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Mixture of herbicides to common bean crops in highlands of Santa Catarina, Brazil

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The objective of this study were to identify incompatibilities in mixtures of herbicides applied in common bean crops and assess the effects of herbicide interactions on weed control. Experiments I e II were conducted in a completely randomized design, with four replications, using a 4 × 4 factorial arrangement consisted of four herbicides (applied alone or in combinations) and four evaluation times (0, 1, 2, and 3 hours). a physical evaluation of the syrup was carried out. Experiments III e IV were conducted under the same design but with solution applied immediately after preparation and evaluations of weed control at 7, 14, and 28 days after application. The results showed homogeneity for all formulations, but persistent foam formation in some cases. No incompatibility was found for the herbicide mixtures. Satisfactory control of *Eleusine indica* and *Euphorbia heterophylla* was not achieved in Experiment III (bentazon and imazamox, alone or in combination) due to the antagonistic effect of the herbicide combination. Combining bentazon and imazamox was promising for controlling *Cyperus esculentus* and *Bidens pilosa*, while combining fomesafen and imazamox was promising for controlling all evaluated weed species.

Key words: Herbicide incompatibility, sustainable production, environmental preservation, sprays solution stability.

INTRODUCTION

Brazil is one of the largest consumers of herbicides due to its vast cultivated areas and high demand for grain exports to meet international market demands. Consequently, agricultural production in the country is carried out on a large scale, requiring extensive herbicide use. However, maintaining or increasing food production, particularly common bean crops, poses significant challenges, mainly related to biotic and abiotic stresses in agricultural fields. Weeds are a major concern for agriculture, directly and indirectly interfering with crop yields by competing for nutrients, water, space and light. They also host diseases and pests that can attack crops and hinder machinery operations in the field (Kubiank et al., 2022; Mehdizadeh et al., 2024). Weeds can cause up

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to 80% loss in common bean yield (Schiessel et al., 2019).

To mitigate crop losses and the evolution of weed resistance to herbicides, several strategies are necessary. These include using machinery to monitor and manage weeds and reducing environmental impacts through rational herbicide use (Mehdizadeh et al., 2024; Oliveira et al., 2023; Anderegg et al., 2024). Additional strategies involve using herbicides with different modes of action from those commonly applied to each crop and combining different modes of action to broaden the control spectrum and delay weed resistance (Marchioretto and Dal Magro, 2017; Costa et al., 2020).

The reduced efficacy of herbicides in controlling various weed species in different crops has led farmers to use higher rates and more frequent applications, increasing costs, selection pressure and negative environmental impacts. However, using herbicide mixtures with different modes of action has shown promise in weed control and preventive management of weed resistance.

Herbicide mixtures have effectively managed weeds in wheat crops (Punia et al., 2020), offering a broader weed control spectrum compared to single herbicide applications (Samota et al., 2024). Although single herbicide applications may not effectively control weeds, combining pyroxasulfone with other herbicides has proven more effective against narrow-leaf weeds than using pendimethalin or metribuzin alone (Chhokar and Sharma, 2023). Despite the benefits, herbicide mixtures pose a recurrent problem: potential incompatibility resulting in clumps and precipitates. This can cause nozzle and filter clogs during application and loss of product efficacy due to reduced active ingredient amounts in spray droplets (Petter et al., 2012).

The mixture of bentazon and imazamox herbicides is commonly used in various Brazilian crops due to its efficacy, selectivity and economic impact. This combination effectively controls several weed species in common bean crops, particularly in postemergence applications (Marchioretto and Dal Magro, 2017; Costa et al., 2020). However, little research has been done on combining fomesafen and imazamox herbicides, especially in Santa Catarina's highlands, which have a temperate climate (Cfb), unlike many Brazilian regions. Herbicide combinations are widely used in Brazil to mitigate selection pressure and prevent new herbicide-resistant weed species from emerging.

Herbicide selectivity in weed control depends on environmental factors, making it crucial to investigate herbicide interactions in Santa Catarina's highlands, where climate conditions frequently vary and common bean crops are prevalent. The hypothesis is that mixing herbicides with different mechanisms of action may be compatible for weed control in bean crops. This study aimed to identify incompatibilities in herbicide mixtures applied to common bean crops and assess herbicide interaction effects on weed control in Santa Catarina's highlands, Brazil.

MATERIAL AND METHODS

Four experiments were conducted at the Faculty of Agricultural and Veterinary Sciences of the State University of Santa Catarina (CAV/UDESC), in Lages, Santa Catarina, Brazil, to assess physical and chemical incompatibilities in herbicide mixtures (Experiments I and II) and the efficacy of these herbicide treatments in controlling weed species (Experiments III and IV).

Experiments I and II

Two experiments were conducted to evaluate herbicide solutions, alone or in combination, based on the methodology described in the NBR13875 pesticides and related products: assessment of physical and chemical compatibility (ABNT, 2014), with some modifications, to visually assess the occurrence of incompatibilities (Table 1).

Physical stability of herbicide solutions

The physical stability of the spray mixture was evaluated by preparing the mixture with well water having a hardness of 20 mg kg^{-1} $CaCO_3$ equivalent, with four replications per treatment. The herbicides were added according to the treatments and rates described in Table 1, utilizing a 250 mL graduated cylinder with a lid, a metal 149 µm mesh sieve, and a graduated pipette. After preparation, the cylinder was capped and shaken 10 times to homogenize the solutions. The solutions were visually evaluated immediately after preparation (0 h), and at 1, 2, and 3 h after preparation and resting. The possible effects of interactions between products were assessed by observing homogeneity, flocculation, sedimentation, phase separation, oil suspension, and formation of clumps, crystals, cream, and foam.

Chemical stability of the solution

The chemical stability of the solution was evaluated using a completely randomized experimental design with four replications in a 4 × 4 factorial arrangement. The first factor consisted of herbicide solutions (alone or in combination) and a control (water), and the second factor consisted of evaluation times (0, 1, 2, and 3 h after preparation). The pH and electrical conductivity (EC) of the mixtures were measured using a benchtop pH meter and a conductivity meter (QUIMIS) that were properly calibrated for acidic and basic ranges.

Surface tension of spray droplets

Surface tension of spray droplets was assessed using a precision balance (grams, with four decimal places), beakers, 1-L volumetric flasks, a 50 ml burette, a stopwatch, and disposable gloves, based on the droplet count method. A calibrated burette was used with only distilled water; a 25 ml beaker containing an oil layer was placed on the balance to prevent potential losses due to evaporation. The burette was calibrated by timing the interval from the initial formation of the drop to its complete fall from the burette tip. The opening and closing of the burette valve were adjusted to maintain the liquid column at 50 ml. The surface tension of spray droplets of all treatments was quantified by the weight of the droplets formed at the burette tip over 30 s; then, the obtained values were converted considering the mean droplet weight of

Table 1. Description of the treatments and herbicides used in Experiments I and II to assess physical and chemical incompatibilities in herbicide mixtures. CAV/UDESC, Lages, SC, Brazil, 2024.

