



## Article

# Dicamba: Dynamics in Straw (Maize) and Weed Control Effectiveness

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**Abstract:** Dicamba is a post-herbicide, showing some activity in soil, and its dynamics can be influenced by several factors, including the presence of straw. Brazil has more than 50% of its production area in a no-till system; thus, a good amount of the herbicide is intercepted by the straw. This study aimed to evaluate dicamba dynamics in straw and weed control efficacy when sprayed as a PRE herbicide. For this, five different studies were conducted: we utilized different straw amounts (1) and different drought periods (2) for straw sprayed with dicamba and dicamba + glyphosate to evaluate its release from straw, different straw amounts (3), different drought periods (4), and wet and dry straw (5) to evaluate pre-emergence weed control (*Bidens pilosa* and *Ipomoea grandifolia*) and dicamba availability in medium-texture soil. Around 80% of dicamba was released from the straw after 100 mm of rainfall. One day after dicamba application, 65–70% of dicamba was released from the straw with 20 mm of rainfall, while for 7 and 14 DAA, 60% was released. Dicamba was efficient in controlling the pre-emergence of both species studied, and the amount of straw did not interfere in weed control; however, dicamba was less available in the soil after rainfall when sprayed in the straw than when sprayed directly in the soil. Up to 80% of dicamba can be released from the straw after 100 mm of rainfall and weed control was efficient for the species studied; however, the carryover effect in sensitive crops might become an issue.

**Keywords:** synthetic auxin herbicides; LCMSMS; no-till system; environmental behavior; chemical control; *Bidens pilosa*; *Ipomoea grandifolia*



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## 1. Introduction

Brazil had 61.6 million hectares of planted areas in the 2017/18 growing season [1]; around 53.5% of this area was under a no-till crop production system and continues to expand [2]. The presence of the straw modifies the behavior of the herbicides because it acts as a physical barrier that prevents their arrival into the soil [3] and might be necessary rainfall or irrigation to promote the transposition of the herbicide through the straw [4–6].

The adoption of a no-till system has been increasing, especially in row crops (soybean, corn, and cotton), and, linked to this, dicamba uses have also shown an increasing trend due to the dicamba-tolerant soybean (Intacta2 Xtend<sup>®</sup>), approved and available in Brazil since 2022 [7–9]; therefore, a significant part of the applied dicamba will be deposited over straw and some of the total deposited will be slowly released into the soil [10].

The intercepted herbicides in the straw are subjected to retention, volatilization, thermal degradation, and photolysis, till they are leached to the soil [11,12] and the leaching

is dependent on several factors, such as the amount and origin of the straw, herbicide characteristics, environmental conditions, and the time between the application and rainfall [4,13,14]. For example, for clomazone and sulfentrazone, about 50–100% and 80%, respectively, can be released into the soil after 20–30 mm of rainfall [15]. Other studies have shown that almost all amicarbazone, atrazine, metribuzin, tebuthiuron, and sulfentrazone were leached from straw after 20 mm of rainfall or irrigation for the 24 h period after their application [3–6,16].

Dicamba (3,6-dichloro-2-methoxy benzoic acid) is a synthetic auxin herbicide (Group 4—WSSA) that belongs to the benzoic acid chemical group and is commonly used to control broadleaf post-emergence weeds in cereal crops [17–19]; however, it can show some activity in soil. Plants that naturally produce auxins and auxin herbicides are auxin analogs and use the same receptors to bind, which causes an “overdose” effect [20]. Auxin herbicides are usually absorbed by the leaves and translocated by phloem, but some root absorption and xylem translocation can occur [21].

Once sprayed, dicamba will stimulate cell elongation and differentiation, leading to growth disorder [18,22]. The disordered growth will disrupt the cellular transport systems and lead to plant death [17]. When susceptible plants are exposed to dicamba application, plants will show the visual symptoms of epinasty of the petiole, stem, and leaves, abnormal growth, and, after a few days, chlorosis followed by necrosis [18,20,21].

Dicamba solubility in water is 250,000 mg L<sup>-1</sup> (highly soluble), is weakly adsorbed in the organic carbon in the soil (Koc 2.0 mL g<sup>-1</sup> and Kow 1.32 × 10<sup>-2</sup>), and its pKa is 1.87 at 25 °C; thus, dicamba can be easily leached to the soil and is classified as moderately volatile, with a vapor pressure of 1.67 mPa [23–26]. Several edaphoclimatic factors such as soil texture, pH, and organic matter, as well as rainfall, can influence dicamba persistence [27] and the degradation of this pesticide is mainly influenced by microbial activity and soil temperature [28]. Some studies have reported the time in days to degrade 50% of the initial dose of dicamba: Kah et al. [27] found that dicamba can take from 7.6 (sandy clay soil with a high organic carbon content) to 46.1 (sandy soil with a low OC content) days to be degraded, in a range of nine different soils tested.

As dicamba is mostly used as a post-herbicide, very little is known about it when it is sprayed as a PRE herbicide, especially in no-till systems. Thus, this paper aimed to answer the following questions: does dicamba reach the soil after application in different amounts of maize straw? What is the release rate of dicamba depending on rainfall? How does retention time in the straw before rain affect the release of dicamba from the straw to the soil? Is dicamba applied over the straw effective in controlling weeds as a pre-emergence herbicide? What is the availability in the soil when applied over the straw? And is weed control efficacy and soil availability affected by straw moisture at the moment of application, as well as the amount of mulch, and periods of drought?

