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Performance of Single and Sequential Applications of Dicamba and Glyphosate on Weed Control in Dicamba-Resistant Soybean

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ABSTRACT

The Intacta 2 Xtend system was developed to allow selective dicamba use in dicamba-resistant soybean (DRS), aiding in the management of tolerant and resistant broadleaf weeds. This study evaluated the control of broadleaf weeds following single or sequential postemergence applications of dicamba (alone or tank-mixed with glyphosate) in DRS. Experiments were arranged in a randomized block design with four replications. Treatments included single and sequential applications of dicamba (360 and 720 g a.e. ha⁻¹) and its tank mixture with glyphosate (1,080 g a.e. ha⁻¹), alongside weedy and weed-free checks. Weed control was assessed for *Conyza* spp., *Amaranthus viridis*, *Amaranthus hybridus*, *Euphorbia heterophylla*, *Ipomoea* spp., and *Raphanus raphanistrum*, along with soybean yield. Single dicamba applications at 360 g a.e. ha⁻¹ were insufficient to control *A. viridis*. Effective control of *A. hybridus*, *E. heterophylla*, and *Ipomoea* spp. required sequential dicamba at 720 g a.e. ha⁻¹ or dicamba (360 or 720 g a.e. ha⁻¹) tank-mixed with glyphosate. For *R. raphanistrum*, only sequential dicamba + glyphosate treatments were effective, whereas *Conyza* spp. was controlled only by sequential applications of dicamba (720 g a.e. ha⁻¹) + glyphosate. Overall, sequential dicamba + glyphosate applications provided superior weed control, without negatively impacting DRS yield.

1 | Introduction

The interference of weeds is a major limitation to crop productivity (Vitorino et al. 2017), and one of the main challenges in soybean crops is the widespread evolution of herbicide-resistant species. Among these, glyphosate resistance is especially prevalent, with 194 resistant biotypes reported globally in soybean production systems (Heap 2025).

New technologies for corn, soybeans, and other crops, which increase resistance to multiple herbicides and incorporate improved formulations, are additional tools for the effective and sustainable management of weeds (Nandula 2019). One of the technologies is dicamba-resistant soybean (DRS), which

was developed to improve postemergence control of problematic broadleaf weed species, allowing the use of dicamba alone or in combination with glyphosate (Behrens et al. 2007; Nandula 2019).

Dicamba is a synthetic auxin herbicide (Group 4) that binds to the auxin receptor in plant cells and disrupts several critical processes, leading to abnormal growth, cessation of growth, and vein deformation, ultimately causing plant death (Grossmann 2010; Underwood, Soltani, Robinson et al. 2017). It is absorbed by leaves, stems, and roots and has systemic action (Grossmann 2010; Egan and Mortensen 2012). The resistance in DRS is conferred by the expression of dicamba monooxygenase (DMO),

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which metabolizes dicamba into nonphytotoxic compounds, allowing for the selective control of weeds in soybeans (Behrens et al. 2007). In addition to dicamba, DRS is also resistant to glyphosate (Arias et al. 2017).

Dicamba stands out as a tool for managing resistant broadleaf weed species, especially when used in conjunction with herbicides with different mechanisms of action (MoA), which can mitigate selection pressure. However, the combined use of herbicides can either increase or decrease weed control (Soltani et al. 2020; Meyer, Peter et al. 2020). Synergism occurs in situations of greater control, which can result in higher rates of weed mortality and reduced interference of weeds in soybean crops (Soltani et al. 2020; Behrens and Lueschen 1979). On the other hand, in the case of antagonism, there is a reduction in weed control, a situation that is more frequently reported for combinations of auxinic herbicides with acetyl-CoA carboxylase (ACCase) inhibitors, primarily for grass weeds (Meyer, Norsworthy et al. 2020; Meyer, Peter et al. 2020).

Although several studies have evaluated dicamba–glyphosate mixtures and sequential applications, most of the available information is derived from North American production systems (Johnson et al. 2010; Soltani et al. 2020; Underwood et al., 2017; Underwood, Soltani, Robinson et al. 2017), which significantly differ in weed community composition from those in Santa Catarina, Brazil. Moreover, there is limited information on the soil and climate conditions in southern Brazil, particularly in Santa Catarina, where variations in temperature, rainfall distribution, soil texture, and organic matter can influence the performance of weed management.

Furthermore, the differential response of individual broadleaf weed species to single versus sequential applications of dicamba and glyphosate remains poorly documented, especially under field conditions. This lack of understanding at the species level limits the development of robust and locally adapted recommendations for weed management and may compromise long-term sustainability in DRS systems.

Therefore, this study aimed to evaluate the control of the main broadleaf weed species after single and sequential postemergence applications of dicamba, either alone or tank-mixed with glyphosate, in DRSs. Moreover, the study evaluated the relationship between the efficiency of weed control and soybean grain yield under the specific edaphoclimatic conditions of Santa Catarina, Brazil, addressing knowledge related to the specific responses of species and the regional adaptation of dicamba-based management strategies.

2 | Material and Methods

Each experiment was independently conducted during the 2021/2022 and 2022/2023 growing seasons at the Experimental Agricultural Farm of the Federal University of Santa Catarina, Curitibanos campus (27°16′36.01″S, 50°30′03.99″W; altitude of 998 m). Although conducted in different crop years, both experiments were carried out at the same site and during the same cultivation period, corresponding to the spring–summer transition in Brazil. This period is traditionally devoted to grain production, particularly soybean, ensuring that the experiments

represent typical soil and climatic conditions for soybean production in Santa Catarina State.

The regional climate is classified as Cfb (temperate, humid mesothermal climate with mild summers) according to Köppen (1948), with an average altitude of approximately 1,000 m. The mean annual rainfall is approximately 1,500 mm, and average temperatures range from 15°C to 25°C. The soil at the experimental site is classified as a Haplic Cambisol (Santos et al. 2025), corresponding to an Inceptisol according to the U.S. Soil Taxonomy (Brazilian Agricultural Research Corporation 2025). The soil physicochemical attributes were as follows: 52.5% clay, 23.80% silt, 23.70% sand, 4.75% organic matter, pH (H₂O) 6.00, 17.25 mg dm⁻³ of P, 78.00 mg dm⁻³ of K⁺, 10.72 cmolc dm⁻³ of Ca²⁺, 5.44 cmolc dm⁻³ of Mg²⁺, effective cation exchange capacity of 16.36 cmolc dm⁻³, and base saturation of 76.74%.

