Managing itchgrass and morningglory in plant cane: a strong decision on associating herbicides for pre-emergence control

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Abstract

To enhance weed control in sugarcane systems, the application of herbicide association is widely practiced. This approach broadens the spectrum of weed control and ensures a successful sugarcane yield. Therefore, this study aimed to assess the efficacy of herbicide combinations in controlling *Rottboellia exaltata* (itchgrass) and *Ipomoea quamoclit* (morningglory) during pre-emergence while also evaluating the potential impact on the sugarcane variety RB85 5156. The experimental design employed a randomized block structure with seven treatments and four replications. The treatments were as follows: 1 - no herbicide application; 2 - indaziflam + sulfentrazone (120 + 750 g i.a ha^{-1}); 3 - indaziflam + diclosulam (120 + 110 g i.a ha^{-1}); 4 - indaziflam + tebuthiuron (120 + 900 g i.a ha^{-1}); 5 - flumioxazin + diclosulam (150 + 110 g i.a ha^{-1}), 6 - flumioxazin + pyroxasulfone (200 + 200 g i.a ha^{-1}) and 7 - clomazone + sulfentrazone (1,080 + 750 g i.a ha^{-1}). The following parameters were evaluated: percentage of itchgrass and morningglory control, green coverage percentage (Canopeo® system), weed biomass (g m^{-2}), and itchgrass height. Tiller counts were also assessed to characterize the effects of the herbicides on sugarcane plants. Several herbicide associations have been proven effective alternatives for managing itchgrass and morningglory. The most successful treatments for itchgrass control were indaziflam + tebuthiuron and indaziflam + diclosulam, whereas for morningglory, the top performers were indaziflam + sulfentrazone, indaziflam + diclosulam, indaziflam + tebuthiuron, flumioxazin + diclosulam, and clomazone + sulfentrazone. All treatments significantly reduced the weed biomass, with indaziflam + tebuthiuron being the safest option for protecting sugarcane.

1. Introduction

In Brazil, sugarcane (*Saccharum* spp.) production has an important position due to its favorable edaphoclimatic conditions that permit great results in the potential yield, representing nearly 40% of world sugarcane production (FAO 2021). However, there are many factors that can damage crop yield (Presoto et al. 2022), such as weed infestation (Azania et al. 2002; Araldi et al. 2015), soil compaction (Cherubin et al. 2021), and harvesting or planting without traffic control (Castioni et al. 2021). Therefore, it is necessary to adjust the agronomic practices, such as improving weed control using herbicides in the early crop stage of pre-emergence, to augment agronomic efficiency and achieve better results in the field, by increasing the stalk and sugar yield (Castro et al. 2023; Araldi de Castro et al. 2023).

Especially for sugarcane crops, it is important to have a strong agronomic activity plan during the plant cane cycle, mainly in the planting operation, considering the relevant cost of soil preparation and planting (~ U$$ 3,200 per hectare) – (Conab 2022). Furthermore, it is important to emphasize that in Brazil the area destined for renewable operations (sugarcane planting), represents 11% of the total sugarcane area in Brazil. In this context, new knowledge in weed science that contributes to achieving better agronomic efficiency in sugarcane is welcome, increasing the production, and reducing the costs (Bordonal et al. 2018).

One area that needs new studies is the weed control in plant cane (Santos et al. 2011; Presoto et al. 2022), because the crop and the weed begin the emergence process at the same time (after the planting). Therefore, the weed interference is very critical in planting cane because of the weed community, the crop itself, the time and the duration of the co-existence period between the crop and the weed (Kuva et al. 2000; Freitas et al. 2004). For weed management in sugarcane, the most used method is herbicide application under pre-emergence conditions, as it ensures a prolonged residual effect and control effectiveness during the critical period of competition with the sugarcane crop (Mascarenhas et al. 1995; Carbonari et al. 2010; Toledo et al. 2015; Ghirardello et al. 2021; Presoto et al. 2022). Another aspect that is crucial to know the composition of the weed community present in the field, given that this information would enable decision-making about the herbicide molecule to apply on the field after the planting.

In the last decade, a new problem has arisen in weed control: Although several herbicides are recommended for sugarcane cultivation, little is known about their efficiency in controlling *Rottboellia exaltata* (Freitas et al. 2004). *Rottboellia*, a small genus of grasses including five species, belongs to the family Poaceae (Sun and Phillips 2006). It is known to cause significant agricultural losses in subtropical and tropical regions, especially in sugarcane cultivation (Lencse and Griffin 1991;

Millholon 1992; Correia et al. 2013; Spaunhorst 2020). This species is listed among the world's most problematic weeds (Millhollon and Burner 1993; Funez et al. 2016). Very vigorous and prolific, a single plant is capable of issuing up to 100 tillers and producing 15,000 seeds, which remain dormant in the soil for up to four years (Lorenzi 2000; Freitas et al. 2004; Correia et al. 2013). The seeds are small and exhibit rapid germination and field colonization (Silva et al. 2021). In Brazilian sugarcane fields (Oliveira and Freitas 2009; Correia 2016), the occurrence of *R. exaltata* promoted losses of up 80% in ratoon cane and 100% in plant cane (Arévalo and Bertoncini 1994; Sousa et al. 2020). Therefore, Correia and Gomes(2014) also highlighted a reduction in yield for ratoon cane with a high infestation of *R. exaltata*, in this case, with losses of 56%. Two *R. exaltata* biotypes commonly infest sugarcane in Louisiana (Spaunhorst 2020).

Another weed problem in sugarcane crops is the morningglory species. The genus *Ipomoea*, belonging to the Convolvulaceae family is traditionally known as morningglory. Among the many characteristics of this family, the one that stands out is production, in which it is possible to produce 50–300 diaspores per plant. From these, only a small percentage germinate quickly; the others germinate randomly through time (Kissmann and Groth 1999; Toledo et al. 2017). It has been reported that the competition from *Ipomoea* spp. can reduce the production of sugarcane stalks from 27–36% (Jones and Griffin 2009; Bhullar et al. 2012). Thus, tackling morningglory in the sugarcane fields is a serious challenge for producers and agriculture technicians (Bhullar et al. 2012).

To achieve better control of these weeds – *Rottboellia exaltata* and *Ipomoea quamoclit* – in plant cane, it is necessary to use more than one herbicide molecule in the same application. The application of an association of herbicides is a widespread practice in weed management in Brazil and worldwide (Sousa et al. 2020). Azania et al. (2009) observed positive control over weeds of the genus *Ipomoea* by using amicarbazone and sulfentrazone herbicides in pre-emergence. Against the morningglory species *Ipomoea quamoclit*, (Toledo et al. 2015) observed that pre-emergence sulfentrazone and sequential tebuthiuron application provided an excellent level of control (100%). Therefore, finding efficient herbicides against monocot and eudicot weeds that are selective for sugarcane has become necessary (Silva et al. 2021). The association of amicarbazone + isoxaflutole + indaziflam applied in pre-emergence provided a satisfactory level of control over itchgrass, namely 92% at 120 DAA, while also ensuring good selectivity for sugarcane. The isolated tebuthiuron treatment proved to be inefficient for controlling itchgrass, providing only 32.5% in relation to the control (Moita 2022).

