eISSN: 1984-3909
Coffee Science, e161963, 2021

Doi: https://doi.org/10.25186/.v16i.1963

Effectiveness and selectivity of herbicides applied under pre-emergence conditions in weed management for coffee crops

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Received in September 5, 2021 and approved in November 24, 2021

ABSTRACT

The coffee plant is sensitive to weed competition, which negatively affects its growth and development. Thus, the proper and safe use of herbicides is extremely important for weed management to allow the crop to develop its maximum productive potential. The objective of this study was to evaluate the control efficacy of different herbicides under pre-emergence conditions and assess their selectivity for coffee crops. Two experiments were carried out in the field, in randomized block designs, with four replicates and eight treatments, totaling 32 experimental plots. The treatments were: unweeded control; weeded control; sulfentrazone + diuron 1.4 L ha^{-1}; sulfentrazone + diuron 1.7 L ha^{-1}; sulfentrazone + diuron 2.0 L ha^{-1}; sulfentrazone + diuron with indaziflam 1.4 + 0.15 L ha^{-1}; respectively, indaziflam 0.15 L ha^{-1}; and oxyfluorfen + chlorimuron 3.0 L ha^{-1} + 0.08 kg ha^{-1}, respectively. The treatments were applied prior to the emergence of weeds in a directed spray between the crop rows. Evaluations of weed control in the area, phytotoxicity to the crop, branch length, and internode distance of coffee were conducted at 30, 60, 90, and 120 days after treatment application (DAA). In general, all treatments guaranteed greater than 80% efficacy up to 60 DAA. After this, some treatments suffered reductions in efficacy, and did not guarantee satisfactory control up to 120 DAA. For *Digitaria nuda*, the most effective treatments were those that contained indaziflam alone or in combination with sulfentrazone + diuron, and oxyfluorfen + chlorimuron for 60 DAA. In both experiments and the two species analyzed, the indaziflam treatments guaranteed efficacy percentages above 80%, even at 120 DAA. All treatments were equally selective for the coffee plants under the conditions evaluated.

Key words: *Coffea arabica*; Chemical control; Phytotoxicity.

1 INTRODUCTION

The cultivation of coffee (*Coffea arabica* L.) has great importance to the Brazilian economy. Coffee production occupies a total of 1.803.392 million hectares, with an 30.729,9 thousand bags processed and an average productivity of 21.6 bags per hectare (Companhia Nacional do Abastecimento - CONAB, 2021). It is the world's largest coffee producer and exporter, with producing areas concentrated in the central-south region, particularly the states of Minas Gerais, São Paulo, Espírito Santo, and Paraná. Minas Gerais is the main producing region, with approximately 55% of the national production (Conab, 2021). However, this production can be affected by several factors, including weed interference. Such interference occurs because of competition for water, light, nutrients, and CO_2 with the main crop, limiting the basic environmental resources necessary for growth and development (Fialho et al., 2011; Lorenzi, 2014).

Weed competition with coffee plants is intense, especially during the formation of the plantation and in the months from October to March, which coincide with the fruiting period (Fialho et al., 2010). During these stages, the cultivation rows should be maintained without weeds to avoid competition, and the most common method of controlling these plants is through the use of herbicides. According to Ronchi et al. (2014), 85% of these applications use glyphosate herbicide; however, the use of repetitive applications during the crop cycle results in the selection of biotypes resistant or tolerant to the herbicide, causing complications in the management system.

Weed control in coffee planting lines has further challenges, since manual control is expensive and labor is scarce. In addition, several post-emergent herbicides registered for the culture are not indicated for direct application on plants, thereby frustrating management techniques (Ronchi; Silva; Ferreira, 2001).

Thus, the application of herbicides in pre-emergence conditions is an interesting alternative for the crop, since these compounds target the soil and, depending on the product, are selective to the crop. They also endure for a residual period in the area, when they are able to control several emergence flushes, and reduce the occurrence of resistant biotypes due to the rotation of action mechanisms. Therefore, the objectives of this study were to evaluate the control efficacy of different herbicides under pre-emergence conditions and assess their selectivity for coffee crops.

2 MATERIAL AND METHODS

Two experiments were carried out between January and May of 2020. One experiment was conducted in the city of Franca in the state of São Paulo (950 m altitude, 20º32′51″ S, 47º29′13″ W), and the other was performed in Paraguaçu in the state of Minas Gerais (810 m altitude, 21º33′22″ S, 45º44′2″ W). The coffee cultivar used was Catuaí Amarelo IAC 62 (9 years old) with spacing between rows of 3.0 m, between plants of 1.2 m, and a density of 2777 plants/ha.

Fertilization was based on the results of soil analysis and the nutritional needs of the coffee plant, as described by Guimarães et al. (1999). The soil from Franca/SP was characterized according to its chemical characteristics and granulometry analysis, namely: pH (H_2O) 5.0, M.O. = 2.5 dag. kg^{-1}, P = 4.5 mg.dm^{-3}, K = 104 mg.dm^{-3}, Ca^{2+} = 1.5 cmol$_c$.dm^{-3}, Mg^{2+} = 0.5 cmol$_c$.dm^{-3}, H+Al = 0.2 cmol$_c$.dm^{-3}, SB = 2.26 cmol$_c$.dm^{-3}, V = 91,86%. This soil was classified in clay soil, with 69 % with clay + silt and 31% with sand. In relation to soil of Paraguaçu/MG, pH (H_2O) 4.6, M.O. = 1.3 dag.kg^{-1}, P = 1.4 mg.dm^{-3}, K = 48 mg.dm^{-3}, Ca^{2+} = 0.5 cmol$_c$.dm^{-3}, Mg^{2+} = 0.2 cmol$_c$.dm^{-3}, H+Al = 0.5 cmol$_c$.dm^{-3}, SB = 0.82 cmol$_c$.dm^{-3}, V = 62.12 %. This soil was classified in clay soil, with 66.6 % with clay + silt and 33.5% with sand.