The experimental design was a randomized complete block design (RCBD) with 10 treatments and four replications (Table 1), conducted in both growing seasons. Dicamba and glyphosate doses were selected according to label recommendations. The single application (or the first application in sequential treatments) was performed at 14 days after soybean emergence (DAE), and the sequential application at 28 DAE.

The commercial products used were Atectra (dicamba, 480 g a.e. L⁻¹, DGA salt-2-(2-aminoethoxy)ethanol of 3,6-dichloro-o-anisic acid) and Trop (glyphosate, 360 g a.e. L⁻¹, isopropylamine salt). Herbicide applications were performed using a CO₂-pressurized backpack sprayer equipped with four flat-fan air-induction nozzles (AI 110.015), spaced 0.5 m apart, operating at a pressure of

TABLE 1 | Treatments with dicamba (Dic) and glyphosate (Gly): alone, mixed (+), or sequential (/), applied at postemergence of soybean, including weed-free and weedy checks in the 2021/2022 and 2022/2023 harvest seasons—Curitibanos, SC.

Treatment	First application	Second application
Dic	360 g a.e. ha ⁻¹	—
Dic	720 g a.e. ha ⁻¹	—
Dic/Dic	360 g a.e. ha ⁻¹	360 g a.e. ha ⁻¹
Dic/Dic	720 g a.e. ha ⁻¹	720 g a.e. ha ⁻¹
Dic + Gly	360 g a.e. ha ⁻¹ + 1080 g a.e. ha ⁻¹	—
Dic + Gly	720 g a.e. ha ⁻¹ + 1080 g a.e. ha ⁻¹	—
Dic + Gly/ Dic + Gly	360 g a.e. ha ⁻¹ + 1080 g a.e. ha ⁻¹	360 g a.e. ha ⁻¹ + 1080 g a.e. ha ⁻¹
Dic + Gly/ Dic + Gly	720 g a.e. ha ⁻¹ + 1080 g a.e. ha ⁻¹	720 g a.e. ha ⁻¹ + 1080 g a.e. ha ⁻¹
Weed-free check	—	—
Weedy check	—	—

189 kPa and a speed of 3.6 km h⁻¹, resulting in an application rate of 150 L ha⁻¹.

The first herbicide application was carried out on November 24 and November 30 in the 2021/2022 and 2022/2023 growing seasons, respectively, when soybean plants had fully developed unifoliolate leaves. At this stage, the leaflet edges of the first trifoliolate leaf no longer touched, characterizing the V1 stage (Fehr et al. 1971). The sequential application was performed 14 days after the first application (December 8 and December 14 for the 2021/2022 and 2022/2023 seasons, respectively), when soybean plants were at the V4 stage, corresponding to the third fully developed trifoliolate leaf (Fehr et al. 1971). During applications, air temperature ranged from 22.4°C to 26.5°C, relative humidity from 68% to 86%, and wind speed did not exceed 3 km h⁻¹.

Each experimental plot measured 2.25 m in width and 5.0 m in length (11.25 m²), comprising five soybean rows spaced 0.45 m apart. For evaluations, including harvest, the usable area consisted of the three central rows over a 3.0 m length, totaling 4.05 m².

The soybean cultivar used in the 2021/2022 growing season was Soytech 591 i2x (maturity group 5.9), with indeterminate growth habit, white flowers, and gray pubescence (BASF 2025a). In the 2022/2023 season, the cultivar Soytech 580 i2x (maturity group 5.8), also with indeterminate growth habit, purple flowers, and gray pubescence, was used (BASF 2025b).

Sowing was performed on November 3 and November 9 for the 2021/2022 and 2022/2023 growing seasons, respectively, following regional climatic zoning recommendations. In both seasons, soybean was established under a no-tillage system on *A. strigosa* straw, which was burndown 30 days prior to sowing. The seeding rate was adjusted to achieve a final plant population of 280,000 plants ha⁻¹. Fertilization, pest, and disease management followed the recommendations for soybean production in Santa Catarina (Martin et al. 2022).

Weed species composition and density were determined using the quadrat inventory method. An open quadrat measuring 0.5 × 0.5 m (0.25 m²) was randomly placed once within each experimental unit, excluding a 0.5-m border from plot edges. Based on these assessments, the weed community and density of each species were determined. Weed control was visually assessed for *Conyza* spp. (2-leaf stage to regrowth plants; 3 plants m⁻²), *A. viridis* (2–4 leaves; 15 plants m⁻²), *A. hybridus* (2–4 leaves; 12 plants m⁻²), *E. heterophylla* (4–6 leaves; 10 plants m⁻²), *Ipomoea* spp. (4–6 leaves; 5 plants m⁻²), and *R. raphanistrum* (4–8 leaves; 4 plants m⁻²), using a visual control scale ranging from 0 to 100% (0 = no control and 100 = complete control) at 15 and 30 days after the second herbicide application (DAA), according to the Brazilian Weed Science Society methodology (BWSS 1995). These broadleaf weed species are widely distributed in soybean fields in Santa Catarina State.

At preharvest, the number of soybean plants per meter (two samples per plot) and the number of pods per plant (five samples per plot) were determined. Soybean was harvested manually at the R8.0 growth stage (95% of pods with mature color) (Fehr et al. 1971). After harvest, hundred-seed weight and grain yield (kg ha⁻¹) were determined, with seed moisture standardized to 13%.

Data were tested for compliance with the assumptions required for parametric statistical analyses. After confirmation, the data were subjected to analysis of variance (ANOVA) at a 5% significance level ($p < 0.05$). When the *F* test was significant, treatment means were grouped using the Scott–Knott clustering test at a 5% significance level. This test groups treatments into statistically distinct clusters by maximizing between-group variation and minimizing within-group variation, facilitating interpretation in experiments with a large number of treatments, and avoiding overlapping groups commonly observed with pairwise comparison tests. Data were analyzed separately by growing season due to biologically distinct responses associated with differences in climatic conditions, weed species composition, and precipitation. All analyses were performed using SISVAR software (Ferreira 2019).