Among the advantages observed after applying an association of herbicides are synergism, elevation of the control spectrum, facilitation in the management of resistant species, an increased residual period resulting from the different characteristics of the products, and decreased production costs, thus making the application by the broad spectrum of control more efficient (Riley and Bradley 2014; Souza et al. 2020; Presoto et al. 2022). Herbicide associations that result in antagonistic effects negatively influence the performance of herbicides, and may result in incompatibility or require an increase in the dose and/or separate application of herbicides. On the other hand, associations that result in synergistic or additive effects are of interest, because they allow an increase in the spectrum of action and the use of lower doses (Trezzi et al. 2016; Presoto et al. 2022).

The hypotheses of the present study were: a) the herbicide association adopted during pre-emergence produces excellent control of weeds and guarantees selectivity for the sugarcane; b) the weed emergence in the area with herbicide application shows a reduction development - less aboveground and belowground biomass development. Thus, this research aimed to verify the efficiency of herbicide associations in the control of *R. exaltata* and *I. quamoclit* in pre-emergence, and to verify the presence or absence of intoxication in the sugarcane crop – plant cane cycle.

2. Material and methods

Site Description

The experiment was conducted at AgroQuatro-S Experimentation and Applied Agronomic Consultancy, located in Sales Oliveira, Sao Paulo state, Brazil, 20º51'35" S, 47º56'24" W and altitude of 575 m. Sugarcane planting occurred in March 2023 with mechanical planting using the bud density equaling 24 viable buds per meter. The sugarcane variety adopted in the area was RB855156, which is responsive, adapted to cultivation in a green cane system, precocious and exhibits good tillering.

After the soybean harvest during the renewable period, and before the installation of the experiment, the soil was sampled at different depths, namely 0-0.2, 0.2–0.4 and 0.4-0.6m, and characterized by chemical and physical attributes, according to the methodology described by Raij et al. (2001) and Embrapa (2018), respectively. Considering the soil fertility and physical attributes, the soil was classified through Eutrudox (Staff 2014) as having a very clayey texture (Table 1); the Brazilian soil classification system is Rhodic Oxissoil (Embrapa 2018). The fertilizer rates adopted were 40, 150 and 80 kg ha^{-1} of N, P_2O_5 and K_2O, respectively, applied at the planting moment.

Table 1
Soil fertility characterization and physical attributes evaluated, before the treatment application in the sugarcane ratoon area. Sales de Oliveira/SP – 2023.

Layer	————Soil Fertility parameters————												Soil Physical attributes			
	pH	SOM	S	P	K	Ca	Mg	H + Al	Al	BS	CEC	V	Sandy	Clay	Silt	Texture
m	$CaCl_2$	g dm^{-3}	-mg dm^{-3}-		——— mmol$_c$ dm^{-3} ———							%	—— g kg^{-1} ——			
0-0.2	5.4	26	7	54	10.5	49	15	31	0	74	106	70	105	532	363	C
0.2–0.4	5.3	20	20	37	2.2	29	7	31	0	38	69	55	90	594	316	C
0.4–0.6	5.5	15	25	7	1.1	19	5	22	0	25	47	53	85	665	250	VC

SOM – Soil Organic Matter; BS – Sum of Bases; CEC – Cation Exchange Capacity; V – Bases Saturation; C – clayey; VC – very clayey. The soil fertility parameters were evaluated by the methodology described by Raij et al. 2001, and the soil physical attributes were evaluated by the Embrapa 2018 methodology.

Experimental design and herbicide treatments

The experimental design adopted was randomized blocks with seven treatments and four replications. Each plot consisted of 6 sugarcane rows with a length of 5 m. The sugarcane inter-row spacing adopted in the experimental field was 1.5 m. The main area in each plot was considered to be the four central rows. The weeds were sown within each plot in subplots of 1.0 x 1.0 m and embedded at depths from 0 to 0.04 m. Two weeds were sown: *Rottboellia exaltata* and *Ipomoea quamoclit* using a quantity of seeds to obtain 50 emerged plants per square meter.

The treatments adopted were as follows: 1 - without herbicide application (control); 2 - indaziflam + sulfentrazone (120 + 750 g i.a ha^{-1}); 3 - indaziflam + diclosulam (120 + 110 g i.a ha^{-1}); 4 - indaziflam + tebuthiuron (120 + 900 g i.a ha^{-1}); 5 - flumioxazin + diclosulam (200 + 110 g i.a ha^{-1}), 6 - flumioxazin + pyroxasulfone (200 + 200 g i.a ha^{-1}) and 7 - clomazone + sulfentrazone (1,080 + 750 g i.a ha^{-1}).

The herbicide application was done at 2 days after the planting (DAP), in each experimental plot in total pre-emergence of weed and sugarcane crop. For this application, a backpack sprayer was used, at constant pressure (maintained by compressed CO_2) of 2.2 kgf / kgF cm^{-2}, equipped with a bar containing four-point 11003 AD flat jet spray nozzles, spaced 0.25 m apart, and with a spray consumption equivalent to 200 L ha^{-1}. At the time of application, the values were recorded for air temperature (26.3°C), relative humidity (88%), and wind speed (1.3 km h^{-1}).

Data assessment

Regarding the parameters evaluated, the control percentages of *R. exaltata* and *I. quamoclit* was measured at 7, 15, 30, 45 and 90 days after application (DAA) of herbicides. The evaluation of visual symptoms of control plants was performed using a scoring scale from 0 to 100%, where zero represents the absence of control and 100 represents the death of the plant (Gazziero 1995). These control scores were established as a function of the control kept infested throughout the experimental period, without herbicide application in pre-emergence. Furthermore, in the same evaluation period, visible injuries on the sugarcane plants were assessed; percentage scores were also assigned for the control (Gazziero 1995). Itchgrass height was evaluated at 30, 45, and 90 DAA. Because of morphological issues in relation to *I. quamoclit*, its height was not recorded.

The percentage of green coverage (%) was measured at 90 DAA by the Canopeo® system. According to Patrignani and Ochsner (2015), the fractional green canopy coverage can be calculated using the mobile device application Canopeo® (Oklahoma State University, Stillwater, OK), which automatically classifies pixels as green or not green. The app can access the phone camera (mounted on a drone) and analyze and classify all pixels in the image using color values in the red-green-blue system (Patrignani and Ochsner 2015; Campana et al. 2023). It turns the color green into white with a smooth manual adjustment and produces the percentage of white pixels in a given frame that corresponds to the pixels that meet the selection criteria green canopy (Campana et al. 2023). The software Canopeo® permits rapid measurement and allows user-friendly measurements (Bourega et al. 2023).