The application of herbicides to pre-emergent weeds, was made in a directed spray in the central 2 m between the coffee rows, to avoid contaminating the lateral branches. A handheld sprayer was used with constant pressure (2.0 bar), propelled by CO_2, with four fan spray tips (TTI 11002) calibrated for spray solution consumption proportional to 200 L.ha^{-1}. Meteorological data for the trial periods are shown in Figure 1. The application date, time, temperature, relative humidity, and wind were measured using a Kestrel 3000 thermohygrometer (Table 1).

The experimental design used in both experiments was a randomized block design with four replicates and eight treatments, totaling 32 experimental plots. The commercial doses and active ingredients of the treatments are shown in Table 2.

The herbicide molecules used in this work have distinct mechanisms of action and physicochemical characteristics. In the case of sulfentrazone, it is a herbicide that inhibits PROTOX (protoporphyrinogen oxidase), which is responsible for the oxidation of protoporphyrinogen to protoporphyrin IX, in the biosynthesis of chlorophyll. It has a water solubility of 490 mg L^{-1} and a vapor pressure of 1x10^{-9} mmHg at 25 °C. In soil, it has moderate mobility, low adsorption, with Koc of 43, pKa of 6.56 and Kow of 1.48 (Freitas et al., 2014; Rodrigues; Almeida, 2018). Oxyfluorfen, belonging to the same mechanism of action, is a non-ionizable (neutral) herbicide that, in solution, remains in molecular form, not being influenced by soil pH. When it reaches the soil, this herbicide is highly adsorbed to the colloids, especially in soils with high levels of organic matter and clay (Rodrigues; Almeida, 2018).

Diuron causes photosystem II (FSII) inhibition, is a non-ionizable molecule (pKa dissociation coefficient not applicable) and is considered a poorly mobile herbicide with low water solubility (Garcia et al., 2012). Indaziflam, an inhibitor of cellulose biosynthesis, has low water solubility (0.0028 kg m^{-3} at 20 °C), with Koc < 1,000 mL g^{-1} organic carbon, pka = 3.5 and log Kow at pH 4, 7 or 9 = 2.8, being this herbicide considered moderately to mobile (Rodrigues; Almeida, 2018).

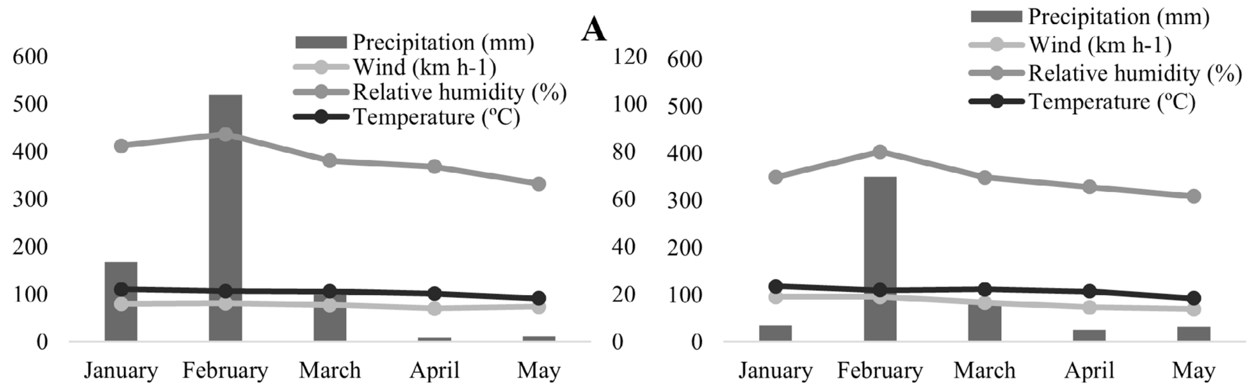

Figure 1: Meteorological data of herbicide experiments for coffee crops in two areas, Franca (A) and Paraguaçu (B).

Table 1: Date, time, and weather conditions of the herbicide treatments on pre-emergent weeds in the experimental areas (Franca/SP and Paraguaçu/MG).

Areas	Date	Time	T(ºC)	RH (%)	Wind (km h^{-1})
Franca/SP	24/01/2020	10:00 – 10:45	23.0	90.0	1.8
Paraguaçu/MG	27/01/2020	10:00 – 10:45	23.0	83.0	2.7

T (temperature), RH (relative humidity).

Table 2: Description of the treatments adopted in the experimental trial of efficacy and selectivity of herbicides under pre-emergence conditions for both experimental areas (Franca/SP and Paraguaçu/MG).

Treatments	Active ingredient	Dose	
		kg or L.ha^{-1}	g a.i. ha^{-1}
1. Unweeded control	-	-	-
2. Weeded control	-	-	-
3. Stone®	Sulfentrazone + Diuron	1.4	245 + 490
4. Stone®	Sulfentrazone + Diuron	1.7	297.5 + 595
5. Stone®	Sulfentrazone + Diuron	2.0	350 + 700
6. Stone® + Alion®	Sulfentrazone + Diuron with Indaziflam	1.4 + 0.15	245 + 490 + 75
7. Alion®	Indaziflam	0.15	75
8. Goal® + Classic®	Oxyfluorfen + Chlorimuron	3.0 + 0.08	720 + 20

kg or L ha^{-1}: kg or L of commercial product per hectare; g a.i. ha^{-1}: grams of active ingredient per hectare.