## 2. Materials and Methods

In this research, five experiments were performed in the Center of Advanced Research in Weed Science (NUPAM) at the College of Agricultural Sciences, São Paulo State University in Botucatu, São Paulo State. The maize straw used in all experiments and the soil with medium texture used in experiments 3, 4, and 5 were collected previously. The soil's chemical and physical characteristics are represented in Table 1.

**Table 1.** A chemical and granulometric analysis of the soil used in studies 3, 4, and 5.

| Sand             | Clay                 | Silt           | Texture          | pH                                 | O.M.               | P <sub>resin</sub>  |
|------------------|----------------------|----------------|------------------|------------------------------------|--------------------|---------------------|
|                  | g kg <sup>-1</sup>   |                |                  | CaCl <sub>2</sub>                  | g dm <sup>-3</sup> | mg dm <sup>-3</sup> |
| 603              | 339                  | 58             | Medium           | 4.2                                | 7                  | 4                   |
| Al <sup>3+</sup> | H + Al <sup>3+</sup> | K <sup>+</sup> | Ca <sup>2+</sup> | Mg <sup>2+</sup>                   | SB                 | CEC                 |
|                  |                      |                |                  | mmol <sub>c</sub> dm <sup>-3</sup> |                    |                     |
| 2                | 36                   | 0.1            | 2                | 1                                  | 3                  | 39                  |
| V                | S                    | B              | Cu               | Fe                                 | Mn                 | Zn                  |
| %                |                      |                |                  | mg dm <sup>-3</sup>                |                    |                     |
| 8                | 13                   | 0.18           | 0.3              | 6                                  | 0.1                | 0.2                 |

### 2.1. Studies 1 and 2—Dynamics in Straw: Effects of Different Straw Amounts and Time without Rainfall

For studies 1 and 2, the treatments are described in Table 2. For both studies, the following herbicides were used: 720 g i.a. of dicamba (Atectra<sup>®</sup>, 480 g i.a. L<sup>-1</sup>, BASF S.A., Guaratingueta, Brazil) alone and 720 g i.a. of dicamba + 1440 g i.a. of glyphosate potassium salt (Roundup Transorb R<sup>®</sup>, 588 g i.a. L<sup>-1</sup>, Monsanto do Brasil Ltda, Não-Me-Toque, Brazil). The experiments were carried out in a completely randomized design (CRD) with 4 replications each.

**Table 2.** A description of the treatments for studies 1 and 2.

| Herbicide            | Amount of Maize Straw | Days without Rainfall |
|----------------------|-----------------------|-----------------------|
| <i>Study 1</i>       |                       |                       |
| Dicamba + glyphosate | 2 t ha <sup>-1</sup>  | -                     |
| Dicamba + glyphosate | 4 t ha <sup>-1</sup>  | -                     |
| Dicamba + glyphosate | 6 t ha <sup>-1</sup>  | -                     |
| Dicamba              | 4 t ha <sup>-1</sup>  | -                     |
| <i>Study 2</i>       |                       |                       |
| Dicamba + glyphosate | 4 t ha <sup>-1</sup>  | 1                     |
| Dicamba + glyphosate | 4 t ha <sup>-1</sup>  | 7                     |
| Dicamba + glyphosate | 4 t ha <sup>-1</sup>  | 14                    |
| Dicamba              | 4 t ha <sup>-1</sup>  | 1                     |
| Dicamba              | 4 t ha <sup>-1</sup>  | 7                     |
| Dicamba              | 4 t ha <sup>-1</sup>  | 14                    |

For both experiments, the maize straw was placed in small plastic containers (capsules) of the same size. After the applications, 5 accumulative rainfall simulations were carried out: 0, 10, 20, 35, 50, and 100 mm. In each simulation, the leached water was collected in Falcon tubes, then weighted and frozen for subsequent chromatographic quantification. For study 1, the rainfall was simulated right after the application, and in study 2, the capsules were kept in the greenhouse.

### 2.2. Studies 3, 4, and 5—Weed Control Efficacy and Dicamba Availability: Different Amounts of Maize Straw, Periods without Rainfall, and Dry and Wet Mulch

For all three studies, 3 L plastic pots were filled with sieved medium-texture soil. The experiments were carried out in the greenhouse, under a completely randomized design with four replications per treatment. The treatments regarding studies 3, 4, and 5 are described in Table 3.