3 | Results

Weed control results, expressed as a percentage, are presented for 15 and 30 DAA. Figure 1 shows weed control for *Conyza* spp., *A. viridis*, *E. heterophylla*, and *I. spp.* for the 2021/2022 season. Figure 2 presents control data for *R. raphanistrum*, *A. hybridus*, *E. heterophylla*, and *I. spp.*, for the 2022/2023 season. Table 2 presents the results of the analysis of variance for soybean yield and yield components in the 2021/2022 and 2022/2023 growing seasons. Table 3 shows soybean productivity and the number of pods per plant following the application of dicamba and glyphosate in DRS during the 2021/2022 and 2022/2023 seasons.

3.1 | *Conyza* spp.

In the 2021/2022 season, the highest levels of control of *Conyza* spp. at 15 DAA were observed in treatments with a single application of dicamba (720 g a.e. ha⁻¹) tank-mixed with glyphosate and in sequential applications of dicamba, either alone (720 g a.e. ha⁻¹) or in combination with glyphosate, regardless of dose. These treatments resulted in control levels ranging from 61.25% to 73.75%.

At 30 DAA, only the sequential application of dicamba (720 g a.e. ha⁻¹) + glyphosate did not differ statistically from the weed-free control. This treatment clearly outperformed the others, which exhibited control levels between 38.75% and 77.50%. The single application of dicamba at 360 g a.e. ha⁻¹ resulted in the lowest control (38.75%), performing significantly worse than all other herbicide treatments.

These results highlight the difficulty of achieving effective control of *Conyza* spp.; among the eight herbicide treatments evaluated in this study, only one achieved a control level equal to or greater than 85% at 30 DAA. The findings reinforce the need to adopt more robust and integrated weed management (IWM) strategies, particularly given the variable response of *Conyza* spp. to the different herbicide application schemes evaluated. Even with the adoption of DRS technology, effective control of *Conyza* spp. must be carefully planned prior to soybean sowing.

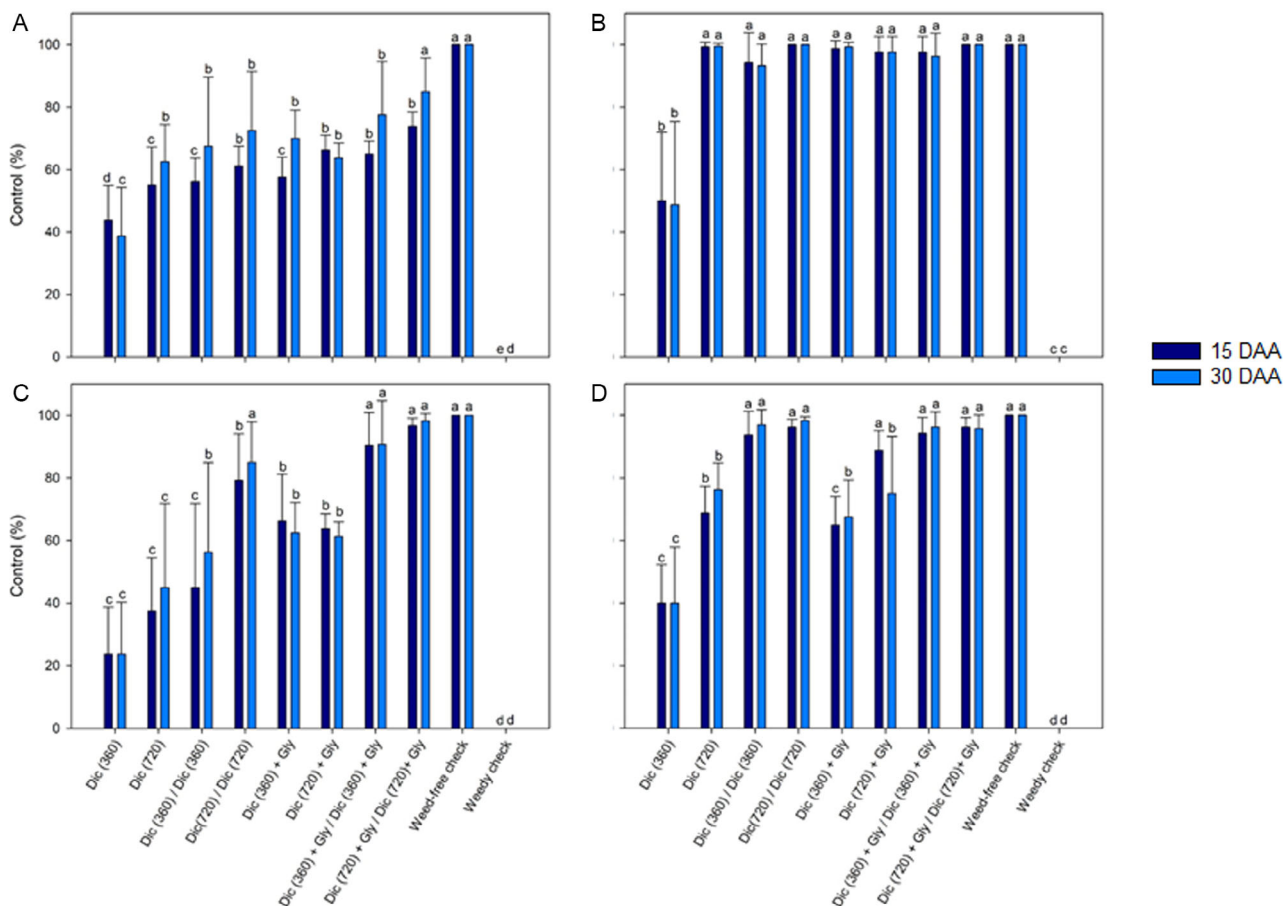


FIGURE 1 | Percentage control (%) of *Conyza* spp. (A), *Amaranthus viridis* (B), *Euphorbia heterophylla* (C), and *Ipomoea* spp. (D) at 15 and 30 days after application (DAA) of dicamba and glyphosate in dicamba-resistant soybean. Data refer to the 2021/2022 season, Curitibaanos, SC. Means followed by the same lowercase letter within each evaluation period do not statistically different according to the Scott-Knott test at the 5% significance level. The vertical bars in each treatment indicate the standard deviation of the mean ($n = 4$).

3.2 | *R. raphanistrum*

The species *R. raphanistrum* infested soybean only in the 2022/2023 season. The treatments applied exclusively at stage V1 or sequentially, using only dicamba (360 g a.e. ha⁻¹ or 720 g a.e. ha⁻¹), as well as a single dicamba application tank-mixed with glyphosate, resulted in control levels $\leq 80.75\%$ at 15 DAA. At 30 DAA, the control rates remained similar. Control efficiency for *R. raphanistrum* at 30 DAA ($\geq 98.25\%$) was achieved only with the sequential application of the dicamba + glyphosate mixture, regardless of the dose of the auxinic herbicide.

