Nevertheless, the 2021/2022 crop was exceptional in terms of rainfall volume and its temporal distribution during the phenological cycle of the crops planted in the period. This fact repeatedly made it difficult to record differences that reached a statistical level of difference.

In this context, given the evidence and records in the literature about morphophysiological changes and changes in components of the plant population and/or yield of the soybean crop, due to the interaction of the factors studied here, gaps in the understanding of the dynamics of herbicide molecules applied to compacted soils are perceptible. Changes will be observed in each new study; however,

factors external to this interaction can minimize or enhance this effect, depending on the conditions observed in different agricultural years. Recurring studies with assertive answers on the subject are required so that the best management practices are presented to the rural producer at each new harvest.

4. Conclusion

As an isolated factor, the application of herbicides did not change the morphophysiological characteristics evaluated. Compaction alone had a negative impact on the relative index of chlorophyll *b*, carbon assimilation rate, and root system growth.

The interaction between the factors preemergence herbicide application and soil compaction influenced only root dry mass, demonstrating that all treatments, except for [pyroxasulfone + flumioxazin], resulted in lower accumulation of root dry mass in compacted soil, compared to the noncompacted soil.

The visual symptoms of phytotoxicity observed were considered low intensity (mild). Moreover, soil compaction has a negative impact on the plant stand and the thousand soybean grain mass, with reductions of 17.0% and 8.1%, respectively. Furthermore, all herbicide treatments applied in preemergence are selective in the doses at which they were evaluated.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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