**Table 3.** Description of the treatments for studies 3, 4, and 5.

| Herbicide                   | Amount of Maize Straw | Rainfall–DAA * | Dry/Wet   |
|-----------------------------|-----------------------|----------------|-----------|
| <b>Study 3</b>              |                       |                |           |
| -                           | 0 t ha <sup>-1</sup>  | 20 mm—1 DAA    | -         |
| -                           | 2 t ha <sup>-1</sup>  | 20 mm—1 DAA    | -         |
| -                           | 4 t ha <sup>-1</sup>  | 20 mm—1 DAA    | -         |
| -                           | 6 t ha <sup>-1</sup>  | 20 mm—1 DAA    | -         |
| 720 g i.a. ha <sup>-1</sup> | 0 t ha <sup>-1</sup>  | 20 mm—1 DAA    | -         |
| 720 g i.a. ha <sup>-1</sup> | 2 t ha <sup>-1</sup>  | 20 mm—1 DAA    | -         |
| 720 g i.a. ha <sup>-1</sup> | 4 t ha <sup>-1</sup>  | 20 mm—1 DAA    | -         |
| 720 g i.a. ha <sup>-1</sup> | 6 t ha <sup>-1</sup>  | 20 mm—1 DAA    | -         |
| <b>Study 4</b>              |                       |                |           |
| -                           | 0 t ha <sup>-1</sup>  | 20 mm—1 DAA    | -         |
| -                           | 4 t ha <sup>-1</sup>  | 20 mm—1 DAA    | -         |
| 720 g i.a. ha <sup>-1</sup> | 0 t ha <sup>-1</sup>  | 20 mm—1 DAA    | -         |
| 720 g i.a. ha <sup>-1</sup> | 4 t ha <sup>-1</sup>  | 20 mm—1 DAA    | -         |
| 720 g i.a. ha <sup>-1</sup> | 0 t ha <sup>-1</sup>  | 20 mm—7 DAA    | -         |
| 720 g i.a. ha <sup>-1</sup> | 4 t ha <sup>-1</sup>  | 20 mm—7 DAA    | -         |
| 720 g i.a. ha <sup>-1</sup> | 0 t ha <sup>-1</sup>  | 20 mm—14 DAA   | -         |
| 720 g i.a. ha <sup>-1</sup> | 4 t ha <sup>-1</sup>  | 20 mm—14 DAA   | -         |
| <b>Study 5</b>              |                       |                |           |
| -                           | 4 t ha <sup>-1</sup>  | 20 mm—3 DAA    | Straw     |
| 720 g i.a. ha <sup>-1</sup> | 4 t ha <sup>-1</sup>  | 20 mm—3 DAA    | Dry straw |
| 720 g i.a. ha <sup>-1</sup> | 4 t ha <sup>-1</sup>  | 20 mm—3 DAA    | Wet straw |

\* DAA = days after application.

For these studies, two weed species were planted: *Bidens pilosa* and *Ipomoea grandifolia*. The planting occurred before the applications for all studies.

Weed control evaluation for all studies occurred at 7, 14, 21, and 28 days after emergence; the weed control was evaluated using visual evaluation, where 0% meant no control of weeds and 100% meant that all plants were controlled, as suggested by the Brazilian Society of Weed Science [29].

In study 4, soil samples were collected 14 days after the rainfall simulation. The samples were frozen for subsequent chromatographic quantification.

### 2.3. Applications and Rainfall Simulations

All 5 studies were sprayed under the same conditions. The applications were carried out using a stationary sprayer in a closed room equipped with a spray boom containing four nozzles (TTI 110 025-VP) spaced 0.5 m from each other and positioned 0.5 m above the targets. The system was operated under 1 m s<sup>-1</sup> speed, 29 PSI, which corresponds to 200 L ha<sup>-1</sup> spray volume.

The accumulative rainfall was simulated using the same device described for the application of the herbicides but using a spray boom with eight high-flow spray nozzles (TK20-SS Teejet®, Wheaton, IL, USA) spaced 0.1 m apart, 1.4 m above the targets.

### 2.4. Dicamba Extraction and Quantification

For studies 1 and 2, aliquots of the solution that passed through the maize straw after each rainfall simulation were collected and filtered using Millipore filters of 0.45 µm (Millex-HV® filter, 13.0 mm diameter, Merck Millipore Ltd., Carrigtwohill, IE, USA) and stored in vials for later chromatographic detection of dicamba.

For 5, aliquots of 7 g of each soil sample were weighed and placed into syringes, and 2.0 mL of water was added. The syringes were kept in the dark and covered for 24 h. After that, the samples were centrifuged for 5 min at 2800× g at 20 °C. The supernatant was

filtered using Millipore filters of  $\mu\text{m}$  and stored in vials for later chromatographic detection of dicamba in the soil.

The dicamba detection was assessed using a high-performance liquid chromatograph (Proeminence UFLC, Shimadzu, 576 Tamboré Av, Barueri, São Paulo, Brazil), coupled to a hybrid triple quadrupole mass spectrometer (AB Sciex Triple Quad 4500, 500 Old Connecticut Path, Framingham, MA, USA), an LC-MS/MS system. A  $100 \times 21$  mm Kinetex 2.6  $\mu\text{M}$  Phenyl-Hexyl column (Phenomenex, 411 Madrid Av, Torrance, CA, USA) with a 20- $\mu\text{L}$  injection volume was used. The methodology used was the same as described by Mundt et al. [30].

### 2.5. Data Analysis

For dicamba detections in the collected rainfall that passed through the maize straw with different periods of drought and different amounts of maize straw, the Mitscherlich model was fitted for studies 1 and 2 (Equation (1)):

$$Y = a \left[ 1 - 10^{(-c(X+b))} \right] \quad (1)$$

where  $y$  is the amount of dicamba recovered from the rainwater (%);  $a$  is the maximum recovery of dicamba for the total rain accumulated;  $b$  is the lateral displacement of the curve;  $c$  is the concavity of the curve; and  $x$  is the amount of rainfall applied (mm).

The analyses were performed in SAS (Statistical Analysis System, SAS Institute, version 9.1.3, Carry, NC, USA), and the graphs were prepared using SigmaPlot (Systat Software, version 14.0, San Jose, CA, USA).