3.3 | *A. viridis* and *A. hybridus*

In the 2021/2022 season, *A. viridis* showed excellent control with the study herbicide treatments ($>90\%$), in both assessments, except for the single application of dicamba (360 g a.e. ha⁻¹). In this treatment, there was 48.75% control, which was significantly lower than the other herbicide treatments and the weed-free check at 30 DAA.

In the 2022/2023 season, the experimental area was infested by the species *A. hybridus*. This species was more difficult to control in comparison to *A. viridis*. The single application of dicamba (360 g a.e. ha⁻¹) again resulted in the lowest control, with values

of 47.50% at both 15 and 30 DAA. However, the following treatments did not exceed 84% control at 15 and 30 DAA: the sequential application of dicamba at 360 g a.e. ha⁻¹, or the single application of the mixtures of dicamba (360 or 720 g a.e. ha⁻¹) + glyphosate.

At 30 DAA, only the sequential application of dicamba mixed with glyphosate (regardless of the dose of dicamba) and the sequential application of dicamba alone at a dose of 720 g a.e. ha⁻¹, promoted similar weed control to that of the control treatment. *A. hybridus* requires sequential applications of dicamba alone at the highest dose (720 g a.e. ha⁻¹) or dicamba (360 or 720 g a.e. ha⁻¹) + glyphosate.

These results indicate that the study of herbicide combinations offer different possibilities for efficient management of *Amaranthus*. Some treatments promoted consistently high control, while others presented limited performance.

3.4 | *E. heterophylla*

Control of *E. heterophylla* followed a similar pattern across both growing seasons. In the 2021/2022 season, single applications of dicamba tank-mixed with glyphosate provided 66.25% and 63.75% control at 15 DAA for dicamba rates of 360 and 720 g a.e. ha⁻¹, respectively, whereas the sequential application of dicamba alone at 720 g a.e. ha⁻¹ resulted in 79.25% control.

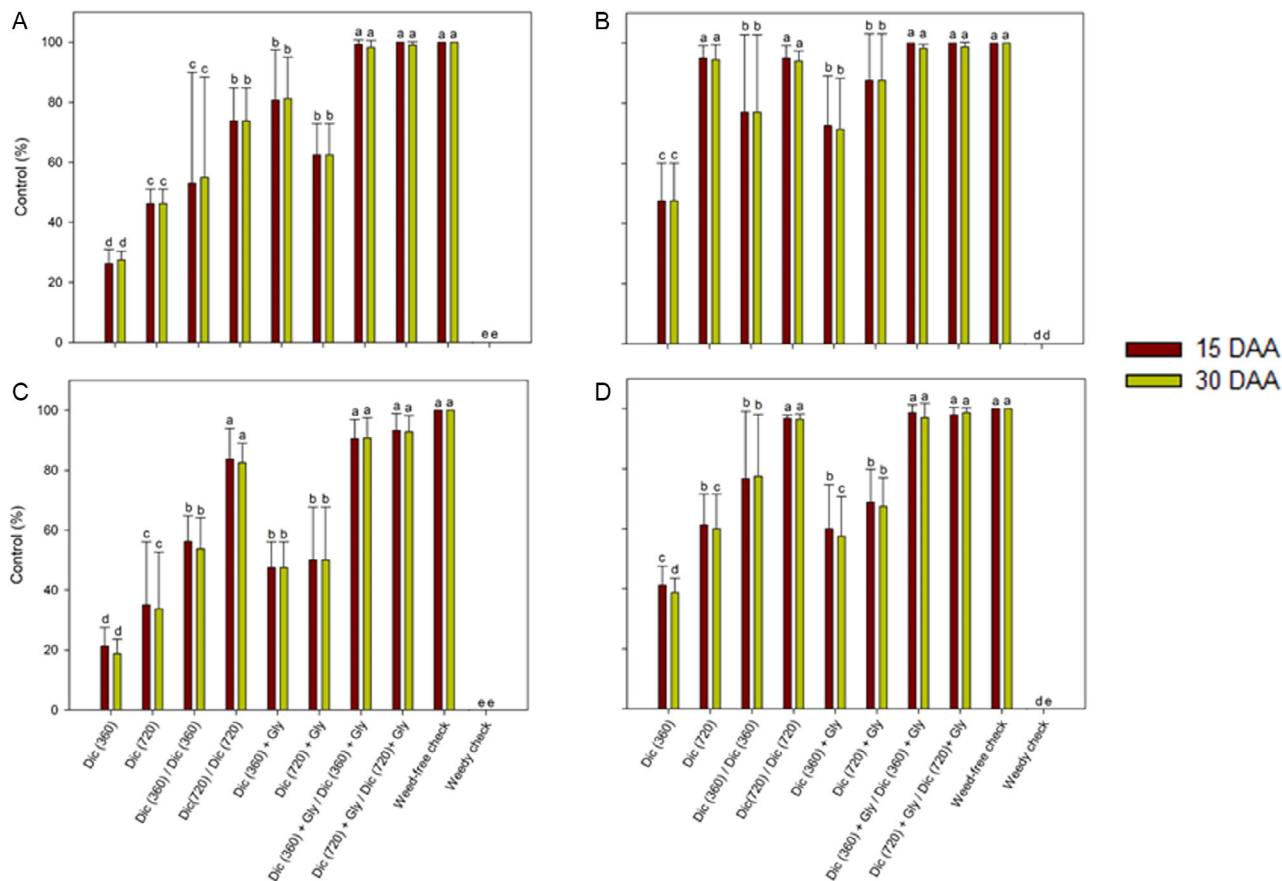


FIGURE 2 | Percentage control (%) of *Raphanus raphanistrum* (A), *Amaranthus hybridus* (B), *Euphorbia heterophylla* (C), and *Ipomoea* spp. (D) at 15 and 30 days after application (DAA) of dicamba and glyphosate in dicamba-resistant soybean. Data refer to the 2022/2023 growing season, Curitiba, SC. Means followed by the same lowercase letter within each evaluation period do not statistically differ according to the Scott–Knott test at the 5% significance level. The vertical bars in each treatment indicate the standard deviation of the mean ($n = 4$).