At 90 DAA of the herbicides, the aboveground and belowground biomasses (g m^{-2}) of the weeds per square meter in the plots were quantified. Thus, the collection of itchgrass and morningglory (green mass) was carried out in an area of 1.0 m^{-2} per plot; this material was separated into aboveground and belowground, weighed and then kept in an oven with air circulation at 65° for 5 days for drying and weighing (dry mass). The number of tillers was evaluated in each plot to characterize the herbicides' effects on the sugarcane plants in June 2023 (90 DAA). In all rows of the plot, the number of tillers per meter was counted, and the mean of the treatments was used.

Throughout the experimental period, the weather conditions were monitored by the automatic weather station installed near the area. Furthermore, the weather metadata and water balance (Fig. 1) were calculated according to the methodology described by Thornthwaite and Mather.

Data analysis

All the data sets were submitted to ANOVA variance analysis (Test F). Following the principles of data normality, the means of the variables were compared using Tukey's test ($p < 0.1$). Statistical analyses were performed using the software AgroEstat (Barbosa and Maldonado Junior 2015). In addition, a correlation was obtained between percentage of green coverage and percentage of itchgrass control.

3. Results

Weather conditions during the experimental period

During the entire experimental period, which ranged from the sugarcane planting (March 2023), installation and evaluation of treatments (herbicides association), ending in June 2023, the accumulated rainfall was 559.7 mm, and the average temperature was 20.7° C (Fig. 1). The highest water surplus and deficit were 216.9 mm and − 15.6 mm, respectively, and occurred in March 2023 and June 2023. It is important to note that 33% of the accumulated rainfall in the year of 2023 (1,329 mm) occurred during the experimental period (Fig. 1), indicating that this high soil moisture and rainfall period and accumulation affect the herbicide interactions between soil and weed control.

Percentage of itchgrass and morningglory control (%) and the agronomic costs

There was a difference between the herbicides treatments for all moments evaluated − 7, 15, 30, 45, and 90 DAA (Table 2) − in relation to percentage of control, considering the two weeds, itchgrass and morningglory, and the herbicide treatment with control (without herbicide application).

Against itchgrass, at 7 DAA the best control results were registered for the following treatments: indaziflam + tebuthiuron (100%); indaziflam + diclosulam (94%) and flumioxazin + pyroxasulfone (98%). In a second category of control were indaziflam + sulfentrazone (86%) and clomazone + sulfentrazone (79%) and the lowest percentage of itchgrass control was flumioxazin + diclosulam (5%). The control trend for itchgrass at 7 DAA was maintained for the other evaluations. Only flumioxazin + diclosulam increased the control percentage by 26% and clomazone + sulfentrazone reduced the control by 21% in the 7 days between the first evaluation and the second one (15 DAA). The treatments clomazone + sulfentrazone and flumioxazin + pyroxasulfone decreased the itchgrass control percentage with the evolution of the evaluations.

At 30 DAA the best treatments maintained were indaziflam + tebuthiuron and indaziflam + diclosulam with respective control levels of 100% and 96%. Furthermore, these treatments (herbicides association) maintained excellent control until the end of the experiment, at 90 DAA. During this monitoring period, there was no presence of itchgrass seedlings in any experimental plot of the indaziflam + tebuthiuron association.

The associations of herbicides presented, in general, excellent control of morningglory (*I. quamoclit*). All treatments recorded control values very close to 100% at 7 and 15 DAA. Initially (7 DAA), flumioxazin + diclosulam treatment showed a low control percentage (16%), but at 15 DAA, this value increased to 98%. At 30 DAA, the flumioxazin + pyroxasulfone treatment showed 95% control, differing from the others with even better control values. The associations with indaziflam ensured 100% control while the other treatments, at 95 to 98%, were also considered optimal (Table 2).

At 45 DAA, there were percentage decreases in control levels produced by flumioxazin + diclosulam, flumioxazin + pyroxasulfone, and clomazone + sulfentrazone, oscillating between 80 and 90%. However, at 90 DAA, the only significant difference was recorded for flumioxazin + pyroxasulfone, with a lower control percentage (79%) than the others, which registered above 94% (Table 2).

Table 2
Percentage of control (%) of itchgrass (*Rottboellia exaltata*) and morningglory (*Ipomoea quamoclit*) associated with herbicide molecules, applied in the pre-emergence period of the crop and the weeds at five evaluation times (7, 15, 30, 45 and 90 DAA). Sales de Oliveira/SP, 2023.

Herbicides	**Evaluation time (*Rottboellia exaltata*)**				
	7 DAA	**15 DAA**	**30 DAA**	**45 DAA**	**90 DAA**
Indaziflam + Sulfentrazone	86 bc	95 b	83 c	83 bc	77 b
Indaziflam + Diclosulam	94 ab	99 ab	96 ab	98 ab	97 a
Indaziflam + Tebuthiuron	100 a	100 a	100 a	100 a	100 a
Flumioxazin + Diclosulam	5 d	31 d	16 e	26 d	33 c
Flumioxazin + Pyroxasulfone	98 a	98 ab	90 bc	78 c	80 b
Clomazone + Sulfentrazone	79 c	58 c	45 d	35 d	40 c
LSD (10%)	9	4	8	12	13
CV (%)	10	5	9	14	15
Herbicides	Evaluation time (*Ipomoea quamoclit*)				
	7 DAA	15 DAA	30 DAA	45 DAA	90 DAA
Indaziflam + Sulfentrazone	100 a	100 a	100 a	98 a	97 a
Indaziflam + Diclosulam	99 a	100 a	100 a	99 a	98 a
Indaziflam + Tebuthiuron	100 a	100 a	100 a	98 a	97 a
Flumioxazin + Diclosulam	16 b	98 b	98 ab	88 b	94 a
Flumioxazin + Pyroxasulfone	99 a	99 a	95 b	79 c	84 b
Clomazone + Sulfentrazone	100 a	99 a	97 ab	90 b	96 a
LSD (10%)	4.0	1.5	3.8	14.0	9.8
CV (%)	3	1	3	12	8

Means followed by the same lowercase letter in the column do not differ from each other according to Tukey's test at the 10% probability level.