## 3. Results

### 3.1. Dynamics in Straw: Effects of Different Straw Amounts and Times without Rainfall

The model parameters regarding study 1 are shown in Table 4. Regardless of the amount of straw and dicamba sprayed alone or in the mixture with glyphosate, up to 80% was released from the straw after the total rainfall (100 mm) was simulated (Figure 1). After 20 mm of accumulated rainfall, up to 70% of the sprayed dicamba was recovered from the straw.

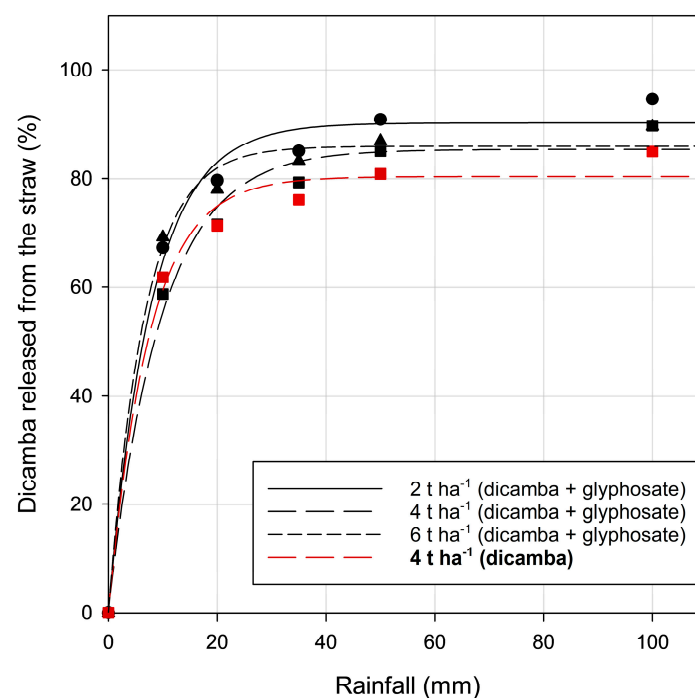


**Figure 1.** The effect of different maize straw amounts and different accumulated rainfall simulations in the release of dicamba from the straw.

**Table 4.** Model parameters regarding study 1.

| Straw (t ha <sup>−1</sup> ) | Model Parameters |        |        |                | F Value   |
|-----------------------------|------------------|--------|--------|----------------|-----------|
|                             | A                | B      | C      | r <sup>2</sup> |           |
| 2 *                         | 89.8112          | 0.0043 | 0.0548 | 0.99           | 170.94 ** |
| 4 *                         | 84.7485          | 0.0078 | 0.0451 | 0.99           | 148.16 ** |
| 6 *                         | 85.7755          | 0.0025 | 0.0663 | 0.99           | 222.84 ** |
| 4 **                        | 80.0469          | 0.0040 | 0.0584 | 0.99           | 140.47 ** |

\* Dicamba + glyphosate; \*\* dicamba alone.

The greatest amount of dicamba released from the maize straw was 89.8%, which occurred when dicamba was sprayed in a mixture with glyphosate at 2 t ha<sup>−1</sup> of maize straw. When dicamba was sprayed alone over the maize straw (4 t ha<sup>−1</sup>), 80% of the herbicide was released from the straw and when sprayed in the mixture with glyphosate at the same amount of straw, 84.7% of the herbicide was recovered after the total amount of rainfall.

The model parameters for Study 2 are shown in Table 5. Rainfall simulations 1 day after the application of dicamba and dicamba + glyphosate released around 65–70% of dicamba from the maize straw, with 20 mm of accumulated rainfall. The maximum recovery of dicamba was 80.4% with dicamba sprayed standalone and 85.9% with dicamba sprayed in a mixture with glyphosate after 100 mm of rainfall simulation (Figure 2).

At 7 and 14 days after spraying dicamba and dicamba + glyphosate, around 50–60% of dicamba was released from the maize straw with 20 mm of accumulated rainfall. Approximately 80% of the sprayed dicamba was released after 100 mm of accumulated rainfall 7 days after spraying. However, 14 days after spraying, around 70% of dicamba was released with 100 mm of accumulated rainfall. These data show that the longer the time without rainfall after spraying, the lower the concentration of dicamba that will be released from the straw.