Herbicide treatments	Rate (c.p.)	Rate (a.i.)	Group HRAC)	Mode of action
Experiment I				
Control (water)	---	---	---	---
Bentazon	1.2 L ha^{-1}	600 g ha^{-1}	6	FSII (6)
Imazamox	60 g ha^{-1}	42 g ha^{-1}	2	ALS (2)
Bentazon + Imazamox	1.2 L ha^{-1} + 60 g ha^{-1}	600 + 42 g ha^{-1}	6 + 2	FSII (6) + ALS (2)
Experiment II				
Control (water)	---	---	---	---
Fomesafen	1.0 L ha^{-1}	250 g ha^{-1}	14	PPO (14)
Imazamox	60 g	42 g ha^{-1}	2	ALS (2)
Fomesafen + Imazamox	1.0 L ha^{-1} + 60 g ha^{-1}	250 + 42 g ha^{-1}	14 + 2	PPO (14) + ALS (2)

c.p. = commercial product; a.i. = active ingredient; 14 = protoporphyrinogen oxidase (PPO/PROTOX) inhibitors; 2 = acetolactate synthase (ALS) inhibitors; 6 = photosystem II inhibitors. Manufacturer's recommended rates. HRAC = Brazilian Herbicide Resistance Action Committee (HRAC, 2024).

distilled water, 71.97 mN m^{-1} at 25°C. The surface tension (ST; mN m^{-1}) was determined using the formula $ST = W1 \times 71.97 / W2$, where *W1* is the weight (grams) of the treatment droplets and *W2* is the weight (grams) of the distilled water droplets (Silva-Matte et al., 2014).

Experiments III and IV

Following the analyses of herbicide solutions in Experiments I and II, the same herbicide treatments and rates (Table 1) were evaluated in Experiments III and IV to assess their control of the following weed species: *Bidens pilosa*, *Euphorbia heterophylla*, *Eleusine indica*, and *Cyperus esculentus* in a greenhouse (Table 1). Both experiments were conducted in a completely randomized design with four replications; the herbicide treatments (Table 1) were applied at post-emergence of weeds.

The evaluated weed species were manually seeded in 1 dm^{-3} pots at a depth of approximately 1 cm, using approximately 5 seeds (*B. pilosa* and *E. heterophylla*) or 7 seeds (*E. indica* and *C. esculentus*) per pot. A density of two plants (*B. pilosa* and *E. heterophylla*) or three plants (*E. indica* and *C. esculentus*) per pot were maintained at the time of treatment application.

Herbicide treatments were applied using a CO_2-pressurized backpack sprayer at a constant pressure of 210 kPa, equipped with boom with four AIXR 110 015 spray nozzles spaced 50 cm apart, for applying a spray volume of 150 L ha^{-1}. Weather conditions at the time of applications were: temperature of 23ºC, relative air humidity of 68%, and wind speed of 3.8 km h^{-1}. Daily irrigation was carried out manually.

The weed control efficacy was assessed at 7, 21, and 28 days after application (DAA) based on a percentage scale from 0 to 100%, in which zero represents no symptoms and 100% represents the death of the plant. The effect of the interaction between herbicides on weed control (%) was determined using the equation proposed by Colby (1997) to calculate the expected value (EV) of the herbicide interaction:

$$EV = X + Y - \frac{XY}{100}$$

where *EV* is the expected control or injury caused by the herbicide combination, and *X* and *Y* are the percentages of weed control provided by herbicide applied separately.

Statistical analysis

The data from Experiments I and II were subjected to univariate analysis of variance (ANOVA) using the F-test ($p < 0.05$). Significant means were subjected to analysis of the interaction effect between factors (herbicide solution and evaluation time); pH data were subjected to regression analysis using polynomial decomposition based on orthogonal contrasts. However, the choice of graphs was based on the significance of degree of polynomials (*), sum of squares (SS), and coefficient of determination (R^2).

The data from Experiments III and IV were subjected to ANOVA using the F-test at a 5% significance level. Significant means were subjected to multiple comparison using the Tukey's test ($p < 0.05$) based on the interaction effect between factors (herbicide application and weed species).

The data obtained through the Colby method were subjected to ANOVA, and means were compared using the Tukey's test ($p < 0.05$). When significant differences were found among treatments, the effect of an herbicide interaction was considered antagonistic or synergistic when the weed control from applying an herbicide combination was lower or higher, respectively, than that expected from the sum of control percentages provided by the herbicides applied separately.

All statistical analyses were carried out using the academic version of the Statistical Analysis System - SAS software (SAS University Edition). Graphs were developed using the SigmaPlot 10.0 software (Systat Software, San Jose, USA).

RESULTS

Experiments I and II

No physical instability was found for the herbicide solutions tested in Experiments I and II, with all solutions (herbicides alone or in combination) showing homogeneity (Table 2). However, foam formation was observed for the

Table 2. Physical characteristics of herbicide solutions at different times after preparation: homogeneity (HG), flocculation (FL), sedimentation (SD), phase separation (FS), oil suspension (OS), and formation of clumps (CL), crystals (CR), cream (CE), and foam (FO).

Time after preparation	Experiment I			
	Control	Bentazon	Imazamox	Herbicide combination
0	HG	HG; FO	HG; FO	HG; FO
1 h	HG	HG; FO	HG; FO	HG; FO
2 h	HG	HG; FO	HG	HG; FO
3 h	HG	HG; FO	HG	HG; FO

Time	Experiment II			
	Control	Fomesafen	Imazamox	Herbicide combination
0	HG	HG; FO	HG; FO	HG; FO
1 h	HG	HG; FO	HG; FO	HG; FO
2 h	HG	HG	HG	HG
3 h	HG	HG	HG	HG

Table 3. Analysis of variance for pH and electrical conductivity of herbicide solutions evaluated at different periods after preparation. UDESC, Lages, Santa Catarina, Brazil, 2024.

Source of variation	Degrees of freedom	pH	Electrical conductivity (S m^{-1})
Experiment I			
Herbicide solution	3	194.81*	36,169.90*
Evaluation time	3	78.43*	1.59^{NS}
Herbicide × Time	9	9.57*	0.82^{NS}
Residue	48	---	---
Total	63	---	---
Mean		7.74	1,117.91
CV (%)		0.92	1.49
Experiment II			
Herbicide solution	3	262.60*	4,707.75*
Evaluation time	3	14.54*	2.19^{NS}
Herbicide × Time	9	10.89*	1.07^{NS}
Residue	48	---	---
Total	63	---	---
Mean		7.71	601.83
CV (%)		2.22	1.88

CV = coefficient of variation; * and NS = significant and not significant ($p < 0.05$), respectively, by the F-test.

bentazon solution (Experiment I) at all evaluation times, whereas imazamox solution exhibited this phenomenon only at one hour after preparation, Moreover, a persistent foam formation was found in the solution combining both herbicides. In Experiment II, foam formation was observed immediately after solution preparation, extending for one hour for solutions with fomesafen and imazamox alone or in combination (Table 2).