TABLE 2 | Summary of analysis of variance (p -value) for the evaluation of yield and productivity components of DRS in the 2021/2022 and 2022/2023 harvest seasons—Curitiba, SC.

2021/2022 harvest				
Source of variation	Yield components			Yield
	NP	NPP	HSW	
Treatment	0.97 ^a	0.11 ^a	0.33 ^a	0.00 [*]
Average	9.18	92.33	18.97	5,197.24
CV (%)	20.85	20.29	2.97	15.67
2022/2023 harvest				
Source of variation	Yield components			Yield
	NP	NPP	HSW	
Treatment	0.20 ^a	0.04 [*]	0.15 ^a	0.00 [*]
Average	9.23	58.53	24.95	5,006.93
CV (%)	12.61	17.47	3.29	14.72

Abbreviations: CV (%), coefficient of variation; HSW, hundred-seed weight;

NP, number of plants per meter; NPP, number of pods per plant.

^aNonsignificant according to the F -test at the 5% probability level.

^{*}Significant according to the F -test at the 5% probability level.

In contrast, sequential applications of dicamba tank-mixed with glyphosate achieved significantly higher control, ranging from 90.50% to 96.75% at 15 DAA.

At 30 DAA, only treatments involving sequential applications—specifically dicamba tank-mixed with glyphosate and dicamba alone at 720 g a.e. ha⁻¹—did not differ statistically from the weed-free check, with control levels ranging from 85% to 98.25%, indicating increased efficacy compared with the 15 DAA assessment.

In the 2022/2023 season, the single application of dicamba at 360 g a.e. ha⁻¹ resulted in the lowest control, with only 21.25% at 15 DAA. Conversely, sequential applications of dicamba at 720 g a.e. ha⁻¹ and dicamba (360 or 720 g a.e. ha⁻¹) tank-mixed with glyphosate provided initial control ranging from 83.75% to 93.25% at 15 DAA, not differing statistically from the weed-free check. This level of control was maintained at 30 DAA, with all sequential treatments exhibiting efficacy above 80% and being statistically grouped as effective for soybean crop protection.

3.5 | *Ipomoea* spp.

For the control of *Ipomoea* spp. in the 2021/2022 season, at 15 DAA, the single application of dicamba tank-mixed with glyphosate at 720 g a.e. ha⁻¹ provided control comparable to that of sequential applications, reaching 88.75%. By contrast, in the 2022/2023 season, the same treatment resulted in 20.00% lower control at 15 DAA, with only 68.75% control observed.

TABLE 3 | Productivity and number of pods per plant after the application of dicamba and glyphosate to DRS in the 2021/2022 and 2022/2023 harvest seasons—Curitibanos, SC.

Treatments	2021/2022	2022/2023	
	Productivity, kg ha ⁻¹	NPP	Productivity, kg ha ⁻¹
Dic (360)	4,907.73 (±527.53) a	55.50 (±14.75) b	4,437.93 (±826.21) b
Dic (720)	5,609.97 (±742.56) a	55.00 (±10.16) b	4,722.60 (±585.46) a
Dic (360)/Dic (360)	5,185.28 (±1,008.21) a	54.00 (±9.83) b	5,790.33 (±918.19) a
Dic(720)/Dic (720)	5,886.99 (±598.01) a	57.50 (±10.47) b	5,348.19 (±544.37) a
Dic (360) + Gly	5,971.54 (±972.56) a	69.25 (±9.94) b	5,165.61 (±1,220.26) a
Dic (720) + Gly	4,832.27 (±472.76) a	52.50 (±8.89) a	5,055.72 (±1,079.76) a
Dic (360) + Gly/Dic (360) + Gly	5,035.49 (±787.80) a	63.75 (±11.47) a	5,783.41 (±633.48) a
Dic (720) + Gly/Dic (720) + Gly	5,571.43 (±966.71) a	70.50 (±9.88) a	5,139.66 (±223.46) a
Weed-free check	6,039.82 (±711.26) a	62.50 (±6.35) a	5,257.33 (±264.91) a
Weedy check	2,931.91 (±1,114.30) b	44.75 (±4.65) b	3,368.47 (±360.76) b
CV (%)	15.67	17.47	14.72

Note: The glyphosate dose was 1,080 g a.e. ha⁻¹; averages followed by the same lowercase letter in the column do not differ from each other, according to Scott Knott's test at 5% probability; values in parentheses indicate the standard deviation.

Abbreviations: CV (%), coefficient of variation, in percentage; NPP, number of pods per plant.

At 30 DAA in the 2021/2022 season, sequential applications maintained significantly higher control than single application. Control levels for sequential treatments ranged from 93.75% to 96.25% at 15 DAA and increased to between 95.75% and 98.25% at 30 DAA. Similarly, in the 2022/2023 season, sequential treatments showed high and sustained efficacy in the control of *Ipomoea* spp., with values ranging from 96.75% to 98.75% at 15 DAA and from 96.50% to 98.75% at 30 DAA. The only exception in this season was the sequential application of dicamba alone at the lowest dose (360 g a.e. ha⁻¹), which resulted in 77.50% control at 30 DAA.

The response pattern observed for *Ipomoea* spp. was similar to that of *E. heterophylla*, for which control equivalent to the weed-free check was achieved only with sequential applications at 30 DAA in both the 2021/2022 and 2022/2023 seasons.

3.6 | Yield and Productivity Components

In the 2021/2022 season, no significant differences among treatments were observed for soybean yield, except for the weedy control. All herbicide-based treatments, applied either alone or in mixtures, and as single or sequential applications, resulted in yields statistically similar to the weed-free control. In contrast, crop-weed coexistence led to a significantly lower yield, reaching 2,931.91 kg ha⁻¹, whereas values above 4,800.00 kg ha⁻¹ were recorded for the other treatments.

In the 2022/2023 season, significant treatment effects were observed for the number of pods per plant and soybean yield. Higher numbers of pods per plant were obtained with dicamba (720 g a.e. ha⁻¹) mixed with glyphosate and with sequential applications of dicamba + glyphosate, which were statistically similar to the weed-free control. In contrast, treatments involving dicamba applied alone and the single application of dicamba (360 g a.e. ha⁻¹) mixed with glyphosate resulted in numbers of pods per plant comparable to the weedy control.

For soybean yield in 2022/2023, the single application of dicamba at 360 g a.e. ha⁻¹ and the weedy control resulted in significantly lower yields (3,368.47 to 4,437.93 kg ha⁻¹), whereas the remaining treatments maintained yields similar to the weed-free condition (4,722.60 to 5,790.33 kg ha⁻¹).