One aspect critical for weed control is the agronomic cost that the farmer and/or mill may spend to buy and apply the herbicide molecules obtained. In particular, in our study, the agronomic cost calculated for the 2023 season according to the treatments were: indaziflam + sulfentrazone (US$ 93 per hectare); indaziflam + diclosulam (US$ 97 per hectare); indaziflam + tebuthiuron (US$ 77 per hectare); flumioxazin + diclosulam (US$ 75 per hectare), flumioxazin + pyroxasulfona (US$ 90 per hectare); clomazone + sulfentrazone (US$ 82 per hectare). In this context, the association indaziflam + tebuthiuron not only provides good weed control but also is cheaper than the other associations.

Itchgrass height

In the present study, at 30 DAA, the best treatment, indaziflam + tebuthiuron, did not present plants for evaluation. Notwithstanding, considering the other treatments, the association between indaziflam + diclosulam and flumioxazin + pyroxasulfone showed a shorter itchgrass height – 0.04m for the first and 0.09m for the second association cited in this paragraph. The other treatments found values close to 0.13 m in height versus 0.17 m in the control (Table 3).

Table 3
Height (m) of itchgrass (*Rottboelia exaltata*) associated with herbicide molecules, applied in the pre-emergence period of the crop and the weed at three evaluation times (30, 45 and 90 DAA) and the growth per day tax (mm) (GPD) between the first and the last evaluation. Sales de Oliveira/SP, 2023.

Herbicides	**Evaluation time (*Rottboelia exaltata*)**			**Growth per day (GPD)**
	30 DAA	**45 DAA**	**90 DAA**	
Control	0.17 d	0.67 d	1.12 e	158 d
Indaziflam + Sulfentrazone	0.13 cd	0.40 bc	0.50 c	62 b
Indaziflam + Diclosulam	0.04 ab	0.12 a	0.20 b	27 a
Indaziflam + Tebuthiuron	0.00 a	0.00 a	0.00 a	00 a
Flumioxazin + Diclosulam	0.13 cd	0.47 c	0.72 d	97 c
Flumioxazin + Pyroxasulfone	0.09 bc	0.30 b	0.72 d	103 c
Clomazone + Sulfentrazone	0.14 cd	0.49 c	0.73 d	99 c
LSD (10%)	0.06	0.13	0.20	0.30
CV (%)	38	29	28	31

Means followed by the same lowercase letter in the column do not differ from each other according to Tukey's test at the 10% probability level.

At 45 DAA, the indaziflam + diclosulam treatment had a shorter height (0.12 m) than the others. The treatment sequence was: flumioxazin + pyroxasulfone (0.30 m) and indaziflam + sulfentrazone (0.40 m). The third classification of lower itchgrass height was: indaziflam + sulfentrazone (0.40 m); flumioxazin + diclosulam (0.47 m) and clomazone + sulfentrazone (0.49 m) and finally, the tallest of all, the control treatment with a mean height of 0.67 m.

At 90 DAA, the classifications from the shortest to tallest plant height were: indaziflam + tebuthiuron (0.00 m); indaziflam + diclosulam (0.20 m); indaziflam + sulfentrazone (0.50 m); flumioxazin + pyroxasulfone (0.71 m); flumioxazin + diclosulam (0.71 m); clomazone + sulfentrazone (0.73 m) and control (1.12 m) (Table 3).

The rate of growth per day (GPD) was calculated considering the height of the plant measured between 30 DAA – first evaluation and 90 DAA – last evaluation, totaling 60 days of monitoring. The treatment indaziflam + tebuthiuron produced the best result due to the absence of this weed's emergence. In other treatments, in which weeds emerged, the control showed the greatest weed growth (158 mm per day), followed by flumioxazin + diclosulam (97 mm per day); flumioxazin + pyroxasulfone (103 mm per day), and clomazone + sulfentrazone (99 mm per day). The other groups that showed a low growth rate (better control of the weed growth) were comprised of indaziflam + sulfentrazone (62 mm per day); indaziflam + diclosulam (27 mm per day) – Table 3.

Green coverage percentages of itchgrass and morningglory by CANOPEO®

The two weed species differed in their green coverage percentages as a function of the herbicide treatments by Canopeo®. First, itchgrass presented a minimal difference in green coverage percentages between the treatments indaziflam + tebuthiuron (0.00%) and indaziflam + diclosulam (0.22%), with emphasis on treatments with better control, followed by treatments indaziflam + sulfentrazone (4.44%). and flumioxazin + pyroxasulfone (5.80%) in the second group. A third group with a slightly higher percentage of green coverage includes the treatments flumioxazin + diclosulam (11.90%) and clomazone + sulfentrazone (12.50%) and finally, the standard treatment control with 30.90% of green cover (Table 4).

Table 4
Percentage of green coverage (%) by Canopeo® system for herbicide treatments applied in the pre-emergence period of the crop and the weed, and evaluation done at 90 DAA. Sales de Oliveira/SP, 2023.

Herbicides	**% of green coverage**	
	Itchgrass	**Morningglory**
Control	30.89 d	25.43 b
Indaziflam + Sulfentrazone	4.44 b	0.12 a
Indaziflam + Diclosulam	0.22 a	0.04 a
Indaziflam + Tebuthiuron	0.00 a	0.23 a
Flumioxazin + Diclosulam	11.90 c	1.54 a
Flumioxazin + Pyroxasulfone	5.81 b	1.15 a
Clomazone + Sulfentrazone	12.51c	1.35 a
LSD (10%)	3.7	3.9
CV (%)	32.0	34.6

Means followed by the same lowercase letter in the column do not differ from each other according to Tukey's test at the 10% probability level.

When data from herbicide treatments for itchgrass are calculated as a percentage of the control treatment, we have the following green coverage percentages, from lowest to highest: 0.0%; 0.7%; 14%; 19%; 38% and 40%, respectively, for the treatments indaziflam + tebuthiuron; indaziflam + diclosulam; indaziflam + sulfentrazone; flumioxazin + pyroxasulfone; flumioxazin + diclosulan and clomazone + sulfentrazone.

Regarding the evaluated morningglory (*I. quamoclit*), there was a difference only between the control treatment and the other herbicide treatments, which did not differ among themselves when evaluated by Canopeo®. In the correlation performed, only for itchgrass, between the percentage of control and the percentage of green coverage, there was a well-adjusted linear regression (Fig. 2). In general, when the condition of itchgrass control of 80% occurs, there will be green coverage of approximately 15% present in the area.

Biomass to itchgrass and morningglory (aboveground and belowground)

Regarding the dry mass (biomass) data in grams per square meter (aboveground and belowground) of itchgrass and morningglory, there was a difference between the herbicide treatments used in the experiment, and they followed the trend of the other monitored parameters and provided the best treatments (Table 5). In the case of itchgrass, the aboveground biomass percentages of the control treatment were 0%, 0.25%, 7.7%, 10.5%, 24.4%, and 35.4%, respectively, for indaziflam + tebuthiuron, indaziflam + diclosulam, indaziflam + sulfentrazone, flumioxazin + pyroxasulfone, flumioxazin + diclosulam, and clomazone + sulfentrazone.