ANOVA showed a significant interaction effect ($p < 0.05$) between the factors (herbicide solution and evaluation time) for pH in both experiments (I and II). This result denotes a pH variation in the herbicide solutions over time; similarly, there was a pH variation for each evaluation time. This indicates that pH may vary as a function of the solution resting time, providing useful information about the ideal timing for herbicide application after solution preparation. No significant interaction effect was found for electrical conductivity, only an individual effect of the herbicide solution factor (Table 3).

Herbicide solutions had a significant effect on surface tension of spray droplets in both experiments (Table 4). The means found differed significantly among single

Table 4. Analysis of variance for surface tension (mNm^{-1}) of spray droplets of herbicide solutions (alone and in combinations), Lages, Santa Catarina, Brazil, 2024.

Source of variation	Degrees of freedom	Sum of squares	Mean square	F-test (p < 0.05)	*p*-value
Experiment I					
Treatment	3	1.058.49	353.16	60.16	< 0.001
Residue	12	70.45	5.87	---	---
Total	15	1.129.92	---	---	---
Mean	80.51				
CV (%)	3.01				
Experiment II					
Treatment	3	1.752.98	584.32	112.35	< 0.001
Residue	12	62.40	5.20	---	---
Total	15	1.815.38	---	---	---
Mean	64.68				
CV (%)	3.53				

CV = coefficient of variation.

herbicide solutions in both experiments, with bentazon showing higher mean than fomesafen, which is explained by the particularities of each product.

The evaluated herbicide solutions presented significant differences in electrical conductivity (EC). Combining bentazon and imazamox resulted in the highest EC, differing significantly from the other treatments (Figure 1A). Analysis of contrasts showed a linear regression for the evaluated treatments; however, the choice of graph was based on the significance of degree of polynomials (*), sum of squares (SS), and coefficient of determination (R^2).

Linear regression for Experiments I and II showed a significant increase in pH in solutions of all treatments as resting time increased (Figure 1B); these increases were 0.07 (bentazon), 0.20 (imazamox), and 0.17 (bentazon + imazamox) for every hour the solution remained at rest (Figure 1B).

The solution with imazamox alone showed lower EC, with means significantly lower than the control in both experiments. This increased EC in solutions combining herbicides is due to the high means found for the solutions with herbicides alone. The surface tension (ST) of spray droplets varied in both experiments. Bentazon alone was the only treatment that increased ST, differing significantly. However, imazamox alone and the combination of these two herbicides did not significantly differ from the control (Figure 1C). The solution combining fomesafen and imazamox increased EC compared to the control (Figure 2A).

Fomesafen alone significantly decreased pH by 0.31 per hour of rest (Figure 2B), whereas imazamox alone and these two herbicides combined significantly increased pH by 0.21 and 0.23, respectively, per each hour of rest (Figure 2B). Moreover, fomesafen alone and its combination with imazamox significantly decreased ST compared to the control, as well as imazamox alone (Figure 2C).

Experiments III and IV

The weed control (phytotoxicity) by the tested herbicide treatments was significantly different ($p < 0.05$) for all species and evaluation times (7, 14, and 28 DAA) in both experiments (III and IV). This result indicates that the treatments promoted different weed control and the control percentage varied according to the herbicide treatment and weed species (Table 5).

In Experiment III, the control of *B. pilosa* and *C. esculentus* was more effective compared to the other species for all herbicide treatments applied, alone or in combination, with control of approximately 100% (Figure 3A, 3B, and 3C).

E. indica was the least affected by the herbicides at all evaluations, with a control of approximately 20%. The control of *E. heterophylla* was gradual over of the evaluations, but not exceeding 50%; however, the application of imazamox alone resulted in 60% and 95% control at 14 DAA and 28 and DAA, respectively (Figure 3B and 3C).

In Experiment IV, the control of *B. pilosa* and *C. esculentus* was more effective at 7 and 14 DAA compared to the other species, in all treatments applied, with a control above 90%; however, imazamox alone resulted in approximately 60% and 80% at 7 and 14 DAA, respectively, being the less effective herbicide treatment (Figure 4A and 4B).

Applying herbicides alone and in combination resulted in approximately 100% control of *B. pilosa*, *C. esculentus*, and *E. Heterophylla* at 28 DAA (Figure 4C). As in Experiment III, *E. indica* was the least affected by the