Chlorimuron is widely used in agriculture. This herbicide belongs to the chemical group of sulfonylurea and its mechanism of action is the inhibition of the enzyme acetolactate synthase (ALS). This herbicide has water solubility of 450 mg L^{-1}, pka of 4.2 and kow at pH 7 of 2.3 (Rodrigues; Almeida, 2018).

The plots consisted of three coffee rows of 6.0 m wide and 10 m long, with 3.0 m spacing between rows totaling 60.0 m^2. The central 20.0 m^2 of each row (40.0 m^2) was used for the evaluations.

To evaluate the level of control, we initially surveyed the main weed species in the area, and determined the effectiveness of the herbicides on each. The species identified in Franca/SP were *Eleusine indica*, *Digitaria nuda*, *Amaranthus* spp., and *Conyza* spp., while Paraguaçu/MG contained *E. indica*, *Digitaria insularis*, *Euphorbia hirta*, and *Conyza* spp. An absence of symptoms from the herbicides was denoted as 0% control and plant death was designated as 100%, according to the method proposed by the Brazilian Weed Science Society (Velini; Osipe; Gazziero, 1995).

For the selectivity evaluations, vegetative growth analyses were performed, including internode distance (cm) and branch length (cm), which were measured with the aid of a graduated ruler, as well as phytotoxicity evaluations using the EWRC scale (1964). All evaluations were performed at 30, 60, 90, and 120 days after application (DAA).

The control data obtained were subjected to analysis of variance (ANOVA), and the significance was verified by the F test ($p<0.01$). The Scott-Knott test was used to study the means. The statistical analyses of the data obtained were performed using R version 3.6.3 (R Development Core Team, 2013).

2 RESULTS

The first experiment was performed in the city of Franca/SP, where *E. indica*, *D. nuda*, *Amaranthus* spp., and *Conyza* spp. were identified as the main weeds infesting the experimental area. With the exception of *Amaranthus* spp., all evaluations of control percentage were significant according to the F test, showing that the density of weeds in the area was significantly affected by the different herbicide treatments used.

The results for *E. indica* at 30 DAA did not differ, keeping the control percentage statistically equal for all treatments (Table 3). However, as the days progressed, the percentages for some treatments reduced, while the association of sulfentrazone + diuron + indaziflam maintained averages higher than 90% up to 120 DAA and was identified as the most effective combination. In contrast, the treatments with sulfentrazone + diuron showed reduced efficiency as the days of exposure in the soil increased, with averages below 80% at doses of 1.4 and 1.7 L ha^{-1}, and 83% at the highest dose evaluated of 2 L ha^{-1} (Table 3). The addition of indaziflam to the sulfentrazone + diuron complex allowed not only a reduction in the dose of these herbicides, but also an increase in the percentage of control.

The results for *D. nuda* followed the same response at 30 DAA, with no significant differences between treatments. However, after 60 DAA, the percentages substantially decreased among all the herbicides evaluated (Table 4). For *D. nuda*, the sulfentrazone + diuron treatments showed results lower than 35% at all doses evaluated and values higher than 90% after the addition of indaziflam to the association and with indaziflam alone. The association of oxyfluorfen + chlorimuron was effective to 60 DAA, with controls higher than 90%. After this time, it would be necessary to increase the herbicide dose to ensure a longer residual period (Table 4).

Regarding the percentage of control of *Amaranthus* spp., there were no significant differences between treatments (Table 5); therefore, all treatments evaluated were satisfactory, maintaining 100% control in all evaluations performed.

Table 3: Control percentage of *E. indica* in the experimental area of Franca/SP evaluated at 30, 60, 90, and 120 days after application.

Treatment	30 DAA[2] (%)	60 DAA (%)	90 DAA (%)	120 DAA (%)
Unweeded control	0 Ba[1]	0 Ca	0 Da	0 Ca
Weeded control	100 Aa	100 Aa	100 Aa	100 Aa
Sulfentrazone + Diuron	87.5 Aa	82.5 Ba	75.0 Cb	73.7 Bb
Sulfentrazone + Diuron	93.7 Aa	85.0 Bb	78.7 Cb	78.7 Bb
Sulfentrazone + Diuron	95.0 Aa	88.7 Ba	82.5 Cb	81.2 Bb
Sulfentrazone + Diuron + Indaziflam	97.0 Aa	95.0 Aa	92.5 Ba	95.0 Aa
Indaziflam	93.7 Aa	95.0 Aa	86.2 Ba	85.0 Ba
Oxyfluorfen + Chlorimuron	96.2 Aa	95.0 Aa	88.7 Ba	86.2 Ba
CV (%) = 8.61				

[1]Means followed by the same letter, upper case in the column and lower case in the row, do not differ by the Scott-Knott test, with 1% significance; [2]Days after application; CV = coefficient of variation; *F test significant at 1% probability.

Table 4: Control percentage of *D. nuda* in the experimental area of Franca/SP evaluated at 30, 60, 90, and 120 days after application.