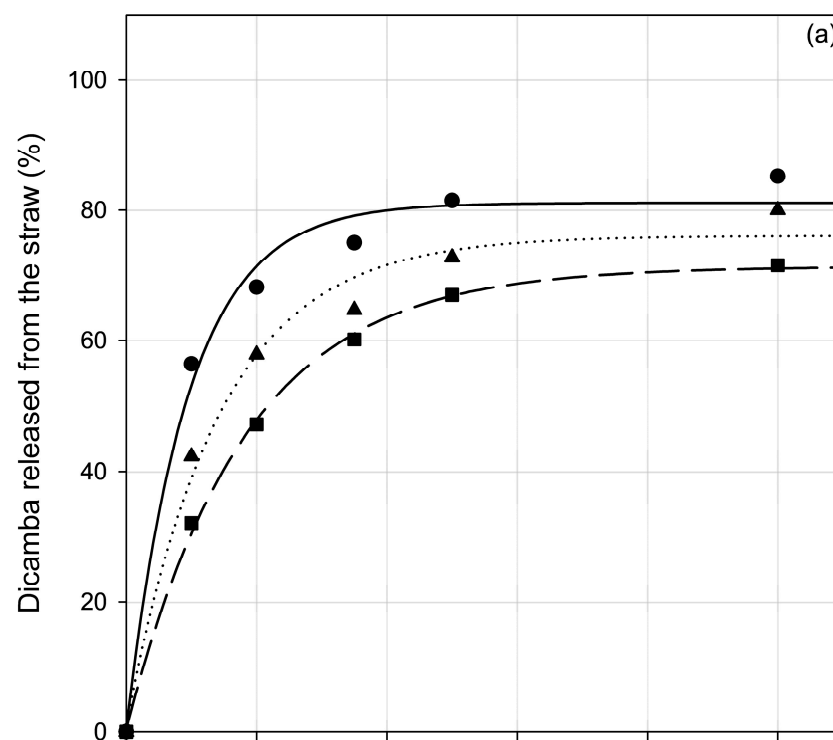


**Figure 2.** Cont.

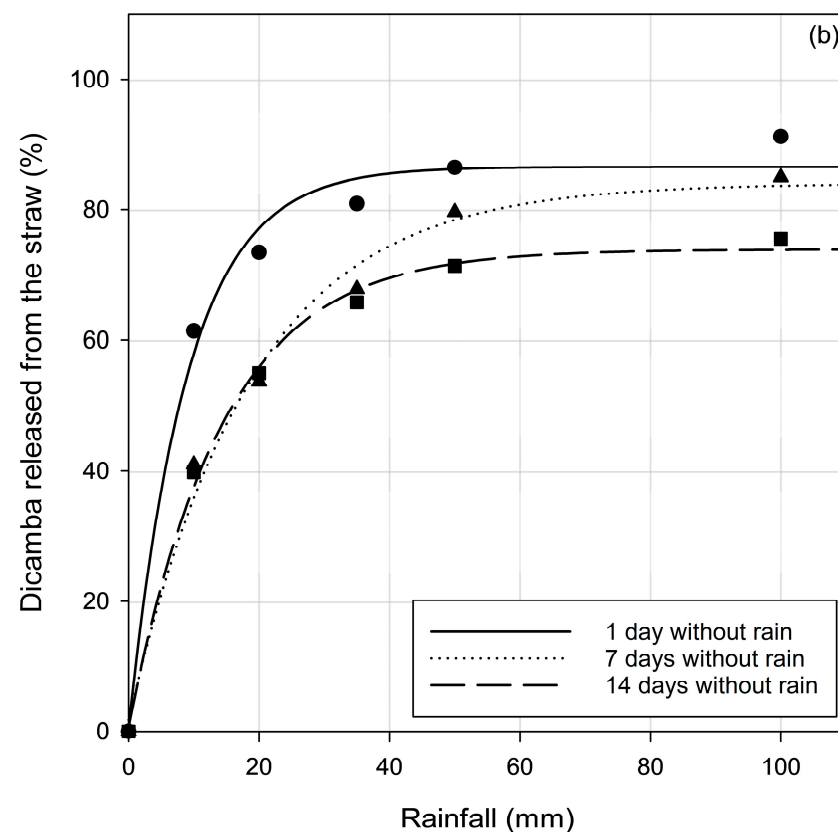


**Figure 2.** The effect of different drought periods for (a) dicamba sprayed standalone and (b) dicamba sprayed in a mixture with glyphosate in terms of dicamba release from straw.

**Table 5.** Model parameters regarding study 2.

| Periods (DAA) | Model Parameters |        |        |                | F Value    |
|---------------|------------------|--------|--------|----------------|------------|
|               | A                | B      | C      | R <sup>2</sup> |            |
| 1 dic         | 80.4970          | 0.0079 | 0.0459 | 0.99           | 132.90 **  |
| 1 dic + gly   | 85.9645          | 0.0070 | 0.0480 | 0.99           | 137.67 **  |
| 7 dic         | 74.8951          | 0.0154 | 0.0307 | 0.99           | 113.81 **  |
| 7 dic + gly   | 82.2741          | 0.0214 | 0.0233 | 0.99           | 144.70 **  |
| 14 dic        | 70.8117          | 0.0074 | 0.0240 | 0.99           | 1262.44 ** |
| 14 dic +gly   | 73.2151          | 0.0090 | 0.0306 | 0.99           | 476.06 **  |

\*\* dicamba alone.

### 3.2. Weed Control Efficacy and Dicamba Availability: Different Amounts of Maize Straw, Periods without Rainfall, and Dry and Wet Mulch

In study 3, weed control was successful for *B. pilosa* in all periods of evaluation, achieving 100% of control at 28 days after emergence (DAE) (Figure 3). For *I. grandifolia*, the control was lower at 7 DAE and 6 t ha<sup>−1</sup> had the lowest control with 90%. However, the evaluations at 14 and 21 DAE had great controls, with 100% of the species controlled, regardless of the amount of straw. At 28 DAE, all the treatments achieved more than 95% of control, and the lowest control was 97.75% for 6 t ha<sup>−1</sup>.