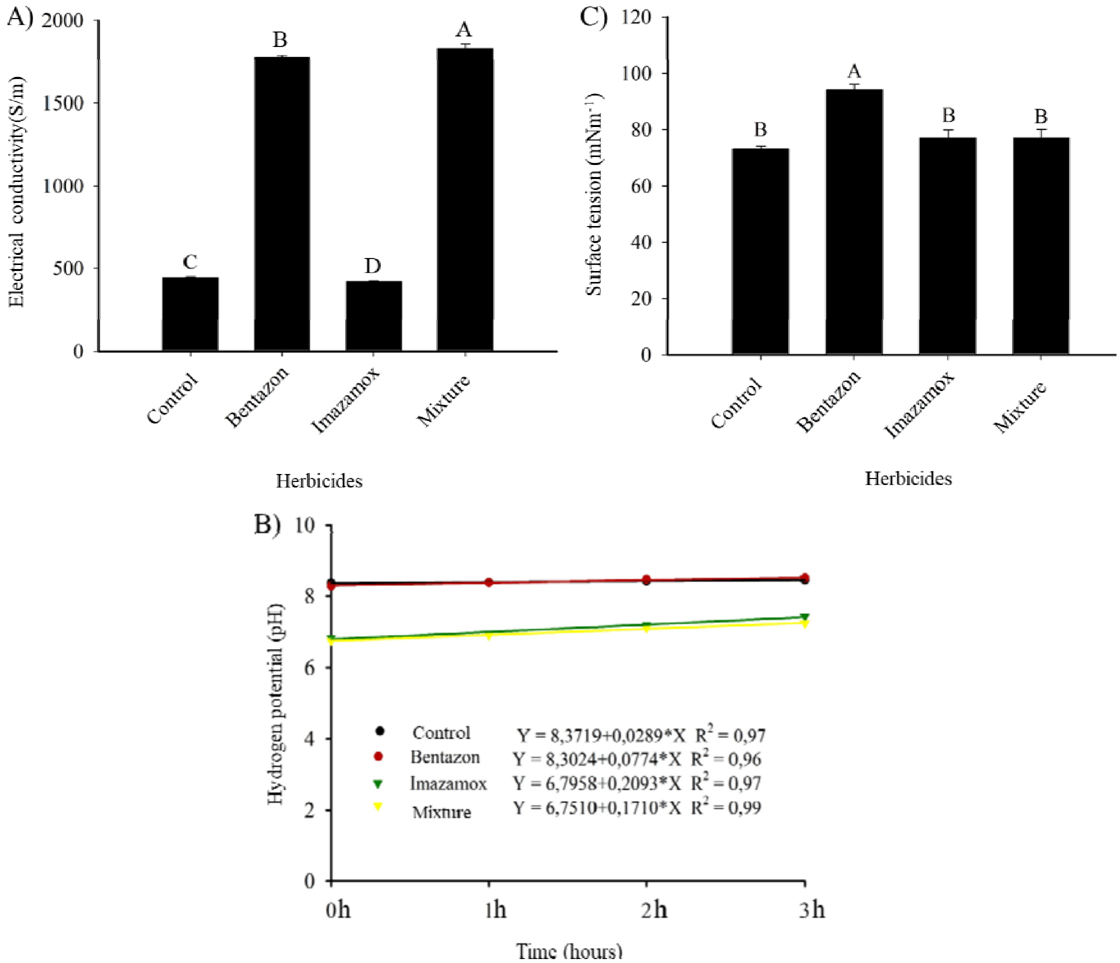

Figure 1. Comparison of means of electrical conductivity (S m^{-1}) (A) and surface tension (mNm^{-1}) (C), and regression for pH (B) of the evaluated herbicide solutions. CAV/UDESC. Lages, SC, Brazil, 2024.
Means followed by the same letter in Figures A and C are not significantly different from each other by the Tukey's test ($p < 0.05$).

herbicide treatments (Figure 4A, 4B and 4C).

In Experiment III, the herbicide combination (bentazon + imazamox) had an additive effect on the control of *C. esculentus* and *B. pilosa;* however, this treatment resulted in an antagonistic effect on the control of *E. indica* and *E. heterophylla*. In Experiment IV, the herbicide combination (fomesafen + imazamox) had an additive effect on all species (Table 6).

DISCUSSION

The results showed no physical incompatibility in the herbicide solutions evaluated in Experiments I and II, with all solutions (herbicides alone or in combination) showing homogeneity. Incompatibility is evident when a solution presents flocs, crystals, clumps, or phase separation, indicating that the products ca1nnot be uniformly mixed. The presence of foam in the solution combining bentazon and imazamox can be attributed to the formation of foam characteristic of bentazon. This effect is explained by agitation immediately after solution preparation, which can disappear after some preparation time, as also found in other studies (Tavarese and Cunha, 2023). A longer duration of foam presence is not an advantage for the applicator, as foams can occupy spaces intended for the spray solution, compromising the accuracy in tank filling, which can result in alterations, errors of rates, and an increased risk of contamination during solution preparation.

The herbicide was the most important factor, which accounted for 94.0% of the variation in pH in the experiment, whereas the evaluation time factor was responsible for 3.8% of the variation. The herbicide factor was responsible for 99.9% of the variation in EC, whereas the evaluation time factor accounted for 0.004% of the variation. This indicates that adjustments in herbicide use are more critical for managing phytotoxicity

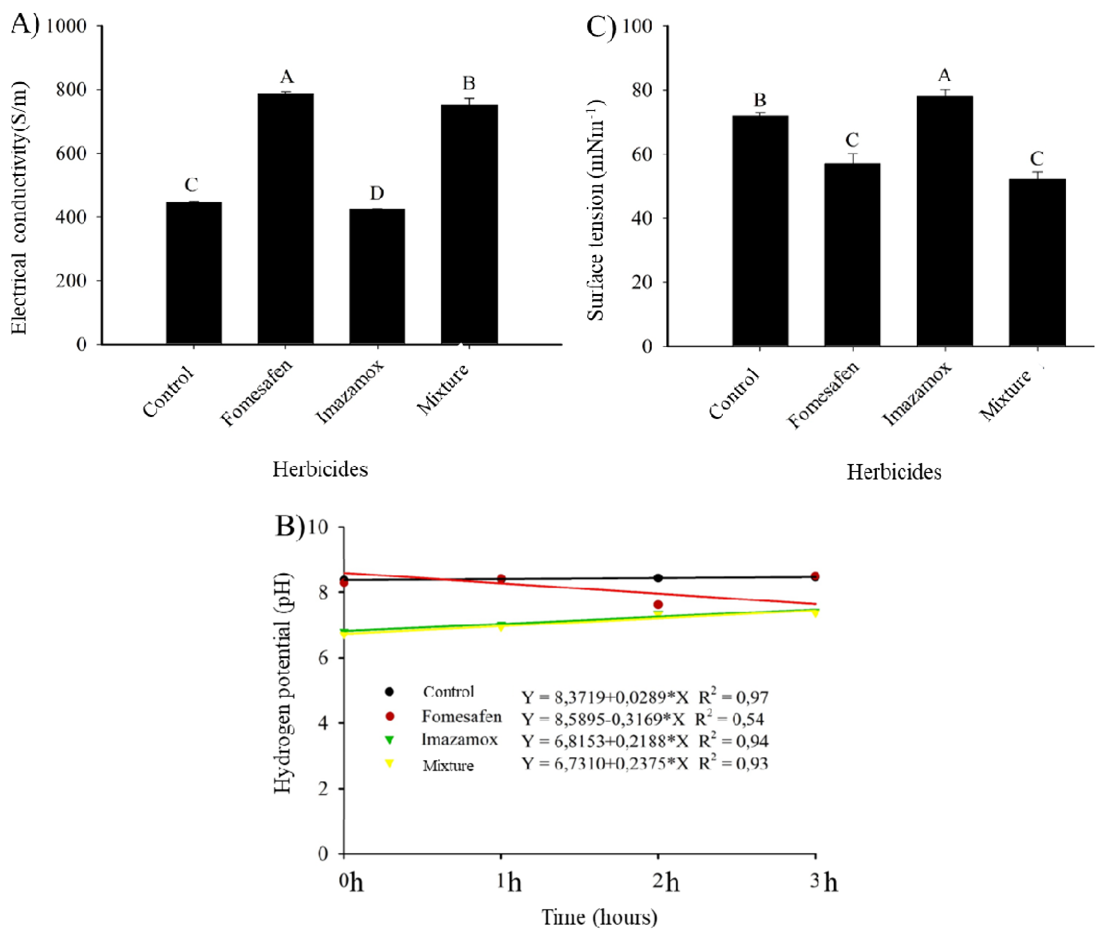

Figure 2. Comparison of means of electrical conductivity (S/m) (A) and surface tension (mNm^{-1}) (C) and regression for pH (B) of the evaluated herbicide solution treatments. CAV/UDESC. Lages, SC, Brazil, 2024. Means followed by the same letter in Figures A and C are not significantly different from each other by the Tukey's test ($p < 0.05$).

in weeds than the selection of species.