Table 5

Aboveground and belowground biomass (g m^{-2}) of itchgrass (*Rottboellia exaltata*) and morningglory (*Ipomoea quamoclit*) when associated with herbicide molecules and applied in the pre-emergence period of the crop and the weed at 90 DAA. Sales de Oliveira/SP, 2023.

Herbicides	itchgrass		morningglory	
	Above-ground	Below-ground	Above-ground	Below-ground
Control	579.9 e	56.9 d	363.3 c	24.0 c
Indaziflam + Sulfentrazone	45.0 b	6.6 b	0.6 a	0.1 a
Indaziflam + Diclosulam	1.5 a	0.4 a	0.0 a	0.0 a
Indaziflam + Tebuthiuron	0.0 a	0.0 a	0.0 a	0.0 a
Flumioxazin + Diclosulam	141.3 c	15.6 c	2.5 a	0.2 a
Flumioxazin + Pyroxasulfone	61.1 b	6.9 b	35.6 b	3.6 b
Clomazone + Sulfentrazone	205.5 d	16.2 c	5.4 a	0.8 ab
LSD (10%)	43.1	6.5	23.8	3.2
CV (%)	26	36	33	34

Means followed by the same lowercase letter in the column do not differ from each other according to Tukey's test at the 10% probability level.

The belowground biomass displayed the same behavior, in which the best values related to the lowest belowground biomass were the treatments in association with indaziflam and flumioxazin + pyroxasulfone. The others: clomazone + sulfentrazone and flumioxazin + diclosulam, obtained a belowground biomass average of 28% of the control treatment.

In general, the treatments against morningglory were highly positive for aboveground biomass, while only flumioxazin + pyroxasulfone was inferior to the control, presenting 10% of the biomass of the control treatment, a result that is still interesting because it reduced the growth of *I. quamoclit* by 90%. For the belowground biomass, the treatment flumioxazin + pyroxasulfone and clomazone + sulfentrazone presented 15% and 3.3% in relation to the control treatment, differing from the others that produced a minimal amount of belowground morningglory biomass (Table 5).

Sugarcane injury level and tiller numbers

The phytointoxication evaluation showed that all the herbicide treatments were safe, and did not produce visual alteration in sugarcane. The sugarcane tiller numbers differed among the treatments, in which the highest and lowest numbers of tillers resulted from indaziflam + tebuthiuron (10.2 tillers.m^{-1}) and flumioxazin + diclosulam (7.7 tillers.m^{-1}). The intermediate values counted in the other treatments ranged from 8 to 9 tillers m^{-1} (Table 6).

Table 6
Number of sugarcane tillers per meter in the experiment with herbicides treatments applied in pre-emergence and evaluated at 90 DAA. Sales de Oliveira/SP, 2023.

Herbicides	Tillers.m^{-1}
Control	8.7 bc
Indaziflam + Sulfentrazone	9.0 b
Indaziflam + Diclosulam	8.2 bc
Indaziflam + Tebuthiuron	10.2 a
Flumioxazin + Diclosulam	7.7 c
Flumioxazin + Pyroxasulfone	9.0 b
Clomazone + Sulfentrazone	8.2 bc
LSD (10%)	1.03
CV (%)	9.6

Means followed by the same lowercase letter in the column do not differ from each other according to Tukey's test at the 10% probability level.

4. Discussion

Several factors influence weed control in sugarcane crop, such as soil moisture, clay content, organic matter, and pH, as well as the physicochemical characteristics of herbicides, such as solubility and vapor pressure (Walker and Welch 1992; Toledo et al. 2015). These factors intervene in the processes of leaching, adsorption and biological degradation, thus affecting the availability and persistence of these herbicide molecules in the soil solution, and consequently interfering in their absorption by the roots of weeds, and in the efficiency of the herbicide (Walker and Welch 1992; Carbonari et al. 2010; Araldi et al. 2011; Silva Junior et al. 2015; Toledo et al. 2015). In our study, some factors contributed to increasing (clayey content, organic matter - Table 1) or decreasing (moisture and herbicide characteristics) the weed control (itchgrass and morningglory). In addition, it is important to highlight that in experiments with weed control, the control percentage is generally considered "very good" when herbicide application achieves 81 to 90% control of weeds, and "excellent" when control exceeds 91 % (Silva et al. 2021).

During the initial evaluation period in our study, the low control percentage of both weeds, mainly in the association of flumioxazin and diclosulan treatment, is related to the low soil moisture during the first 7 days after application (Fig. 1), so that to achieve the herbicide bioavailability in the soil solution, soil moisture is necessary in the first week after application (Silva et al. 2021). On the other hand, when there is high soil moisture, the flumioxazin provides satisfactory weed control (Correia et al. 2013). As to the itchgrass weed in particular, the treatment clomazone + sulfentrazone quickly reduced the control percentage across the evaluation moments. Also in relation to morningglory, the weed control by herbicide association is related to the soil moisture at the application moment, which considering the rainfall amount accumulated along the experimental period (Fig. 1) reduces the herbicide effectiveness on the soil.

One intrinsically important aspect to highlight is the influence of the weed population of itchgrass *R. exaltata* as a function of herbicide control. To exemplify, under conditions of low infestation by *R. exaltata* (6.1 plants m^{-2}), there was no difference among herbicides applied; furthermore, in a situation with high infestation (19.4 plants m^{-2}), the decision-making about herbicide associations, i.e., clomazone + imazapyr, clomazone + isoxaflutole, and sulfometuron + diuron + hexazinone showed better itchgrass control (Correia and Gomes 2014). In our study, some associations promoted better control, whereas others showed lower control of itchgrass (Table 2). The treatment with flumioxazin + pyroxasulfone decreased the percentage of itchgrass control, due to their residual molecules in the soil, attributable to the intense precipitation that was registered during the conduction of the study (Fig. 1). This behavior was reported in other study (Carbonari et al. 2010) in which the application of flumioxazin on the soil promoted good levels of weed control, but the control persistence reduced until 60 DAA, because the residual herbicides applied to the soil depend not only on the specific characteristics of the herbicide, but also mainly on the rainfall amount accumulated after the application of the product and climatic conditions prevailing during and after application.