4 | Discussion

4.1 | Weed Control

Conyza bonariensis is widely recognized for its interference in soybean crops. For weed control, one available option is the use of single applications of dicamba (300 g a.e. ha⁻¹) + glyphosate (900 g a.e. ha⁻¹). Byker et al. (2013) reported control levels of *C. bonariensis* of 96% and 97% at 4 and 8 weeks after application, respectively. In contrast, the present study showed that only the sequential application of dicamba (720 g a.e. ha⁻¹) + glyphosate resulted in the highest control level (85%) among the evaluated treatments.

Soares et al. (2012) estimated the dicamba dose required to achieve 50% control (C_{50}) of *C. bonariensis* at 35 DAA. The C_{50} for the mixture of glyphosate (540 g a.e. ha⁻¹) + dicamba was 194.22 g a.e. ha⁻¹, compared with 226.41 g a.e. ha⁻¹ for dicamba applied alone. This finding demonstrates that mixing dicamba with glyphosate improves control efficiency, allowing lower doses of the auxinic herbicide to achieve the same level of control.

The glyphosate + dicamba mixture is not antagonistic for *C. bonariensis* control and may even result in additive effects, including in glyphosate-resistant populations (Soares et al. 2012).

For *Amaranthus* spp., applications of dicamba (300 g a.e. ha⁻¹) + glyphosate (900 g a.e. ha⁻¹) resulted in control exceeding 96%, both with a single application at the V2 stage and with sequential applications (V2 + V4). However, when applications were

performed only at the V4 stage, weed control was significantly reduced. Under this condition, dicamba alone provided only 53% control, compared with 89% for glyphosate and 88% for the dicamba + glyphosate mixture 1 week after application (Underwood, Soltani, Robinson et al. 2017). These findings align with the present study, in which sequential applications (V1 + V4) of dicamba + glyphosate, regardless of dose, ensured control above 96% at 15 and 30 DAA for *A. viridis* and *A. hybridus*. Additionally, single applications of dicamba at 720 g a.e. ha⁻¹ also demonstrated efficacy.

Similarly, Joseph et al. (2018) reported 92% control of 30-cm-tall *A. palmeri* using dicamba (840 g a.e. ha⁻¹) + glyphosate (1120 g a.e. ha⁻¹), compared with 84% control with dicamba alone applied to plants of the same height. Although treatments with dicamba or glyphosate alone did not differ statistically, the mixture exhibited a synergistic effect, resulting in an 8% increase in control efficacy.

For *E. heterophylla* biotypes sensitive to dicamba and 2,4-D, Badia (2019) reported difficulties in controlling plants at advanced growth stages (10–12 leaves); even high application rates of auxin-mimicking herbicides (1000 g a.e. ha⁻¹) did not exceed 70% control. Additionally, Steckel et al. (2006) demonstrated that control efficiency is directly related to application rate, corroborating the results of the present study. Consistently, only sequential applications of dicamba (720 g a.e. ha⁻¹), alone or mixed with glyphosate, ensured control exceeding 80% at 30 DAA. It should be noted that *E. heterophylla* plants in this study were at early growth stages (≤ 6 leaves).

Similar behavior has been reported for *Ipomoea* spp. For *I. nil*, dicamba does not achieve complete control even at high rates, making sequential applications or tank mixtures with glyphosate essential (Osipe et al. 2017). According to those authors, plants at the 4- to 6-leaf stage require 292.9 and 268.7 g a.e. ha⁻¹ of dicamba and 2,4-D, respectively, to reach 95% control (C_{95}). In more advanced stages (10–12 leaves), achieving the same level of control requires a 60% increase in the dicamba dose, compared with only a 4.5% increase for 2,4-D. Although, 2,4-D was more effective than dicamba when applied alone, the dicamba + glyphosate mixture was essential to reach 95% control at rates below 201.6 g a.e. ha⁻¹, which is substantially lower than the 731.3 g a.e. ha⁻¹ required for dicamba applied alone. Furthermore, the authors reported that auxinic herbicides combined with glyphosate achieved complete control regardless of plant growth stage.

In the present study, dicamba alone showed unsatisfactory efficacy against *R. raphanistrum*, and only sequential applications of dicamba + glyphosate resulted in control levels $\geq 90\%$. Similar results were reported by Goggin et al. (2018), who observed a positive relationship between dicamba dose and control level. However, complete control (100%) of sensitive *R. raphanistrum* biotypes required rates exceeding 1000 g a.e. ha⁻¹, which surpass the maximum recommended dicamba dose (~ 720 g a.e. ha⁻¹). The high aggressiveness of *R. raphanistrum*, characterized by rapid early growth, high biomass production, and a short life cycle (Silva et al. 2007), contributes to its persistence in agricultural systems. Inadequate desiccation before soybean sowing can expand the soil seed bank and intensify crop-weed competition, resulting in irreversible yield losses (Agostinetto et al. 2014).

The synergistic effect of glyphosate and dicamba has also been demonstrated for *S. rhombifolia*, for which dicamba rates exceeding 1,008 g a.e. ha⁻¹ are required to achieve 80% control (C_{80}). Osipe (2015) reported that tank mixing dicamba with glyphosate reduced the required dicamba dose by 87.70%. This finding was corroborated by Osipitan et al. (2019), who emphasized that herbicides applied alone generally require higher rates to achieve equivalent control. For species such as *A. artemisiifolia*, *C. album*, *P. maculosa*, *E. crus-galli*, and *S. viridis*, dicamba + glyphosate mixtures, applied either singly or sequentially, ensured consistent control throughout the soybean-growing season (Underwood, Soltani, Robinson et al. 2017).

For *A. tenella*, Pereira et al. (2020) reported 100% control at 14 DAA with dicamba + glyphosate or with dicamba alone at rates ≥ 201.6 g a.e. ha⁻¹. This result contrasts with the present study, in which all evaluated weed species showed $< 50\%$ control at 15 DAA when dicamba was applied alone at 360 g a.e. ha⁻¹. Single applications of dicamba at 720 g a.e. ha⁻¹ were effective only for *A. viridis*, with control exceeding 94.5%.