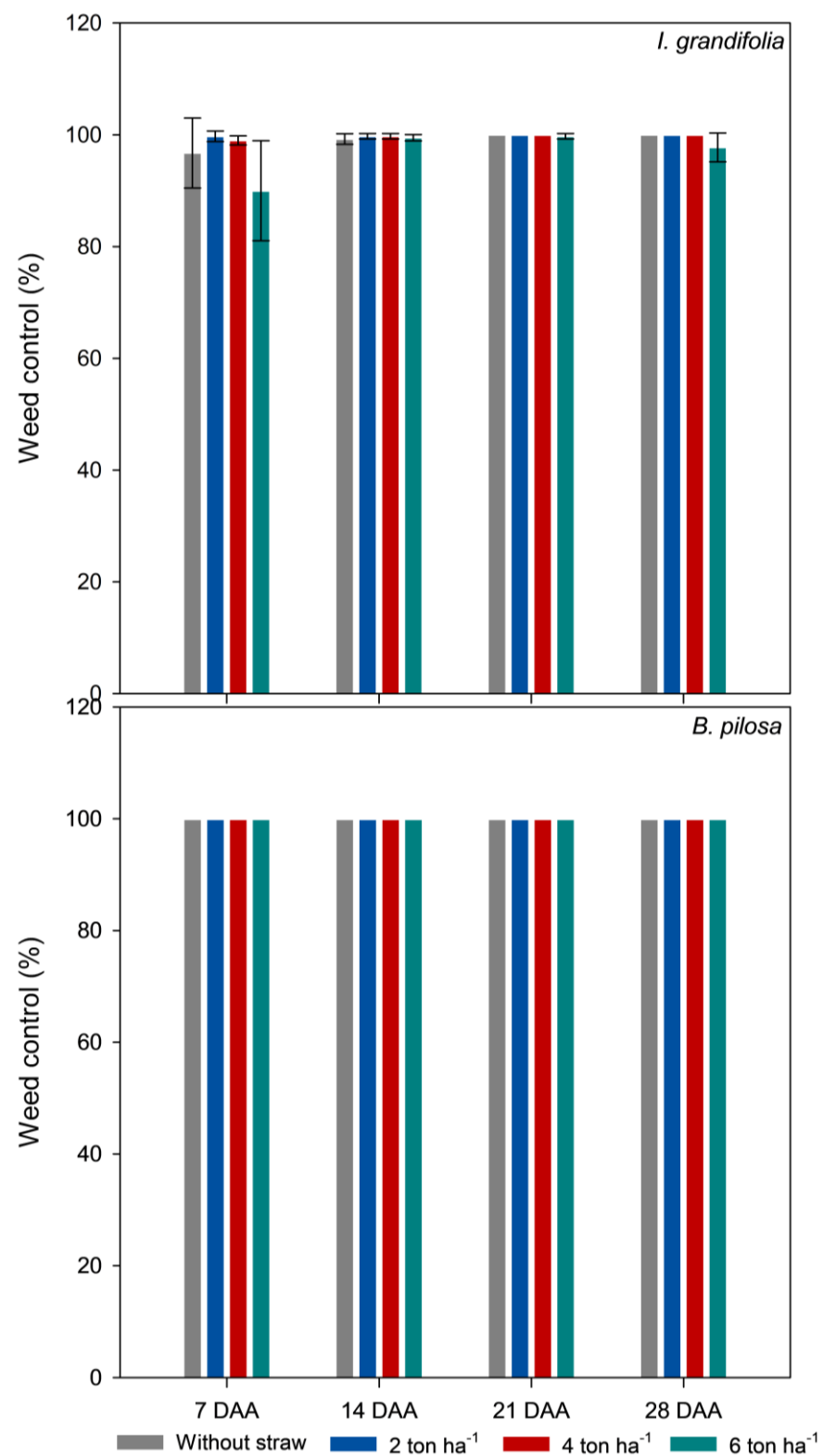


**Figure 3.** Weed control (%) for *I. grandifolia* and *B. pilosa* under different amounts of maize straw (study 3) at 7, 14, 21, and 28 days after emergence (DAE).

*B. pilosa* was greatly controlled in all the evaluation times in Study 4, with 100% of control regardless of the straw or drought period used (Figure 4). For *I. grandifolia*, the control was overall lower in the first evaluation (7 DAE) and the treatment that had the lowest control (88.75%) was the application in the soil with 14 days of drought period. However, in the following evaluations, all the treatments had a control greater than 95%.