One herbicide molecule that may provide a long weed control period against itchgrass and/or morningglory, independent of the rainfall accumulated, is indaziflam, as occurred in our study (Table 2). Ghirardello et al. (2021) found that indaziflam (100 g i.a ha^{-1}) provides a long period of controlling weeds of the family Poaceae, including *R. exaltata*, especially in soils of a more clayey texture, as in our situation. Rodrigues et al. (2022) stated that *R. exaltata* was controlled by the herbicide indaziflam at dosages of 75, 150, and 225 mL in pre-emergence, as the control percentages remained high (above 91%) after 84 DAA compared with the control treatment, a fact that expresses the long residual effect of indaziflam (Rodrigues et al. 2022). Control of *R. exaltata* by isolated indaziflam, in the emergence periods at 0, 30, and 60 DAT was over 80% in ratoon cane (Silva et al. 2021). The results obtained by Silva et al. (2021) indicated that the isolated application of indaziflam achieves better control over monocotyledonous species than over eudicot ones. Furthermore, when the indaziflam is associated with other molecules, as adopted in our study using diclosulan, tebuthiuron or sulfentrazone association, control of both itchgrass and morningglory increases significantly. When indaziflam was associated with other molecules, there was good control of *I. quamoclit* (morningglory) and itchgrass (*R. exaltata*). The association of amicarbazone + isoxaflutole + indaziflam applied in pre-emergence provided satisfactory control over itchgrass, 92% at 120 DAA, while also ensuring good selectivity for sugarcane. The isolated tebuthiuron treatment proved to be inefficient in controlling itchgrass, providing only 32.5% in relation to the control (Moita 2022).

The herbicide associations were highly effective for morningglory control, while only at 90 DAA did the association flumioxazin + pyroxasulfone present a lower percentage of control (79%). The herbicide flumioxazin was initially considered a latifolicide, but studies have shown its effectiveness on some grasses when applied in pre-emergence at a rate of 125 g ha^{-1} (Rodrigues and Almeida 2018). Similar results from Carbonari et al. (2010) evidence the effectiveness of flumioxazin in grass species, in which the pre-emergence application of 150 g ha^{-1} has promoted 100% control of the species *Brachiaria decumbens* and *Digitaria horizonthalis*. On the other hand, the herbicide pyroxasulfone is a graminicide with a spectrum of action on some dicotyledons; the pyroxasulfone control was usually above 90% (Presoto et al. 2022). Similar results have been obtained by Marcussi et al. (2018) who, in a study of the efficacy and selectivity of pyroxasulfone in a sugarcane crop, have obtained, in addition to the selectivity for the crop, effective control of the grass weeds at the dose of 150 g ha^{-1}. Other results of effective control in grasses have also been reported by Knezevic et al. (2009) and Olson et al. (2011).

The effectiveness of the association between the herbicides flumioxazin and pyroxasulfone against *Panicum maximum* has been confirmed with applications in pre-emergence conditions with means greater than 90% in relation to the control (Presoto et al. 2022). In our experiment, the morningglory control was inferior to 80% in relation to the association of flumioxazin and pyroxasulfone. Junior et al. (2022) evaluated seven herbicide treatments in associations for controlling 11 types of weeds, and found infestation by diverse weeds in the experimental area. The authors concluded that all associations promoted efficient control, and the treatment with the best result was clomazone + diclosulam. Azania et al. (2009) observed positive control over weeds of the genus *Ipomoea* using the herbicides amicarbazone and sulfentrazone in pre-emergence. Toledo et al. (2015) observed that pre-emergence sulfentrazone and sequential tebuthiuron application provided excellent control of the morningglory species *Ipomoea quamoclit* (100%). Therefore, it has become necessary to find efficient herbicides against monocot and eudicot weeds that are selective for sugarcane (Silva et al. 2021).

The height parameter (Table 3) was measured only for the itchgrass. The species *R. exaltata*, belonging to the Poaceae family, is an annual or perennial C4 grass and reproduces by seeds or from stem pieces. The presence of itchgrass in sugarcane is associated with significant losses in crop production (Correia 2016). *R. exaltata* is an erect annual grass that can grow up to 3 m (Funez et al. 2016). Plant height was recorded for *R. exaltata* in conditions without sugarcane competition, and the respective maximum itchgrass heights for the two biotypes, Louisiana-1 and Louisiana-2, were 2.06 and 1.79 m (Spaunhorst 2020). At the end of our current experiment (90 DAA), the heights ranged from 0.20 to 1.12 m respectively from the best (indaziflam + diclosulam) to the worst treatment (control). The plant heights in the control treatment were not greater than those mentioned in the literature (Funez et al. 2016; Spaunhorst 2020), because the evaluations were carried out up to 90 DAA, the initial phase of seed production.

The itchgrass *R. exaltata* is a cosmopolite weed species that occurs in many countries with sugarcane production, such as Brazil (Carvalho et al. 2005; Ramos et al. 2023), Argentina and Colombia in South America (Arévalo and Bertoncini 1994), and the United States in North America (Sebastian et al. 2017; Spaunhorst 2020). In all locations, this weed species showed a strong and fast crop cycle, where in the final stage, flowering occurs until two months after the emergence. Therefore, new studies are necessary to ascertain knowledge about itchgrass control before the weed emergence, as reported in our work, because after the emergence, this weed is difficult to control, which reduces the herbicide molecules available.

All herbicide treatments showed shorter itchgrass height compared with the control treatment. Overall, when applying the herbicide, there was a reduction of 9.3 mm per day in itchgrass growth. Herbicide usage is the most commonly used method for weed management in sugarcane cultivation, especially when positioned in pre-emergence conditions, as it ensures a prolonged residual effect and control effectiveness during the critical period of competition with the crop (Ghirardello et al. 2021; Presoto et al. 2022), as confirmed by the present study.

As to the weed control, again, the association of herbicide molecules contributed to a reduction of itchgrass development (Table 3). When comparing the associations of treatments (T) with indaziflam (T2, T3 and T4) with the other treatments (T5, T6 and T7), the first treatments held back the growth of itchgrass grass on average 3.5 times more than the other herbicide treatments (Table 3). The advantages obtained from some herbicide associations (as in the example above of the associations with indaziflam) may include synergism, an augmented control spectrum and an increased residual period, resulting from the distinct characteristics of the molecules studied (Presoto et al. 2022).

To evaluate the green coverage percentage, we used the Canopeo® system. Recently, the optical methods based on indirect and non-destructive canopy cover, especially in field conditions (Hufkens et al. 2019; Rodrigues et al. 2022; Bourega et al. 2023; Campana et al. 2023). Digital imaging and precision farming have the potential to provide more information to facilitate management decisions on a canopy scale in real time (Lu et al. 2019; Bourega et al. 2023) and in our case, in particular, to understand the right timing for weed control in sugarcane and to check the control efficiency of these weeds (itchgrass and morningglory) (Table 4). Our results highlight that the lowest index of Canopeo® (% green coverage) for the itchgrass was obtained by associations with indaziflam. Indaziflam has been a good alternative for weed control in sugarcane in Brazil since 2016. It is from the alkylazine group of chemicals (Amim et al. 2016; Ghirardello et al. 2021). Indaziflam mainly controls weeds of the Poaceae family and some eudicots in pre-emergence, acting as a potent inhibitor of cellulose biosynthesis (Brabham et al. 2014; Rodrigues et al. 2022). Compared to other pre-emergent herbicides that are often applied in sugarcane, indaziflam appears to have greater persistence in the soil (Kaapro and Hall 2011; Ghirardello et al. 2021; Rodrigues et al. 2022). Sebastian et al. (2017) found that across five application timings, indaziflam treatments also resulted in superior control of invasive winter annual grasses compared with other treatments. According to this parameter of percentage of green coverage studied, all herbicide treatments were efficient in controlling morningglory, with green coverage values ranging from 0.04 to 1.54%, with the latter presenting coverage of only 6% compared to the control treatment.