Joseph et al. (2018) also demonstrated that dicamba (560 g a.e. ha⁻¹) + glyphosate (1540 g a.e. ha⁻¹), applied 28–45 days after soybean sowing, resulted in $> 90\%$ control of *A. palmeri*, *C. album*, and *Abutilon theophrasti* at 14 and 28 DAA, reducing total weed biomass by 98%. These results indicate that consistent weed control with dicamba often depends on higher doses or sequential applications.

Nevertheless, some species may not respond positively to dicamba + glyphosate mixtures. Joseph et al. (2018) observed reduced control of *S. obtusifolia* with dicamba + glyphosate compared with glyphosate alone when applied to plants ≤ 5 cm tall. At heights between 5 and 30 cm, control levels were similar among dicamba, glyphosate, and their mixture.

Radiometric studies have shown that glyphosate absorption and translocation can be reduced when mixed with dicamba, depending on the species (Meyer, Peter et al. 2020). In *E. crus-galli*, ¹⁴C-glyphosate absorption decreased from 25% to 21% when dicamba was added. In *A. palmeri*, dicamba + glyphosate reduced phloem transport of ¹⁴C-glyphosate from 11% to 7% of the applied dose. Despite this, dicamba activity was enhanced in the mixture, as evidenced by increased levels of dicamba-derived metabolites, such as 3,6-dichlorosalicylic acid (DCSA) and 5-OH-dicamba.

The development of dicamba-resistant soybean cultivars enables the introduction of a new mechanism of action, increasing the effectiveness and consistency of postemergence broadleaf weed control programs (Johnson et al. 2010). The present study highlights the importance of dicamba + glyphosate mixtures for effective control of weed species prevalent in Brazilian soybean systems, including glyphosate-tolerant and resistant populations.

Dicamba is an effective herbicide for controlling economically important broadleaf weeds, such as *Amaranthus* spp., *Bidens pilosa*, and *E. heterophylla*. Its combination with glyphosate has been reported to be synergistic, resulting in enhanced weed control efficacy (Byker et al. 2013). Therefore, precise knowledge of herbicide activity and appropriate dose selection are essential for effective weed management in soybean production systems, particularly under summer climatic conditions that favor rapid weed emergence and growth.

In Santa Catarina State, summer is the main growing season, while winter crops occupy more limited areas alongside cover crops and annual pastures. This crop rotation generates heterogeneous management scenarios, ranging from fallow fields—favoring soil seed bank accumulation—to areas cultivated with cover crops or cash crops. Under these conditions, weed interference varies considerably, and exclusive reliance on glyphosate is often insufficient.

Thus, the combined use of herbicides with different mechanisms of action, such as glyphosate (EPSPS inhibitor) and dicamba (synthetic auxin), represents a practical and effective strategy for weed management under field conditions. The association broadens the weed control spectrum, reduces selection pressure for resistance, and minimizes weed interference with soybean yield.

4.2 | Productivity Components

The contrasting responses observed between the 2021/2022 and 2022/2023 growing seasons indicate that soybean performance under different weed management strategies was strongly influenced by environmental conditions. During the 2021/2022 harvest season, soybean productivity was affected exclusively by crop-weed coexistence, whereas no significant differences were detected among herbicide-based treatments. In that season, all treatments containing dicamba—applied alone or tank-mixed with glyphosate—maintained statistically similar productivity to the weed-free check, with yields ranging from 4,832.27 to 6,039.82 kg ha⁻¹. In contrast, the weedy check yielded only 2,931.91 kg ha⁻¹, representing a productivity loss of 51.46% relative to the weed-free control, thereby reinforcing the critical importance of effective weed management.

Data from the 2021/2022 growing season indicate that plots lacking weed control suffered a severe yield decline. This magnitude of loss implies that cultivating 2 ha without weed management would be required to achieve the same production obtained from a single, well-managed hectare of soybeans. These findings suggest that under more favorable growing conditions or reduced weed pressure, soybean plants were able to partially compensate for initial differences in weed management, maintaining productivity levels comparable to the weed-free condition.

Although the yield components evaluated during the 2021/2022 season—number of plants, number of pods per plant, and 100-seed weight—did not differ statistically among treatments, the observed differences in productivity may be attributed to yield components that were not directly measured. These include the number of nodes per plant, number of pods per node, number of seeds per pod, and number of grains per plant (Egli 2023). Yield components can be defined as follows: the number of plants per area, reflecting stand establishment success; the number of pods per plant, indicating branching and fertilization efficiency; the number of seeds per pod, associated with reproductive efficiency; and the 100-seed weight, expressing the plant's capacity for photoassimilate synthesis and translocation during grain filling—a process that is particularly sensitive to competitive stress and herbicide application timing (Osipitan et al. 2019). Due to their multiplicative nature, reductions in one or more of these components can result in substantial yield losses.

In contrast, the 2022/2023 growing season exhibited greater sensitivity to weed management strategies, as evidenced by significant effects on both the number of pods per plant and grain yield, highlighting the interaction between weed control practices and seasonal variability. In this season, treatments involving dicamba applied alone—either as single or sequential applications at 360 and 720 g a.e. ha⁻¹, as well as the single application of dicamba (360 g a.e. ha⁻¹) + glyphosate, resulted in a lower number of pods per plant, statistically similar to the weedy check. These responses are consistent with the lower weed control levels observed in these treatments.

Weed interference restricts essential resources such as light, water, and nutrients, directly impairing the development of soybean reproductive structures (Nichols et al. 2015; Ramos et al. 2019). Osipitan et al. (2019) reported increases of 56.67% and 60.08% in pod number in weed-free areas compared to infested areas, whereas the increase observed in the present study was 28.4%, indicating a strong influence of environmental conditions and weed pressure on reproductive development.

Despite the reduction in pod number, grain yield was significantly reduced only in the treatment with dicamba applied alone at 360 g a.e. ha⁻¹ and in the weedy check. This finding indicates that low weed control levels (< 50%) were insufficient to sustain adequate grain yield ($\geq 4,722.60$ kg ha⁻¹). These results are consistent with previous reports, such as Underwood, Soltani, Hooker et al. (2017), who observed yield losses ranging from 29.63% to 33.33% following single dicamba applications, and El-Metwally et al. (2018), who emphasized the necessity of effective weed control to preserve soybean yield.