Therefore, further studies involving the resting time of herbicide solutions should assess the herbicide factor, alone or in combinations, with different evaluation intervals, despite it presented significant variations. Despite the herbicide treatments showed variation in EC, this was not found over time (Figures 1A and 2A). However, the solutions with imazamox alone showed EC below that of the control in both experiments (I and II), whereas bentazon and fomesafen alone presented increased EC compared to the control; this increase was also found when these herbicides were combined with imazamox.

The effect of EC on herbicide efficacy is not fully understood, as since there is little information on the dynamics of EC in the physiological aspect of plants. However, it is believed that a high EC provides the presence of large amounts of ions, which can decrease product efficacy, affecting water solubility, absorption, and hydrolysis, by plants. Moreover, little is known about the ideal EC range for a satisfactory effect on the plant. Therefore, detailed information is still needed for a better understanding of the dynamics of EC (Tavarese and Cunha, 2023).

EC decreased in the imazamox solution because it is a weak acid that partially dissociates in aqueous solutions, releasing few H^+ and CH_3COO^- ions, resulting in a low EC. EC is dependent on the presence of free ions in the solution, that is, the higher the presence of ions, the higher the solution EC.

The decrease in pH of the solutions shown in Figures 1B and 2B was due to the low pH of imazamox alone; these two treatments had pH below neutrality (7.0), which is considered acid. This may result in a higher efficacy of the herbicides, as their efficacy is higher when the solutions have pH between 6 and 6.5 (Murphy, 2004). In addition, the hydrolysis rate is delayed under a low pH, maintain leaf moist for a longer period, as leaf surfaces have, in general, neutral pH and interact with the solution pH (Cunha and Alves, 2009).

Table 5. Analysis of variance for phytotoxicity in weed species at 7, 14, and 28 days after application (DAA) of herbicide solutions. UDESC, Lages, Santa Catarina, Brazil, 2024.

SV	DF	*C. esculentus*			*E. indica*			*B. pilosa*			*E. heterophylla*		
		7 DAA	14 DAA	28 DAA	7 DAA	14 DAA	28 DAA	7 DAA	14 DAA	28 DAA	7 DAA	14 DAA	28 DAA
Experiment III													
TR	3	7.8*	25.87*	409.4*	6.41*	12.33*	8.4*	93.3*	319.48*	1533.9*	3.46*	7.9*	15.8*
Error	12	---	---	---	---	---	---	---	---	---	---	---	---
Total	15	---	---	---	---	---	---	---	---	---	---	---	---
Mean		50.93	62.62	71.75	8.56	9.43	14.68	67.06	69.87	72.81	15.75	29.37	41.43
CV (%)		49.07	28.39	6.60	52.95	41.23	49.12	13.84	7.46	3.40	76.57	59.29	45.80
Experiment IV													
TR	3	38.6*	471.4*	981.6*	14.4*	34.4*	23.3*	46.3*	325.6*	1801.5*	28.5*	16.8*	26.5*
Error	12	---	---	---	---	---	---	---	---	---	---	---	---
Total	15	---	---	---	---	---	---	---	---	---	---	---	---
Mean		62.12	69.50	71.87	37.50	47.62	52.18	59.12	67.93	71.18	33.75	55.37	69.68
CV (%)		22.52	6.18	4.25	40.74	26.38	28.05	21.36	7.46	3.14	32.57	35.77	26.24

SV = source of variation; DF = degrees of freedom; TR = treatment; * and NS = significant and not significant ($p < 0.05$), respectively, by the F-test.

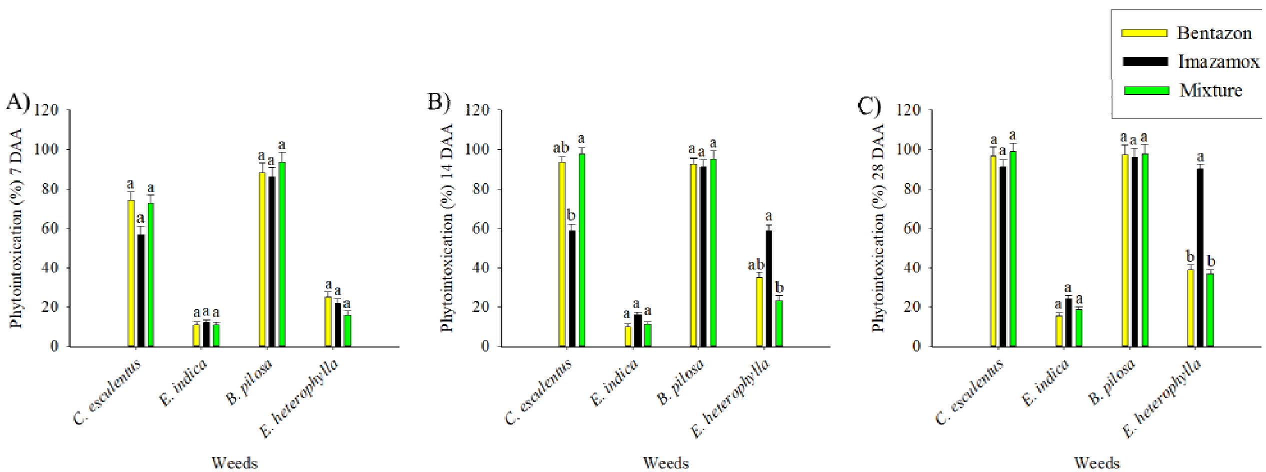

Figure 3. Comparison of means for the interaction effect (herbicide × species) regarding phytotoxicity at 7, 14, and 28 days after application (DAA), in Experiment III. UDESC, Lages, Santa Catarina, Brazil, 2024.
Means followed by the same uppercase letter comparing herbicides or lowercase letter comparing weed species are not significantly different from each other by the Tukey's test ($p < 0.05$).