The aboveground and belowground biomass parameters showed similar behavior in relation to itchgrass and morningglory. Against the first weed, the worst result with a larger biomass was clomazone + sulfentrazone, while against morningglory, the treatment flumioxazin + pyroxasulfone showed the poorest control. Sebastian et al. (2017) studying the effect of indaziflam on the roots of plants showed alteration in symptomologies in root plants, as aberrant root and alteration in cell morphology detected by fluorescence microscopy. By the same mechanism, we can account for the inferior biomass found from the treatment with indaziflam associations in our study. As for the relation between aboveground and belowground, it is interesting that, at the beginning of the development cycle, *R. exaltata* has a greater biomass of roots in relation to the total biomass, evidencing the physiology of plants in starting their growth by colonizing the space and ensuring adequate fixation in the soil (Carvalho et al. 2005). However, the participation of the roots is reduced throughout the cycle, mainly because of the high production of mass by the aerial part (Bianco et al. 2004). The rapid development of the root structure with subsequent aboveground formation favors the domination of the space in which the plant is developing, primarily due to the higher absorption rates of water and nutrients with increasing interception of incident radiation (Carvalho et al. 2005).

The backbone of this study is to ensure the selectivity of the sugarcane crop. Selectivity is the ability of the herbicide to control weeds without impairing the quality of sugarcane (Sousa et al. 2020). This possible damage to some sugarcane varieties is associated with such characteristics of plants as differential absorption and translocation, their age, cultivar, differential metabolism, dimensions of seeds or propagation structures, and factors related to the characteristics of herbicides and their application modes, such as dose, formulation, and selectivity by position (Araldi et al. 2011; Ghirardello et al. 2021). According to the literature, when indaziflam was applied in isolation, it was selective for the IACSP95-5000 sugarcane cultivar (Ghirardello et al. 2021). Maintaining high doses of indaziflam application (300 g ai ha^{-1}) did not cause injury to the sugarcane (RB867515 cultivar) in an area with sandy soil (Simões 2018). In clayey soil, indaziflam was also considered selective, even with the need for higher doses to control species (Ghirardello et al. 2021). According to Martins et al. (2010), diclosulam, also applied alone in pre-emergence, was proven to be selective for the eleven sugarcane varieties tested. Sulfentrazone is also a selective herbicide, widely used in the management system of monocotyledonous and eudicotyledonous weeds in sugarcane fields, in preemergence (Sousa et al. 2020). Just as these herbicides applied in isolation were selective, the associations evaluated in our study also ensured good selectivity for the RB85 5156 variety, especially indaziflam + tebuthiuron (Table 6).

5. Conclusion

Some herbicide associations provide good alternatives for the strategy of managing *R. exaltata* and *I. quamoclit*. The best treatments for *R. exaltata* were: indaziflam + tebuthiuron and indaziflam + diclosulam and for *I. grandifolia* were: indaziflam + sulfentrazone, indaziflam + diclosulam, indaziflam + tebuthiuron, flumioxazin + diclosulam, and clomazone + sulfentrazone. All treatments reduced the weed biomass while the safest treatment for sugarcane was indaziflam + tebuthiuron. In seeking sustainability in sugarcane production, especially in plant cane, the best management is the use of the optimum dose of the right herbicide associations to control weeds in the sugarcane system, aggregating sugarcane plant development and greater economic efficiency due to the fact that the best association – indaziflam + tebuthiuron – has a lower price when compared to other herbicide associations. The graphic summary briefly shows the conclusion of this weed science study based on the control percentage (Fig. 3).

Declarations

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Data availability statement

The data supporting the findings of this study are available from the corresponding author, R. A. C., upon reasonable request.

Authors’ contributions

Conceptualization of the manuscript and development of the methodology: R.A.C., S.G.Q.C., A.P. and L.T.; data collection, analysis and interpretation: R.A.C., S.G.Q.C., S.A.Q.C., G.O.N.S. and L.T.; funding acquisition and resources: S.G.Q.C., S.A.Q.C. and A.P.; project administration: S.G.Q.C.; L.T. and P.J.C.; writing, review and editing: R.A.C., S.G.Q.C., S.A.Q.C., A.P., G.O.N.S., L.T. and P.J.C.

All authors have read and agreed to the published version of the manuscript.

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Figures

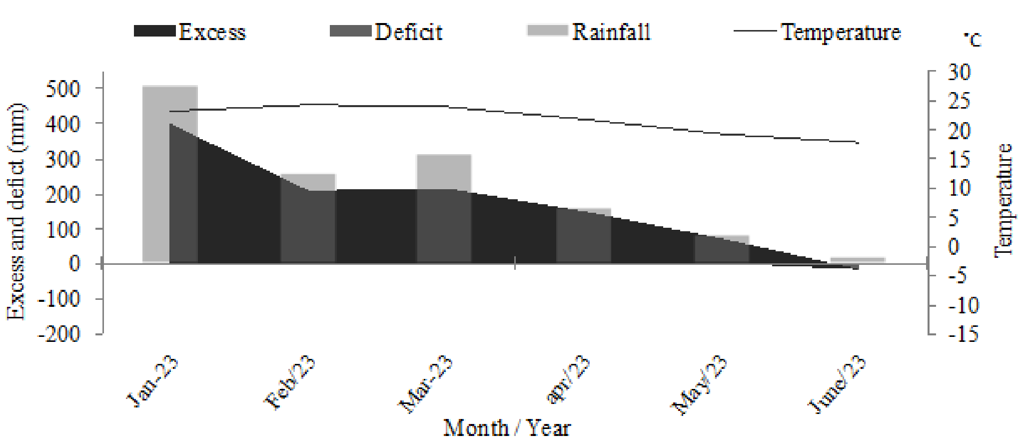

Figure 1

The water balance was calculated during the experimental period in the field area according to the methodology described by Thornthwaite & Mather (1955). Sales de Oliveira/SP - 2023.