Across both growing seasons, crop-weed coexistence resulted in the most pronounced yield losses, reinforcing the critical role of sustained weed control in soybean production. Yield reductions of 51.46% in 2021/2022 and 35.93% in 2022/2023 under weedy conditions demonstrate the strong competitive ability of weed communities for essential resources. These results are consistent with previous studies reporting soybean yield losses ranging from 30% to over 60% under uncontrolled weed interference, underscoring that the absence of weed management poses a greater risk to yield than differences among chemical control strategies.

The comparison between dicamba applied alone and dicamba tank-mixed with glyphosate revealed a clear advantage of herbicide mixtures, particularly during the 2022/2023 season. Treatments involving dicamba alone, regardless of rate or application strategy, resulted in reduced pod number and, in some cases, decreased grain yield, whereas dicamba-glyphosate mixtures maintained yield components and productivity at levels comparable to the weed-free check. The superior performance of herbicide mixtures may be attributed to a broader weed control spectrum and greater consistency of control, reducing weed escapes and competition during critical soybean growth stages.

Application strategy also played a key role in determining treatment efficacy. Sequential applications, especially when dicamba was combined with glyphosate, resulted in higher pod numbers and more stable yields compared with single applications. This response suggests that sequential applications extend the weed-free period and minimize interference from late-emerging weeds, which is particularly important under high weed pressure or prolonged emergence patterns. Conversely, single applications—particularly those involving lower dicamba rates—were more

susceptible to yield penalties, likely due to insufficient duration of weed control.

In the present study, the mixture of glyphosate with dicamba (360 or 720 g a.e. ha⁻¹), particularly under sequential application regimes, ensured weed control levels above 90%, resulting in yields comparable to the weed-free check. Herbicide synergism may be associated with the combined action on different metabolic pathways, as discussed by Meyer, Peter et al. (2020), who emphasized the importance of understanding herbicide behavior in plants through modeling and field validation. Although the treatments exhibited yield ranges of 1,207.55 kg ha⁻¹ in 2021/2022 and 1,352.40 kg ha⁻¹ in 2022/2023, the Scott-Knott test grouped them into homogeneous clusters ($\alpha = 5\%$). This outcome explains why significant differences were observed in weed control, while final grain yield did not differ statistically among several herbicide treatments.

Overall, the results demonstrate that although soybean can tolerate variations in chemical weed management under certain conditions, effective and sustained weed control is essential to safeguard yield potential, particularly in seasons characterized by greater environmental or competitive stress. The use of herbicide mixtures and sequential application strategies represents a reliable approach to improving weed control efficiency, stabilizing yield components, and reducing the risk of productivity losses across growing seasons.

4.3 | Environmental and Ecological Impacts

The use of glyphosate and dicamba tank mixtures presents notable environmental and ecological concerns. A major issue is that the combination lowers the pH of the spray mixture, promoting dicamba volatilization (Muller and Steckel 2019; Carbonari et al. 2022). Although this risk is addressed through the use of mitigating additives, the problem persists. Osipitan et al. (2019) showed that applying the DGA dicamba formulation with VaporGrip + glyphosate reduces volatilization compared to the DGA formulation + glyphosate, indicating that the improved chemistry only minimizes the issue. As a result, vapor drift can still cause phytotoxicity and economic damage to adjacent dicamba-sensitive soybean crops.

A 2017 survey conducted by Werle, Proost et al. (2018) in Nebraska, USA, evaluated dicamba-resistant (DR) soybean use across 11,862 ha. Of this total, 84% of the area also received glyphosate management. While Xtend technology improved weed control across 10,338 ha, its widespread adoption without adequate technical knowledge led to off-target injury on neighboring non-DR soybean crops. This damage was reported in approximately 20% of the areas, primarily attributed to herbicide transport mechanisms: volatilization (69%), physical drift (23%), and thermal inversion (8%). Furthermore, in the United States, over 2,700 farmer complaints were filed in 2017 due to damage to non-DR soybeans (Oseland et al. 2024). Given these risks, the Brazilian Association of Soybean Producers (Aprosoja 2019) issued warnings regarding the use of Xtend technology and dicamba, aimed at mitigating environmental hazards and ensuring application safety. Studies confirm that doses as low as 0.71 g a.e. ha⁻¹ of the DGA formulation can cause a 50% injury level in Roundup Ready (RR) soybeans at the V2 stage (Osipitan et al. 2019).

In Brazil, the application of auxin herbicides is regulated by strict meteorological conditions: Wind speed must be less than 10 km h⁻¹, relative humidity greater than 55%, and temperature below 30°C. In addition, applicators must be certified in Good Agricultural Practices, as required by the Secretariat of Agriculture, Livestock, Sustainable Production and Irrigation (SEAPDR-RS 2019). Other critical operational factors for mitigating herbicide drift include wind direction, droplet size, adjuvants, spray pressure, nozzle type, and spray volume (Butts et al. 2019; Werle, Proost et al. 2018).

In the USA, approximately 60% of soybean production areas are managed exclusively with glyphosate + dicamba (Werle et al. 2018a), significantly increasing selection pressure for herbicide-resistant weed biotypes. Mitigating the rate of resistance evolution requires integrating diverse IWM strategies, including nonchemical control methods such as identification of weed species present in the area; prevention of seed contamination by using propagule-free seeds and minimizing dispersal by humans, animals, or machinery, following the guidelines of the Weed Science Society of America (WSSA 2015); control of established weeds using herbicides with different modes of action; cultural practices, such as utilizing cover crops in the off-season and rotating crops, to reduce weed density and promote maximum soybean growth (Rudell et al. 2022).

In addition, conventional systems can adopt strategies inspired by organic farming: cultural practices (competitive cultivars, reduced row spacing, increased sowing density, cover crops), biological methods (use of biological control agents, allelopathic compounds, or bioherbicides), mechanical techniques (automated weeders, robotic systems), and physical methods (electric weeding) (Costa et al. 2018). These approaches are promising but require technical knowledge, investment, effectiveness evaluation, and incentives for use.

5 | Conclusions

The sequential applications of dicamba associated with glyphosate were more efficient for controlling the weed species evaluated.

The application of dicamba, alone or combined with glyphosate, in either single or sequential applications, did not cause negative effects on soybean crop productivity.

Author Contributions

R.P., C.E.A., L.B., N.G. and A.M.O.N. investigation, formal analysis, visualization, writing original draft. L.L.C., N.G., and A.M.O.N. formal analysis, writing – review and editing, L.L.C. and N.G. writing – reviewing and editing, RP, and NG: resources. R.P. and N.G. conceptualization, resources, funding application.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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