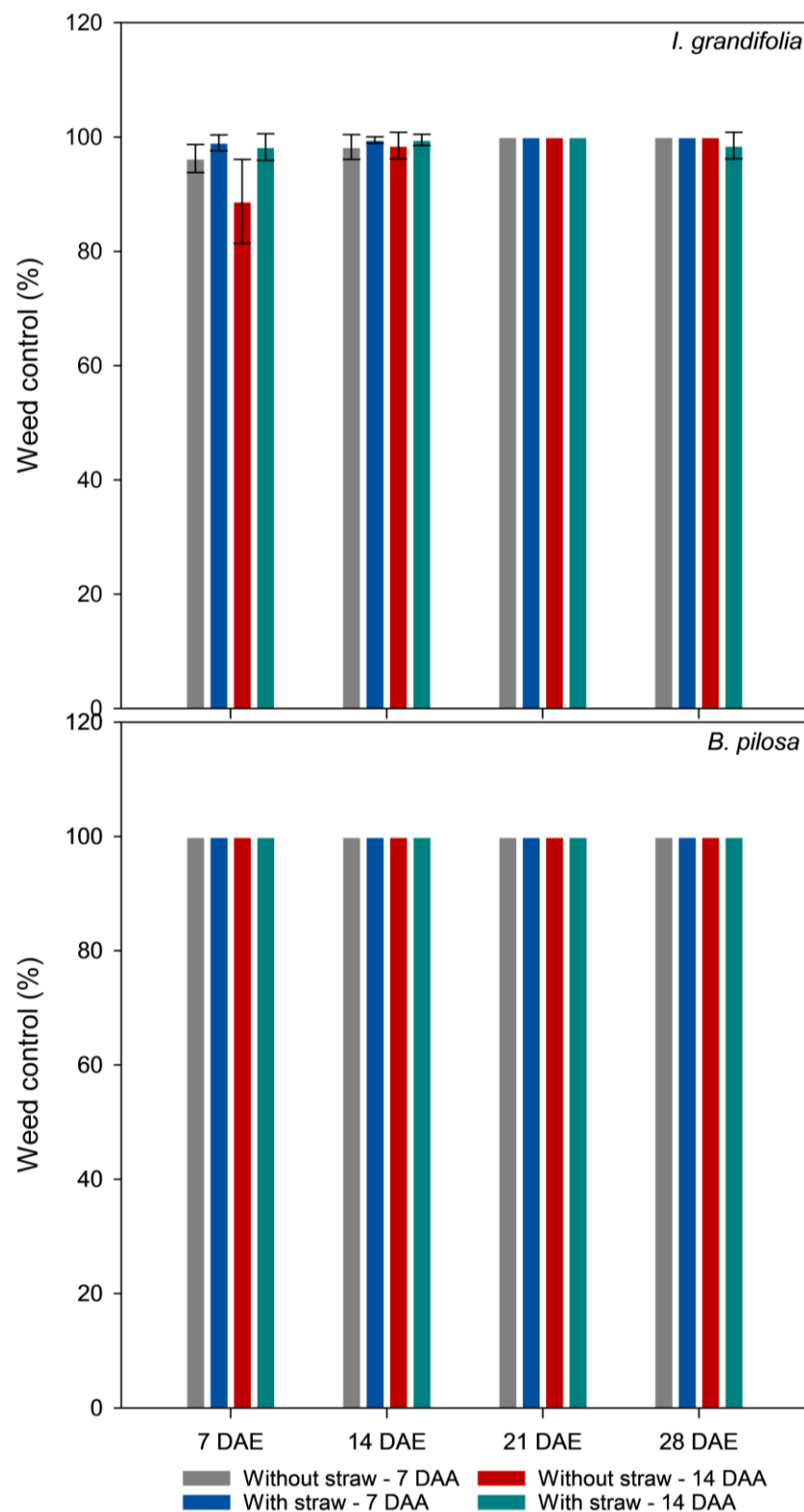


**Figure 4.** Weed control (%) for *I. grandifolia* and *B. pilosa* with and without the presence of straw and different periods of rainfall at 7, 14, 28, and 28 DAE.

Regardless of the drought periods, dicamba availability in the soil was greater in the treatments sprayed directly in the soil, indicating that straw has the potential to retain the chemical (Figure 5). Dicamba availability in the soil with rainfall 1 and 7 days after the application was very similar, however rainfall 14 days after the application decreased dicamba concentration in the soil by almost 30%. These data indicate that the longer the drought period, the less dicamba will be available in the soil.

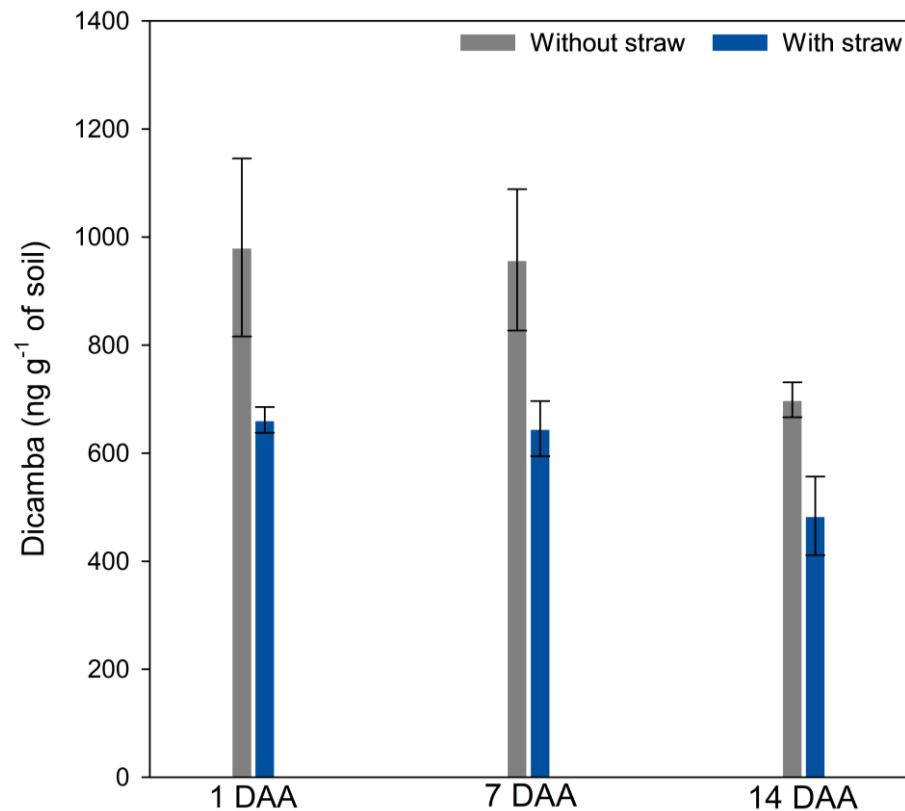


**Figure 5.** Dicamba availability in the soil with and without maize straw and different periods without rainfall sampled 14 days after the rainfall simulation.