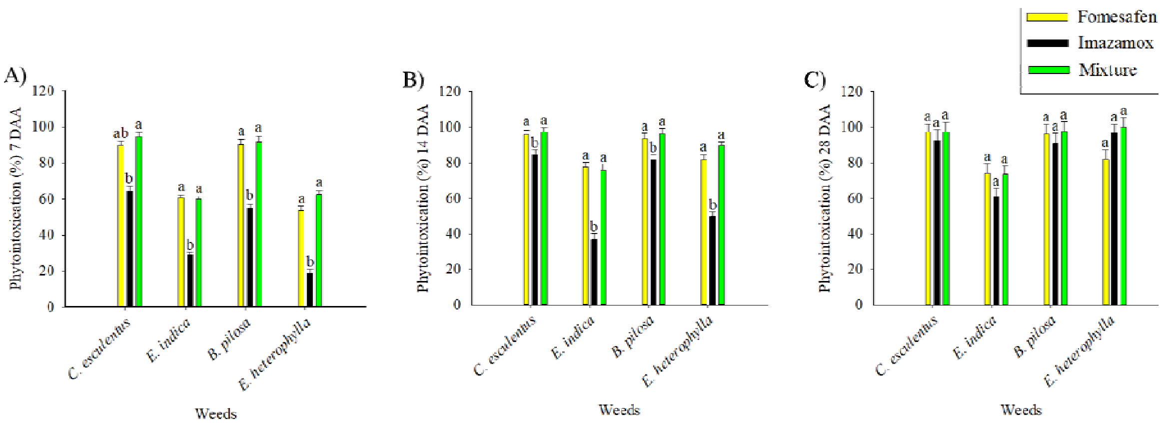

Figure 4. Comparison of means for the interaction effect (herbicide × weed species) regarding phytotoxicity at 7, 14, and 28 days after application (DAA) in Experiment IV. UDESC, Lages, Santa Catarina, Brazil, 2024.
Means followed by the same uppercase letter comparing herbicides or lowercase letter comparing species are not significantly different from each other by the Tukey's test ($p < 0.05$).

Imazamox is a weak acid and its charge depends on pH, thus, when introduced to an acid aqueous solution or medium (pH < pKa), it is not dissociated, resulting in a higher quantity in non-ionic form (HA) and lower quantity in ionic form (dissociated – HA^-); however, when it is introduced to a basic aqueous medium (pH > pKa), it is dissociated, resulting in a lower quantity in non-ionic form (HA) and a higher quantity in ionic form (dissociated –HA^-) (Carvalho, 2013).

Contrastingly, bentazon and fomesafen alone (Figures 1B and 2B) exhibited a pH above neutrality (7.0), which is considered alkaline; this pH can cause mixture instability and consequently ineffective control (Murphy, 2004). Most pesticides decompose rapidly at alkaline pH (Kissmann, 1997). Moreover, excessive acidification is undesirable because the action of these products can be altered due to precipitation (Murphy, 2004). Furthermore, a pH lower than 5.0 increases the potential for volatilization of these products and can promote off-target deposition (drift) (Striegel et al., 2021).

The pH of the evaluated herbicide solutions increased gradually and significantly over time. This indicates that these products should be applied soon after solution preparation. This increased pH over of time can lead to herbicide incompatibility, which can result in negative effects such as changes in stability, efficacy, and degradation molecules, inhibition of target site activity, and stimulation or inhibition of metabolic detoxification processes in some target biotypes (Vechia et al., 2018). However, these results should be confirmed under field experimental conditions.

Additionally, adversities in weed control in crop fields can be determinants for pH variations. A study evaluating the effect of spray solution pH on the efficacy of herbicides against volunteer rapeseed (*Brassica napus* L.) showed that the application of mesotrione at a pH of 4.0 contributed to greater efficacy in controlling rapeseed (87%) (Gzanka et al., 2021).

The surface tension (TS) of spray droplets varied among the herbicide treatments; however, similar to pH, ST decreased with the combination of herbicides (Figure 2C). Imazamox, alone and combined with bentazon, maintained ST similar to the control, with no significant difference. Thus, there was no increase in ST in herbicide combination compared to the control (Figures 1C and 2C). These results show a potential efficiency in the deposition and spreading of the solution on the target when applying a solution combining herbicides (Song et al., 2021), as decreases in droplet surface tension are commonly positively correlated with droplet dispersion, that is, the lower the ST and the contact angle with the target surface, the greater the dispersion and, consequently, the greater the deposit and coverage of the target (Decaro Jr. et al., 2015).

All treatments showed effective control of *B. pilosa* and *C.s esculentus* at 28 DAA, differing from *E. indica* and *E. heterophylla*, which were less affected by the herbicide effect (Figure 3C). The herbicide efficacy in controlling *E. indica* and *E. heterophylla* varied between Experiments III and IV; control was less effective in Experiment III (Figure 3) than in Experiment IV (Figure 4). This may be attributed to the tolerance of these species to bentazon and its antagonistic effect when interacting with imazamox (Table 6). Moreover, there is no current history of resistance of *B. pilosa* and *E. heterophylla* to ALS inhibiting herbicides, which may explain the action of imazamox on these species.

Regarding the control effect of bentazon alone and in combination with imazamox on *E. heterophylla*, this herbicide decreased the effect of imazamox in controlling this species. This can be attributed to antagonism in the interaction between these two herbicides, as bentazon mixed with some herbicides can cause antagonism in weed control. This herbicide can inhibit photosynthetic

Table 6. Weed control percentage (phytotoxicity) at 28 days after application (DAA) of herbicide treatments, UDESC, Lages, Santa Catarina, Brazil, 2024.

Treatment	*Cyperus esculentus*			*Eleusine indica*			*Bidens pilosa*			*Euphorbia heterophylla*		
	Vo	Ve	I	Vo	Ve	I	Vo	Ve	I	Vo	Ve	I
Experiment III												
Control	0.0	--	--	0.0	--	--	0.0	--	--	0.0	--	--
Bentazon	96.8	--	--	15.5	--	--	97.5	--	--	38.8	--	--
Imazamox	91.3	--	--	24.5	--	--	96.0	--	--	90.3	--	--
Mixture	99.0	99.5 ^{NS}	AD	18.8	36.4*	AN	97.8	99.9 ^{NS}	AD	36.8	93.9*	AN
Experiment IV												
Control	0.0	--	--	0.0	--	--	0.0	--	--	0.0	--	--
Fomesafen	97.3	--	--	74.3	--	--	96.3	--	--	82.0	--	--
Imazamox	92.5	--	--	60.8	--	--	90.8	--	--	96.8	--	--
Mixture	97.5	99.8 ^{NS}	AD	73.8	88.0 ^{NS}	AD	97.8	99.7 ^{NS}	AD	100.0	100.0 ^{NS}	AD

Vo = observed value; Ve = expected value (Colby); I = interaction (AN = antagonistic; AD = additive; SG = synergistic). * and ^{NS} = significant and not significant ($p < 0.05$), respectively, by the F-test.

electron flow in chloroplasts of sensitive tissues, which contributes to decreasing photosynthetic activity. The oxidative stress promoted by this herbicide hinders proteins and membranes of photosynthetic cells and causes cell death in weeds (Radwan et al., 2019).