Treatments	30 DAA[2] (%)	60 DAA (%)	90 DAA (%)	120 DAA (%)
Unweeded control	0 Ba[1]	0 Ca	0Da	0 Ca
Weeded control	100 Aa	100 Aa	100 Aa	100 Aa
Sulfentrazone + Diuron	80.0 Aa	20.0 Bb	10.0 Cb	75.0 Cb
Sulfentrazone + Diuron	93.7 Aa	27.5 Bb	12.5 Cc	10.0 Cc
Sulfentrazone + Diuron	98.7 Aa	32.5 Bb	12.5 Cc	7.5 Cc
Sulfentrazone + Diuron + Indaziflam	100 Aa	100 Aa	98.7 Aa	98.7 Aa
Indaziflam	99.5 Aa	100 Aa	97.5 Aa	93.7 Aa
Oxyfluorfen + Chlorimuron	99.5 Aa	90.0 Aa	68.7 Bb	65.0 Bb
CV (%) = 19.09				

[1]Means followed by the same letter, upper case in the column and lower case in the row, do not differ by the Scott-Knott test, with 1% significance; [2]Days after application; CV = coefficient of variation; *F test significant at 1% probability.

Table 5: Control percentage of *Amaranthus* spp. in the experimental area of Franca/SP evaluated at 30, 60, 90, and 120 days after application.

Treatments	30 DAA[1] (%)	60 DAA (%)	90 DAA (%)	120 DAA (%)
Unweeded control	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Weeded control	100^{NS}	100^{NS}	100^{NS}	100^{NS}
Sulfentrazone + Diuron	100^{NS}	100^{NS}	100^{NS}	100^{NS}
Sulfentrazone + Diuron	100^{NS}	100^{NS}	100^{NS}	100^{NS}
Sulfentrazone + Diuron	100^{NS}	100^{NS}	100^{NS}	100^{NS}
Sulfentrazone + Diuron + Indaziflam	100^{NS}	100^{NS}	100^{NS}	100^{NS}
Indaziflam	100^{NS}	100^{NS}	100^{NS}	100^{NS}
Oxyfluorfen + Chlorimuron	100^{NS}	100^{NS}	100^{NS}	100^{NS}

[1]Days after application; ^{NS}not significant.

Finally, for *Conyza* spp. there were no statistical differences between treatments until 60 DAA, after which the treatments with the lowest doses of sulfentrazone + diuron (1.4 and 1.7 L ha^{-1}) and oxyfluorfen + chlorimuron had significant reductions in the percentage of control, with less than 80% at 120 DAA (Table 6).

The second experiment occurred in the municipality of Paraguaçu/MG, and the species surveyed in the area were

E. indica, *D. insularis*, *E. hirta*, and *Conyza* spp. For all evaluations, the control percentage was significant, showing differences in effectiveness between treatments.

For *E. indica*, there were significant differences between treatments, except for sulfentrazone + diuron at the lowest dose studied (1.4 L ha^{-1}). All treatments were effective against this species, even considering the decrease in control over time, with effectiveness higher than 80% until 120 DAA (Table 7).

Similarly, the data on *D. insularis* followed the same response pattern, whereby only the lowest dose treatment of sulfentrazone + diuron showed efficacy less than 80% at 120 DAA (Table 8). This is because, although they are different species, both plants are classified as monocots; therefore, herbicides that act on one likely also affect the other.

However, the statistically superior treatments at 120 DAA were sulfentrazone + diuron at the highest dose (2.0 L ha^{-1}), sulfentrazone + diuron + indaziflam, and indaziflam alone. The least efficiency occurred with sulfentrazone + diuron at the lowest dose from 90 DAA, while the other treatments remained at similar levels (Table 8).

There were no statistically significant differences for *E. hirta* between treatments until 60 DAA. However, from 90 DAA there were decreases in the control levels, chiefly in the treatments with a combination of sulfentrazone + diuron, which differed from the remaining groups (Table 9). To maintain a residual for 120 DAA, only the treatments of indaziflam and oxyfluorfen + chlorimuron were statistically superior; however, as with the other species evaluated numerically, only the treatment of sulfentrazone + diuron at the lowest dose was lower than 80%.

Finally, the results for *Conyza* spp. remained above 80% for all treatments for 90 DAA, after which, the lowest dose of sulfentrazone + diuron at 120 DAA was less than 80% effective (Table 10). The statistically best results at 120 DAA were for the treatments with indaziflam alone and in association with sulfentrazone + diuron, which maintained percentages above 95%.

Table 6: Control percentage of *Conyza* spp. in the experimental area of Franca/SP evaluated at 30, 60, 90, and 120 days after application.

Treatments	30 DAA[2] (%)	60 DAA (%)	90 DAA (%)	120 DAA (%)
Unweeded control	0 Ba[1]	0 Ba	0 Ca	0 Ca
Weeded control	100 Aa	100 Aa	100 Aa	100 Aa
Sulfentrazone + Diuron	98.7 Aa	85.0 Aa	75.0 Bb	62.5 Bb
Sulfentrazone + Diuron	97.5 Aa	91.2 Aa	80.0 Bb	72.5 Bb
Sulfentrazone + Diuron	100 Aa	97.5 Aa	95.0 Ab	90.0 Ab
Sulfentrazone + Diuron + Indaziflam	100 Aa	96.2 Aa	90.0 Aa	87.5 Aa
Indaziflam	100 Aa	91.2 Aa	90.0 Aa	82.5 Aa
Oxyfluorfen + Chlorimuron	100 Aa	85.0 Aa	66.2 Bb	61.2 Bb
CV (%) = 15.24				

[1]Means followed by the same letter, upper case in the column and lower case in the row, do not differ by the Scott-Knott test, with 1% significance; [2]Days after application; CV = coefficient of variation; *F test significant at 1% probability.

Table 7: Control percentage of *E. indica* in the experimental area of Paraguaçu/MG evaluated at 30, 60, 90, and 120 days after application.