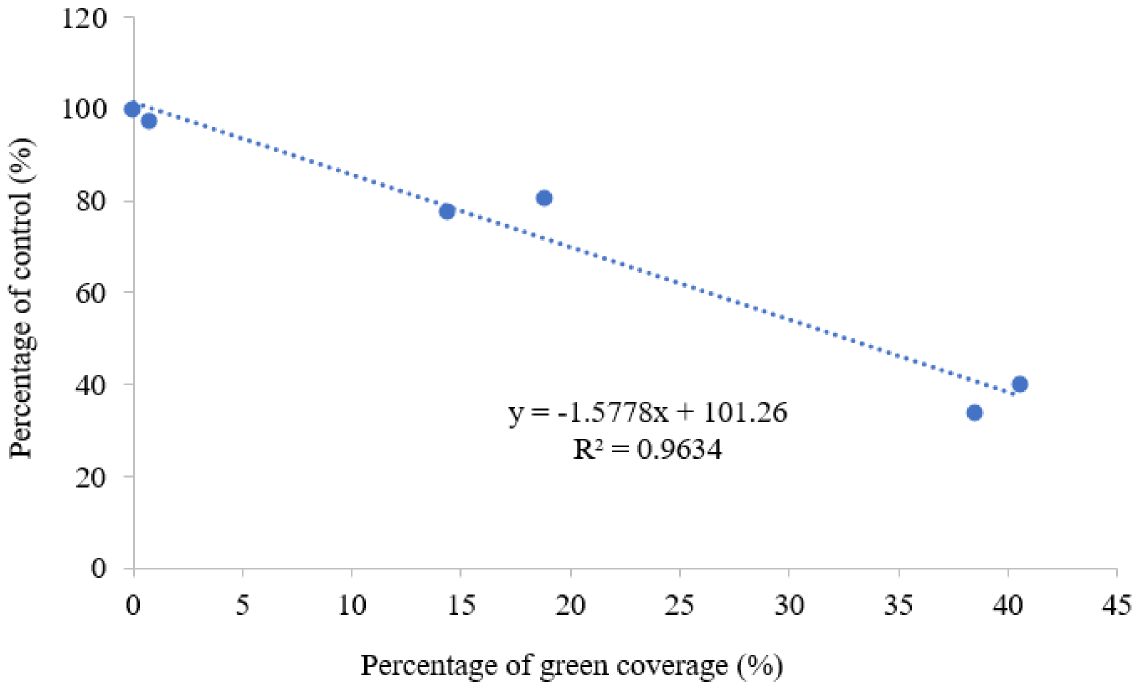

Figure 2

Correlation between the percentage of weed control and the percentage of green coverage of itchgrass (*Rottboelia exaltata*) by Canopeo® when associated with herbicide molecules, applied during weed pre-emergence and evaluated at 90 DAA. Sales de Oliveira/SP, 2023.

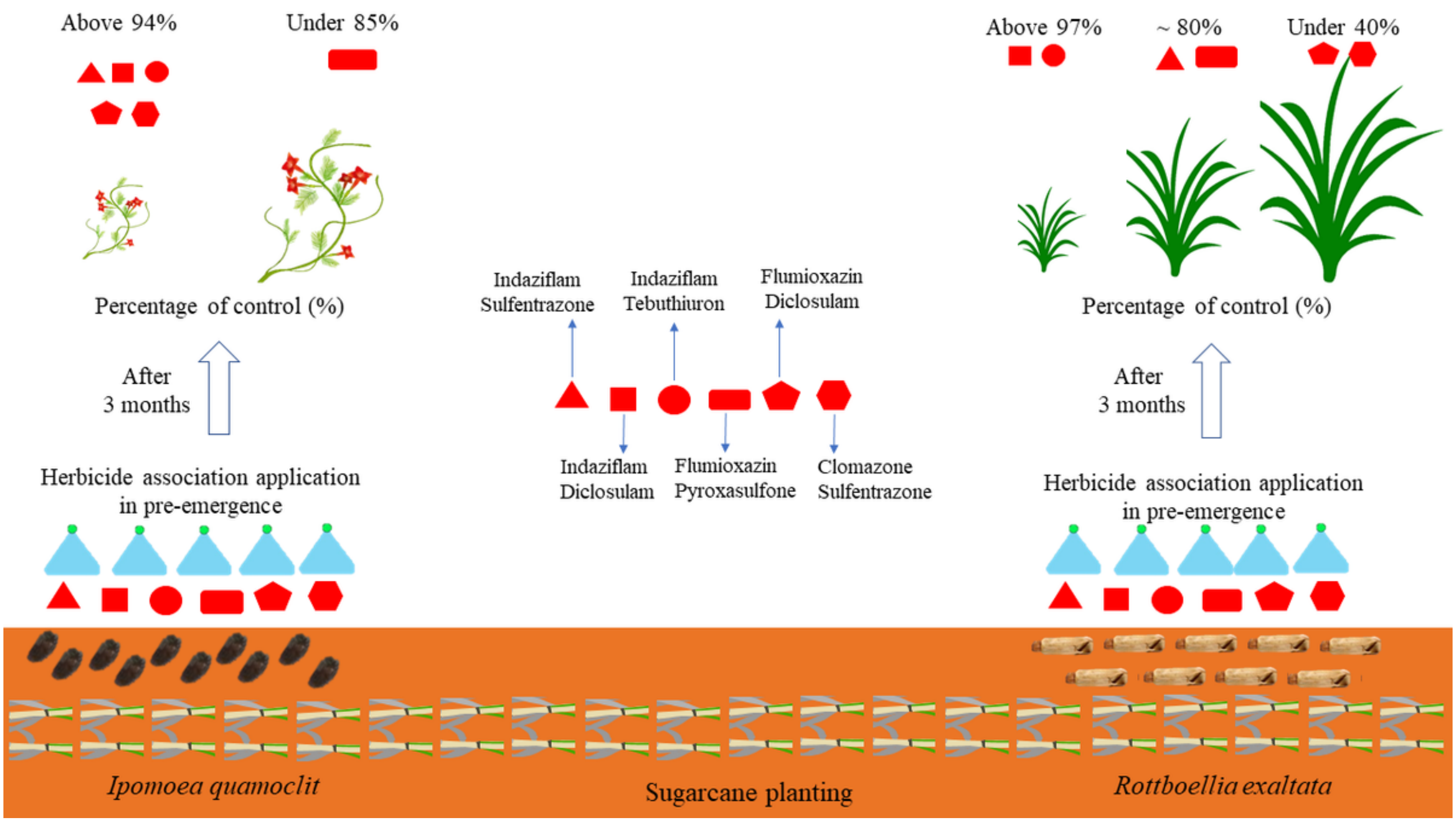

Figure 3

Graphic summary of the conclusion of this weed science study based on percentage of control (%). Sales de Oliveira/SP, 2023.