Therefore, the antagonistic effect of the interaction between bentazon and imazamox may be due to a decreased absorption and/or translocation and changes in the metabolism of imazamox by the action of bentazon. This results in reduced efficacy in weed control, as bentazon promotes a protective effect in the plant against ALS-inhibiting herbicides due to its acting in photosystem II (PSII). It decreases the proportion of production and translocation of photoassimilates, decreasing the rate of absorption and transport of ALS-inhibiting herbicides in the plant phloem (Bauer et al., 1995).

However, these results are consistent with those found by Joaquim Júnior et al. (2023), who reported that the mixture of bentazon and imazethapyr resulted in lower phytotoxicity in cowpea plants (*Vigna unguiculata*), which may be connected to the antagonism found in the mixture.

A mixture is considered antagonistic, additive, or synergic when its effect is, respectively, less than, equal to, or greater than the sum of the effects of applying the products separately (Staker and Oliver, 1998). Therefore, none of the evaluated herbicide combinations showed a synergistic effect in the present study.

The mixture of fomesafen and imazamox showed an additive effect, resulting in a satisfactory weed control. Studies on the combination of these herbicides have shown their efficacy in controlling several weed species in common bean crops, with high control for postemergence applications (Marchioretto and Dal Magro, 2017; Costa et al., 2020). This should raise the interest in similar research under field conditions for this region, as these herbicides have different modes of action and translocation in the plant.

Imazamox is a systemic herbicide that is absorbed and translocated in the plant to the site of action, which is the acetolactate synthase (ALS) enzyme, resulting in the blockage of the production of branched-chain amino acids (valine, leucine, and isoleucine) and in decreases in protein synthesis and cell division (Gurbuz and Yenturk, 2022). Fomesafen is a contact herbicide and does not translocate in the plant, that is, it acts specifically at the site of deposition. It inhibits the action of the protoporphyrinogen oxidase (PROTOX) enzyme, which prevents the formation of chlorophylls and, consequently, the formation of reactive oxygen species, resulting in lipid peroxidation and destruction of cell membranes, leading the total plant collapse (Brusamarello et al., 2021).

Improving product retention on leaves by using adjuvants in the solution formulation is one of the strategies to achieve complete control of *E. indica*, as found for the other evaluated species, as it can assist in overcoming the cuticle barrier, increasing the deposition and efficacy of the spray solution on leaf tissues, resulting in a better penetration of the active ingredient through the plant surfaces (Räsch et al., 2018).

Further investigations should address formulation aspects (rates) to assess whether reduced rates in the herbicides mixtures used in this study result in satisfactory control for these weed species, as some research studies have shown promising weed control with reduced rates of active ingredients (Khaliq et al., 2011; Vechia et al., 2018), with can minimize the environmental impacts of herbicide applications (Kudsk, 2008) and reduce production costs.

The results found in the present study should be tested under field conditions, since the results for weed control by the interaction of herbicides can vary due to experimental conditions and weed species. Research conducted by (Sorensen et al., 1987) showed that the effect of mixing bentazon and acifluorfen to for the control of *Amaranthus retroflexus* L. can be described as antagonistic under greenhouse conditions, but was synergistic under natural environmental conditions. Additionally, combining these herbicides under the greenhouse conditions resulted in a synergistic interaction for controlling *Chenopodium album* L., without the use of adjuvants; however, the same interaction was considered additive when a vegetable oil was used in the formulation.

Conclusion

No physical or chemical incompatibilities were found in the evaluated herbicide mixtures. However, Experiment III revealed that bentazon and imazamox, alone or combined, failed to satisfactorily control *E. indica* and *E. heterophylla* due to an antagonistic effect. In contrast, combining bentazon and imazamox showed promise in controlling *C. esculentus* and *B. pilosa*. Meanwhile, combining fomesafen and imazamox demonstrated potential in controlling all evaluated weed species.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

REFERÊNCES

Anderegg J, Tschurr F, Kirchgessner N, Treier S, Schmucki M, Streit B, Walter A (2024). On-farm evaluation of UAV-based aerial imagery for season-long weed monitoring under contrasting management and pedoclimatic conditions in wheat. Computers and Electronics in Agriculture 107558:1-13. https://doi.org/10.1016/j.compag.2022.107558

Bauer TA, Renner KA, Penner D (1995). 'Olathe' pinto bean (*Phaseolus vulgaris* L.) response to post-emergence imazethapyr and bentazon. Weed Science 43(2):276-282. https://doi.org/10.1017/S0043174500081170

Brazilian Association of Technical Standards (ABNT) (2014). NBR 13875. Related pesticides - assessment of physical-chemical compatibility. Rio de Janeiro P 12. Available at: https://www.normas.com.br/autorizar/visualizacao-nbr/10489/identificar/visitante. Access: Aug. 22, 2024.

Brusamarello PA, Trezzi MM, Pagnoncelli Jr. FB, Oliveira PH, Finatto T, Barancelli MVJ, Schmalz BAH, Pereira PB (2021). Tolerance of Brazilian bean cultivars to protoporphyrinogen oxidase inhibiting-herbicides. Journal of Plant Protection Research 61(2):117-126. https://doi.org/10.24425/jppr.2021.137018

Carvalho LB (2013). Herbicides. 1ªed, Lages-SC. pp. 62. Available at: https://www.fcav.unesp.br/Home/departamentos/fitossanidade/leonardobiancodecarvalho/livro_herbicidas.pdf. Access: Sept. 27, 2024

Chhokar RS, Sharma RK (2023). Weed control in wheat with pyroxasulfone and its combinations with other herbicides. Weed Biology and Management 23(2):58-70. https://doi.org/10.1111/wbm.12268

Colby SR (1967). Calculating synergistic and antagonistic responses of herbicides combinations. Weeds 15:20-22. https://doi.org/10.2307/4041058

Costa JC, Moreira SG, Carvalho AHF, Pimentel GV, Torres DRQ, Silva JCR (2020). Efficacy of tank mixtures of post -emergence herbicides in common bean. Revista Agrogeoambiental 12(4):1-12. http://dx.doi.org/10.18406/2316-1817v12n420201560

Cunha JPAR, Alves GS (2009). Physicochemical characteristics of aqueous solutions with adjuvants for agricultural use. Interciência 34(9):655-659. Available at: http://ve.scielo.org/scielo.php?pid=S037818442009000900012&script=sci_arttext&tlng=pt. Access: Aug. 22, 2024.