Treatments	30 DAA[2] (%)	60 DAA (%)	90 DAA (%)	120 DAA (%)
Unweeded control	0 Ba[1]	0 Ba	0 Ca	0 Ca
Weeded control	100 Aa	100 Aa	100 Aa	100 Aa
Sulfentrazone + Diuron	100 Aa	97.2 Aa	85.0 Bb	76.2 Bc
Sulfentrazone + Diuron	100 Aa	97.2 Aa	93.7 Ba	81.2 Bb
Sulfentrazone + Diuron	100 Aa	98.2 Aa	93.7 Ba	82.2 Bb
Sulfentrazone + Diuron + Indaziflam	100 Aa	100 Aa	100 Aa	98.7 Aa
Indaziflam	100 Aa	100 Aa	100 Aa	98.7 Aa
Oxyfluorfen + Chlorimuron	100 Aa	99.5 Aa	98.7Aa	82.5 Bb
CV (%) = 4.72				

[1]Means followed by the same letter, upper case in the column and lower case in the row, do not differ by the Scott-Knott test, with 1% significance; [2]Days after application; CV = coefficient of variation; *F test significant at 1% probability.

Table 8: Control percentage of *D. insularis* in the experimental area of Paraguaçu/MG evaluated at 30, 60, 90, and 120 days after application.

Treatments	30 DAA[2] (%)	60 DAA (%)	90 DAA (%)	120 DAA (%)
Unweeded control	0 Ba[1]	0 Ba	0 Da	0 Ea
Weeded control	100 Aa	100 Aa	100 Aa	100 Aa
Sulfentrazone + Diuron	100 Aa	95.0 Ab	83.7 Cc	78.7 Dd
Sulfentrazone + Diuron	100 Aa	96.2 Aa	92.5 Bb	85.0 Cc
Sulfentrazone + Diuron	100 Aa	97.5 Aa	93.7 Bb	90.0 Bb
Sulfentrazone + Diuron + Indaziflam	100 Aa	97.5 Aa	95.7 Bb	92.5 Bb
Indaziflam	100 Aa	98.7 Aa	94.5 Bb	91.2 Bb
Oxyfluorfen + Chlorimuron	100 Aa	98.7 Aa	94.5 Bb	87.5 Cc
CV (%) = 3.2				

[1]Means followed by the same letter, upper case in the column and lower case in the row, do not differ by the Scott-Knott test, with 1% significance; [2]Days after application; CV = coefficient of variation; *F test significant at 1% probability.

Table 9: Control percentage of *E. hirta* in the experimental area of Paraguaçu/MG evaluated at 30, 60, 90, and 120 days after application.

Treatments	30 DAA[2] (%)	60 DAA (%)	90 DAA (%)	120 DAA (%)
Unweeded control	0 Ba[1]	0 Ba	0 Da	0 Da
Weeded control	100 Aa	100 Aa	100 Aa	100 Aa
Sulfentrazone + Diuron	97.0 Aa	94.5 Aa	82.5 Cb	76.2 Cc
Sulfentrazone + Diuron	98.2 Aa	96.5 Aa	88.7 Bb	82.5 Bc
Sulfentrazone + Diuron	100 Aa	95.0 Aa	90.0 Bb	83.7 Bc
Sulfentrazone + Diuron + Indaziflam	100 Aa	99.5 Aa	98.7 Aa	98.7 Aa
Indaziflam	100 Aa	100 Aa	100 Aa	98.7 Aa
Oxyfluorfen + Chlorimuron	100 Aa	99.0 Aa	96.2 Aa	82.5 Ab
CV (%) = 4.6				

[1]Means followed by the same letter, upper case in the column and lower case in the row, do not differ by the Scott-Knott test, with 1% significance; [2]Days after application; CV = coefficient of variation; *F test significant at 1% probability.

Table 10: Control percentage of *Conyza* spp. in the experimental area of Paraguaçu/MG evaluated at 30, 60, 90, and 120 days after application.

Treatments	30 DAA[2] (%)	60 DAA (%)	90 DAA (%)	120 DAA (%)
Unweeded control	0 Ba[1]	0 Da	0 Ca	0 Da
Weeded control	100 Aa	100 Aa	100 Aa	100 Aa
Sulfentrazone + Diuron	97.7 Aa	92.5 Cb	83.7 Bc	75.7 Cd
Sulfentrazone + Diuron	99.5 Aa	95.7 Ca	88.7 Bb	82.5 Cc
Sulfentrazone + Diuron	100 Aa	97.5 Ba	95.0 Aa	87.5 Bb
Sulfentrazone + Diuron + Indaziflam	100 Aa	99.0 Aa	96.2 Aa	96.5 Aa
Indaziflam	100 Aa	98.7 Aa	97.5 Aa	97.5 Aa
Oxyfluorfen + Chlorimuron	100 Aa	98.7 Aa	95.0 Ab	85.0 Bc
CV (%) = 3.53				

[1]Means followed by the same letter, upper case in the column and lower case in the row, do not differ by the Scott-Knott test, with 1% significance; [2]Days after application; CV = coefficient of variation; *F test significant at 1% probability.

With respect to the phytotoxicity evaluation, no visual injury caused by the herbicides was observed in either experiment (Tables 11 and 12), and evaluations of the length of the lower, middle, and upper branches, number of nodes, and internode length also showed no significant differences between treatments for any duration evaluated (Tables 13, 14, 15, and 16).

Table 11: Phytotoxicity percentage of the cultivar Catuaí Amarelo IAC 62 in the experimental area of Franca/SP evaluated at 30, 60, 90, and 120 days after application.

Treatments	30 DAA[1] (%)	60 DAA (%)	90 DAA (%)	120 DAA (%)
Unweeded control	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Weeded control	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Sulfentrazone + Diuron	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Sulfentrazone + Diuron	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Sulfentrazone + Diuron	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Sulfentrazone + Diuron + Indaziflam	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Indaziflam	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Oxyfluorfen + Chlorimuron	0^{NS}	0^{NS}	0^{NS}	0^{NS}

[1]Days after application; NS not significant.

Table 12: Phytotoxicity percentage of the cultivar Catuaí Amarelo IAC 62 in the experimental area of Paraguaçu/MG evaluated at 30, 60, 90, and 120 days after application.

Treatments	30 DAA[1] (%)	60 DAA (%)	90 DAA (%)	120 DAA (%)
Unweeded control	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Weeded control	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Sulfentrazone + Diuron	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Sulfentrazone + Diuron	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Sulfentrazone + Diuron	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Sulfentrazone + Diuron + Indaziflam	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Indaziflam	0^{NS}	0^{NS}	0^{NS}	0^{NS}
Oxyfluorfen + Chlorimuron	0^{NS}	0^{NS}	0^{NS}	0^{NS}

[1]Days after application; NS not significant.

Table 13: Branch length in the lower, middle, and upper thirds of the cultivar Catuaí Amarelo IAC 62 in the experimental area of Franca/SP evaluated at 30, 60, 90 ,and 120 days after application.

Treatments	30 DAA[1]	60 DAA	90 DAA	120 DAA
Branch length lower third (cm)				
Unweeded control	72.50^{NS}	84.75^{NS}	87.25^{NS}	86.50^{NS}
Weeded control	83.00^{NS}	79.00^{NS}	81.25^{NS}	80.25^{NS}
Sulfentrazone + Diuron	79.00^{NS}	81.50^{NS}	82.50^{NS}	82.00^{NS}
Sulfentrazone + Diuron	80.75^{NS}	87.75^{NS}	91.25^{NS}	86.20^{NS}
Sulfentrazone + Diuron	84.75^{NS}	88.50^{NS}	90.00^{NS}	88.75^{NS}
Sulfentrazone + Diuron + Indaziflam	84.50^{NS}	89.25^{NS}	95.00^{NS}	90.50^{NS}
Indaziflam	82.50^{NS}	87.50^{NS}	89.75^{NS}	89.00^{NS}
Oxyfluorfen + Chlorimuron	84.25^{NS}	88.25^{NS}	91.50^{NS}	95.25^{NS}
CV (%) =	10.67	7.90	7.86	6.15

Continue...

Table 13: Continuation.

Treatments	30 DAA[1]	60 DAA	90 DAA	120 DAA
Branch length middle third (cm)				
Unweeded control	51.25 NS	54.00 NS	56.25 NS	57.25 NS
Weeded control	54.50 NS	57.75 NS	61.25 NS	59.25 NS
Sulfentrazone + Diuron	49.50 NS	53.25 NS	57.00 NS	56.50 NS
Sulfentrazone + Diuron	56.75 NS	60.75 NS	62.25 NS	61.50 NS
Sulfentrazone + Diuron	56.75 NS	60.75 NS	62.25 NS	61.25 NS
Sulfentrazone + Diuron + Indaziflam	59.00 NS	63.00 NS	64.50 NS	64.00 NS
Indaziflam	51.00 NS	54.50 NS	58.25 NS	58.25 NS
Oxyfluorfen + Chlorimuron	54.50 NS	59.75 NS	62.00 NS	59.50 NS
CV (%) =	13.14	12.58	11.64	10.68
Branch length upper third (cm)				
Unweeded control	36.75 NS	40.75 NS	42.25 NS	40.00 NS
Weeded control	34.25 NS	38.00 NS	42.00 NS	41.25 NS
Sulfentrazone + Diuron	28.75 NS	31.75 NS	35.50 NS	36.25 NS
Sulfentrazone + Diuron	35.75 NS	39.50 NS	42.25 NS	41.25 NS
Sulfentrazone + Diuron	35.00 NS	34.50 NS	36.25 NS	36.25 NS
Sulfentrazone + Diuron + Indaziflam	35.00 NS	39.25 NS	42.50 NS	40.00 NS
Indaziflam	34.25 NS	36.00 NS	40.00 NS	42.50 NS
Oxyfluorfen + Chlorimuron	34.75 NS	38.25 NS	42.50 NS	45.00 NS
CV (%) =	16.34	15.12	13.04	13.09

[1]Days after application; CV = coefficient of variation; NS not significant.

Table 14: Number of nodes and internode distance of the cultivar Catuaí Amarelo IAC 62 in the experimental area of Franca/SP evaluated at 30, 60, 90, and 120 days after application.