Decaro Jr ST, Ferreira MC, Lasmar O (2015). Physical characteristics of oily spraying liquids and droplets formed on coffee leaves and glass surfaces. Engenharia Agrícola 35(3):588-600. https://doi.org/10.1590/1809-4430-Eng.Agric.v35n3p588- 600/2015

Gurbuz R, Yenturk O (2022). Determination of minimum doses of imazamox for Controlling *Xanthium strumarium* L. and *Chenopodium album* L. in bean (*Phaseolus vulgaris* L.). Agronomy 12(1557):1-16. https://doi.org/10.3390/agronomy12071557

Gzanka M, Sobiech L, Skrzypczak G, Piechota T (2021). Herbicides efficacy against volunteer oilseed rape as influenced by spray solution pH. Agronomy 11(5):1-11. https://doi.org/10.3390/agronomy11050887

HRAC (2024). HRAC-BR: Herbicide Resistance Action Committee Available at: https://www.hrac-br.org/. Access: Aug. 15, 2024.

Joaquim Júnior CZ, Barbosa IJ, Costa YKS, Tejada JL, Costa N, Mango BD, Silva LGC, Oliveira Neto AM, Carvalho LB (2023). Selectivity of isolated and mixed herbicides for cowpea “BRS-Pujante”. Delos 6(50):4159-4181. https://doi.org/10.55905/rdelosv16.n50-009

Khaliq A, Matloob A, Tanveer A, Areeb A, Aslam F, Abbas N (2011). Reduced doses of a sulfonylurea herbicide for weed management in wheat fields of Punjab, Pakistan. Chilean Journal of Agricultural Research 71(3):424-429. https://doi.org/10.4067/S0718-58392011000300013

Kissmann KG (1997). Adjuvants for pesticide sprays. In: Brazilian Congress of Weed Science. Lectures and round tables. Viçosa: Brazilian Society of Weed Science. Brazilian Society of Weed Science pp. 61-77

Kubiank A, Wolna-Maruwka A, Niewiadomska A, Pilarska AA (2022). The Problem of weed infestation of agricultural plantations vs. the assumptions of the european biodiversity strategy. Agronomy 12(8):1808. https://doi.org/10.3390/agronomy12081808

Kudsk P (2008). Optimising herbicide dose: a straightforward approach to reduce the risk of side effects of herbicides. Environmentalist 28:49-55. https://doi.org/10.1007/s10669-007-9041-8

Marchioretto LM, Dal Magro T (2017). Weed control and crop selectivity of post-emergence herbicides in common beans. Ciência Rural 47(3):e20160295. https://doi.org/10.1590/0103-8478cr20160295

Mehdizadeh M, Al-Taey DKA, Omidi A, Abbood AHY, Askar S, Topildiyev S, Pallathadka H, Asaad RR (2024). Advancing agriculture with machine learning: a new frontier in weed management. Frontiers of Agriculture Science and Engineering pp. 1-20. https://doi.org/10.15302/J-FASE-2024564

Murphy G (2004). Water pH and its effect on pesticides. Ontario: Ministry of Agriculture and Food. Available at: https://www.gov.on.ca/OMAFRA/english/crops/hort/news/grower/2004/08ng04a1.htm. Access: Aug. 12, 2024.

Oliveira GR, D’Alevedo LB, Lessa S da S, Caetano MMM, Goveia D, Tonello PS (2023). Chitosan biopolymer in glyphosate adsorption: use in environmental monitoring or remediation. Holos 6(39):1-13. https://doi.org/10.15628/holos.2023.16367

Petter AF, Segate D, Almeida FA, Neto FA, Pacheco LP (2012). Physical incompatibility of mixtures between herbicides and insecticides. Planta Daninha 30(2):449-457. https://doi.org/10.1590/S0100-83582012000200025

Punia SS, Soni J, Singh MSS, Kamboj P (2020). Management of herbicide resistant P. minor in wheat. Indian Journal of Weed Science 52(3):237-240. https://doi.org/10.5958/0974-8164.2020.00045.3

Radwan DEM, Mohamed AK, Fayez KA, Abdelrahman AM (2019). Oxidative stress caused by Basagran® herbicide is altered by salicylic acid treatments in peanut plants. Hel Iyon 5(5):1-8. https://doi.org/10.1016/j.heliyon.2019.e01791

Räsch A, Hunsche M, Mail M, Burkhardt J, Noga G, Pariyar S (2018). Agricultural adjuvants may impair leaf transpiration and photosynthetic activity. Plant Physiology and Biochemistry 132:229-237. https://doi.org/10.1016/j.plaphy.2018.08.042

Samota SR, Chhokar RS, Yadav DB, Kumar N, Gill SC, Mamrutha HM (2024). Pyroxasulfone based tank-mix herbicide combinations for diverse weed flora control in wheat. Crop Protection 181(106695):1-5. https://doi.org/10.1016/j.cropro.2024.106695

Schiessel JJ, Mello GR, Schmitt J, Pastorello LF, Bratti F, Oliveira Neto AM, Guerra N (2019). Weed interference periods in the common bean crop. Ravista de Ciências Agroveterinárias 18(4):430-437. https://doi.org/10.5965/223811711842019430

Silva-Matte SC, Costa NV, Pauly T, Coltro-Roncato S, Oliveira AC, Castagnara DC (2014). Variability of the droplet surface tension breakdown by the adjuvant (Aureo®) depending on water capture locations. Revista Agrarian **7**(24):264-270. https://ojs.ufgd.edu.br/index.php/agrarian/article/view/2609

Song Y, Huang G, Zheng L, Huang Q, Cao H. Li F, Zhao P, Zhang L, Cao C (2021). Polymer additives regulate the deposition behavior of pesticide droplets on target plants. Polymer Testing 93:1-8. https://doi.org/10.1016/j.polymertesting.2020.106958

Sorensen VM, Meggitt WF, Penner D (1987). The Interaction of acifluorfen and bentazon in herbicidal combinations. Weed Science 35(4):449-456. https://doi.org/10.1017/s0043174500060379

Staker RJ, Oliver LR (1998). Interaction of glyphosate with chlorimuron, fomesafen, imazethapyr and sulfentrazone. Weed Science 46(6):652-660. https://doi.org/10.1017/S0043174500089670

Striegel S, Oliveira MC, Arneson N, Conley SP, Stoltenberg DE, Werle R (2021). Spray solution pH and soybean injury as influenced by synthetic auxin formulation and spray additives. Weed Technology 35(1):113-127. https://doi.org/10.1017/wet.2020.89

Tavarese RM, Cunha JPAR (2023). Pesticide and adjuvant mixture impacts on the physical–chemical properties, droplet spectrum, and absorption of spray applied in soybean crop. AgriEngineering 5(1):646-659. https://doi.org/10.3390/agriengineering5010041

Vechia JFD, Ferreira MC, Andrade DJ (2018). Interaction of spirodiclofen with insecticides for the control of *Brevipalpus yothersi* in citrus. Pest Management Science 74:2438-2443. https://doi.org/10.1002/ps.4918