Treatments	30 DAA[1]	60 DAA	90 DAA	120 DAA
Number of nodes				
Unweeded control	5.50 NS	4.75 NS	5.25 NS	5.50 NS
Weeded control	5.25 NS	4.50 NS	5.25 NS	5.75 NS
Sulfentrazone + Diuron	5.75 NS	4.50 NS	5.25 NS	5.75 NS
Sulfentrazone + Diuron	5.50 NS	4.75 NS	5.50 NS	6.00 NS
Sulfentrazone + Diuron	5.50 NS	4.75 NS	5.00 NS	5.75 NS
Sulfentrazone + Diuron + Indaziflam	6.00 NS	4.25 NS	5.25 NS	5.75 NS
Indaziflam	5.75 NS	4.50 NS	4.75 NS	5.50 NS
Oxyfluorfen + Chlorimuron	5.50 NS	4.75 NS	4.75 NS	5.75 NS
CV (%) =	10.79	14.76	10.21	9.08
Internode distance (cm)				
Unweeded control	1.83 NS	2.10 NS	1.91 NS	1.83 NS
Weeded control	1.91 NS	2.00 NS	1.91 NS	1.75 NS
Sulfentrazone + Diuron	1.75 NS	2.37 NS	1.91 NS	1.75 NS
Sulfentrazone + Diuron	1.83 NS	2.02 NS	1.83 NS	1.66 NS
Sulfentrazone + Diuron	1.83 NS	2.00 NS	2.04 NS	1.75 NS
Sulfentrazone + Diuron + Indaziflam	1.69 NS	2.37 NS	1.91 NS	1.75 NS
Indaziflam	1.75 NS	2.25 NS	2.12 NS	1.83 NS
Oxyfluorfen + Chlorimuron	1.83 NS	2.12 NS	2.12 NS	1.75 NS
CV (%) =	10.83	16.18	10.57	9.83

[1]Days after application; CV = coefficient of variation; NS not significant.

Table 15: Branch length in the lower, middle, and upper thirds of the cultivar Catuaí Amarelo IAC 62 in the experimental area of Paraguaçu/MG evaluated at 30, 60, 90 ,and 120 days after application.

Treatments	30 DAA[1]	60 DAA	90 DAA	120 DAA
Branch length lower third (cm)				
Unweeded control	112.50 NS	103.75 NS	128.75 NS	102.00 NS
Weeded control	88.25 NS	104.25 NS	135.00 NS	97.25 NS
Sulfentrazone + Diuron	103.50 NS	103.00 NS	135.00 NS	91.75 NS
Sulfentrazone + Diuron	101.00 NS	101.50 NS	135.00 NS	92.50 NS
Sulfentrazone + Diuron	101.25 NS	103.25 NS	132.50 NS	90.50 NS
Sulfentrazone + Diuron + Indaziflam	104.25 NS	104.25 NS	140.00 NS	98.50 NS
Indaziflam	108.25 NS	103.25 NS	135.00 NS	98.00 NS
Oxyfluorfen + Chlorimuron	111.75 NS	102.25 NS	136.25 NS	93.00 NS
CV (%) =	19.21	6.30	6.23	10.13
Branch length middle third (cm)				
Unweeded control	76.50 NS	79.25 NS	77.00 NS	75.75 NS
Weeded control	73.75 NS	82.00 NS	80.00 NS	88.50 NS
Sulfentrazone + Diuron	70.50 NS	78.75 NS	78.75 NS	69.00 NS
Sulfentrazone + Diuron	72.50 NS	78.50 NS	83.75 NS	80.25 NS
Sulfentrazone + Diuron	78.75 NS	79.75 NS	78.75 NS	70.50 NS
Sulfentrazone + Diuron + Indaziflam	81.25 NS	86.00 NS	78.75 NS	73.00 NS
Indaziflam	80.00 NS	77.50 NS	80.00 NS	82.50 NS
Oxyfluorfen + Chlorimuron	78.75 NS	77.00 NS	78.75 NS	81.25 NS
CV (%) =	7.03	7.01	7.80	13.09
Branch length upper third (cm)				
Unweeded control	42.75 NS	51.75 NS	35.00 NS	54.75 NS
Weeded control	44.25 NS	56.50 NS	35.00 NS	54.00 NS
Sulfentrazone + Diuron	47.25 NS	53.25 NS	35.00 NS	51.25 NS
Sulfentrazone + Diuron	48.25 NS	54.50 NS	33.75 NS	51.00 NS
Sulfentrazone + Diuron	43.75 NS	56.50 NS	37.50 NS	53.00 NS
Sulfentrazone + Diuron + Indaziflam	46.50 NS	53.50 NS	40.00 NS	54.25 NS
Indaziflam	42.25 NS	55.75 NS	35.00 NS	48.25 NS
Oxyfluorfen + Chlorimuron	42.50 NS	57.75 NS	38.75 NS	47.50 NS
CV (%) =	9.88	11.04	22.07	17.86

[1]Days after application; CV = coefficient of variation; NS not significant.

3 DISCUSSION

All evaluations were conducted up to 120 DAA, to determine the residual period of each herbicide (Rodrigues; Almeida, 2018), and to consider that each crop has a certain period where it is more sensitive to productivity losses due to weed competition. According to Pitelli (1985), this interval is known as the critical period of interference prevention (CPIP), when weeds and crops are directly contending for environmental resources; therefore, the management of the weed community must be effective during this particular time.

For coffee, weed competition is most critical during the months from October to March, coinciding with the flowering and fruiting season, as the coffee plant has a greater demand for photoassimilates (Blanco; Oliveira; Pupo, 1982), although competition occurs throughout the year, mainly during rainy periods for nutrients and dry periods for water (Fialho et al., 2012). Therefore, it is important to understand the residual period of a herbicide, not only to increase the control period in the area, but also to reduce the number of applications of a product such as glyphosate, which is the most globally used herbicide in agriculture, to mitigate the problems arising from resistance in post-emergence conditions (Galli; Montezuma, 2005; Duke; Powles, 2008).

However, although the number of residual days is described in the literature, each herbicide has different physicochemical characteristics and formulations that interact with soil attributes and environmental conditions and directly affect its permanence period in the soil and its herbicide activity (Rossi et al., 2013).

Another factor in the evaluation of control percentage was the minimum efficacy level of 80%, with some statistical differences by the Scott-Knott test, because according to Frans et al. (1986), the minimum acceptable control efficacy for a herbicide treatment is 80%, which is the percentage required for registration of the product for treatment of a particular weed species. For the treatments with efficacies below 80%, it is necessary to consider the increase in herbicide dose to ensure a longer residual period, complementing what was lost during this exposure time.

Overall, the results of the research were satisfactory, as the pre-emergence control effectiveness for the herbicides tested and the species found in the experimental areas were proven (Rodrigues; Almeida, 2018), with a decrease in control over the course of the evaluations, although, the results for *D. nuda* were the lowest found for the treatments of sulfentrazone + diuron, at less than 35% (Table 4). This can be explained by the tolerance of this species to photosystem II inhibitor herbicides, in this case diuron, herbicide that would be responsible for the spectrum of control of this species, although this was not observed in other species such as *D. horizontalis* and *D. ciliaris* (Dias et al., 2007).

Many phytotoxicity cases occur, with the majority due to inadequate use of the product, either by inappropriate dosing, unfavorable environmental conditions, or errors in the application technology. Understanding the peculiarity of each herbicide component is extremely important for selectivity; for example, the use of a dose higher than that recommended by the manufacturer may lead to the loss of the selective property (Oliveira Junior; Inoue, 2011; Magalhães et al., 2012).

The term selectivity is not absolute because it depends on several factors related to the application. For a herbicide to be considered selective to a crop, it must kill or significantly delay the growth of the weed, without causing damage to the crop of interest. Nevertheless, selectivity cannot be based only on visual symptoms of phytotoxicity, since the herbicide may cause internal disorders in plants, thereby reducing their productive potential (Negrisoli et al., 2004). Thus, adding biometric evaluations to the phytotoxicity analyses provides more conclusive results.

Table 16: Number of nodes and internode distance of the cultivar Catuaí Amarelo IAC 62 in the experimental area of Paraguaçu/ MG evaluated at 30, 60, 90, and 120 days after application.

Treatments	30 DAA[1]	60 DAA	90 DAA	120 DAA
	Number of nodes			
Unweeded control	4.75 NS	6.25 NS	6.50 NS	4.75 NS
Weeded control	5.25 NS	6.75 NS	6.25 NS	5.00 NS
Sulfentrazone + Diuron	4.50 NS	6.50 NS	6.25 NS	4.75 NS
Sulfentrazone + Diuron	5.00 NS	6.00 NS	5.75 NS	5.00 NS
Sulfentrazone + Diuron	4.75 NS	5.75 NS	6.25 NS	5.00 NS
Sulfentrazone + Diuron + Indaziflam	5.25 NS	5.75 NS	5.75 NS	5.50 NS
Indaziflam	5.00 NS	6.50 NS	6.25 NS	5.00 NS
Oxyfluorfen + Chlorimuron	4.75 NS	5.25 NS	6.00 NS	4.75 NS
CV (%) =	11.26	12.49	8.36	7.16
	Internode distance (cm)			
Unweeded control	1.95 NS	1.60 NS	1.54 NS	2.12 NS
Weeded control	1.95 NS	1.48 NS	1.60 NS	2.00 NS
Sulfentrazone + Diuron	1.87 NS	1.56 NS	1.60 NS	2.12 NS
Sulfentrazone + Diuron	2.00 NS	1.69 NS	1.75 NS	2.00 NS
Sulfentrazone + Diuron	2.12 NS	1.77 NS	1.60 NS	2.00 NS
Sulfentrazone + Diuron + Indaziflam	1.91 NS	1.75 NS	1.75 NS	1.83 NS
Indaziflam	2.00 NS	1.54 NS	1.60 NS	2.00 NS
Oxyfluorfen + Chlorimuron	1.88 NS	1.95 NS	1.66 NS	2.12 NS
CV (%) =	10.11	13.68	8.30	8.01

[1]Days after application; CV = coefficient of variation; NSnot significant.

Under the experimental conditions evaluated, herbicide applications were conducted in a way to preserve the coffee plant from coming into contact with the product, by applying them in the center of the inter-rows, although drifting and/or root absorption of the products could occur. Moreover, coffee plants can become more tolerant to herbicides as they age (Magalhães et al., 2012), and since the plants were 9 years old, this is the most plausible justification for the results found.

The herbicides sulfentrazone and oxyfluorfen are PPO inhibitors, and can present herbicidal activity with applications in both pre- and post-emergence conditions. The selectivity in adult plants is likely related to the rapid metabolization, along with the absence of translocation within the plant, which ensures the quality of meristems, since they have not come into contact with the herbicide (Arruda; Lopes; Bacarin, 1999; Carvalho; López-Ovejero, 2008).

4 CONCLUSIONS

All herbicide treatments were effective for all weeds evaluated, apart from *D. nuda*, until 60 DAA. Subsequent to that time, it was necessary to increase the dose for the herbicides with shorter residual effects.

For *D. nuda*, the most effective treatments were those containing indaziflam alone or in combination with sulfentrazone + diuron, as well as oxyfluorfen + chlorimuron until 60 DAA.

In both experiments and over all treatments, the herbicides containing indaziflam guaranteed efficacy higher than 80%, even at 120 DAA.

All treatments were equally selective to coffee plants under the conditions evaluated.

5 AUTHORS' CONTRIBUTIONS

AGN conducted the experiments and supervised the research; JCP wrote the manuscript; LSR data analysis and data interpretation; MRM conducted the experiments; JFA data collection and curation; MN and SJPC review and approved the final version of the work; MRR and MBTM made it possible to implement the experiments. All authors read and agreed to the published version of the manuscript.

6 ACKNOWLEDGMENTS

The authors would like to thank FMC Agrícola and Agro do Mato Soluções Agronômicas.

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