In study 5, in which weed control was evaluated after dicamba application in dry and wet straw, no significant differences were observed for *B. pilosa* and *I. grandifolia* (Figure 6). By the end of the experiment, 28 DAE, weed control was 100% for *B. pilosa*, independent of whether the application was in wet or dry straw. For *I. grandifolia*, the control was effective as well, achieving more than 95% control in all treatments.

No differences were observed in dicamba availability in the soil when sprayed in wet or dry straw (Figure 7). However, as mentioned in the previous studies, the availability of the herbicide decreases after a period of drought and whether the straw was wet/dry did not have any influence in these results.

Since weed control was really satisfactory for all studies, with more than 95% of the plants controlled, no weed biomass was harvested.

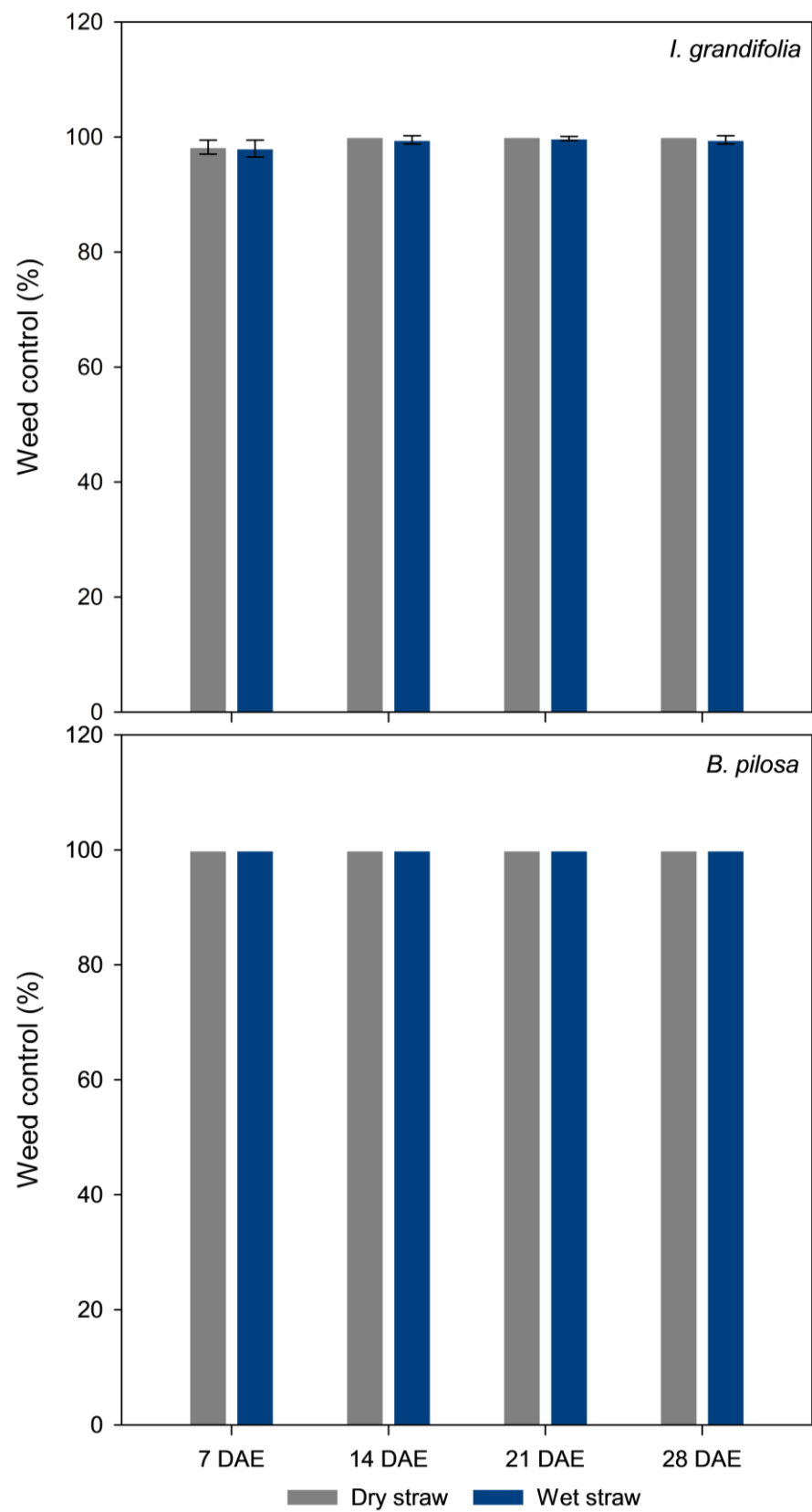


**Figure 6.** Weed control for *I. grandifolia* and *B. pilosa* with dicamba sprayed in dry and wet maize straw at 7, 14, and 21 days after emergence.

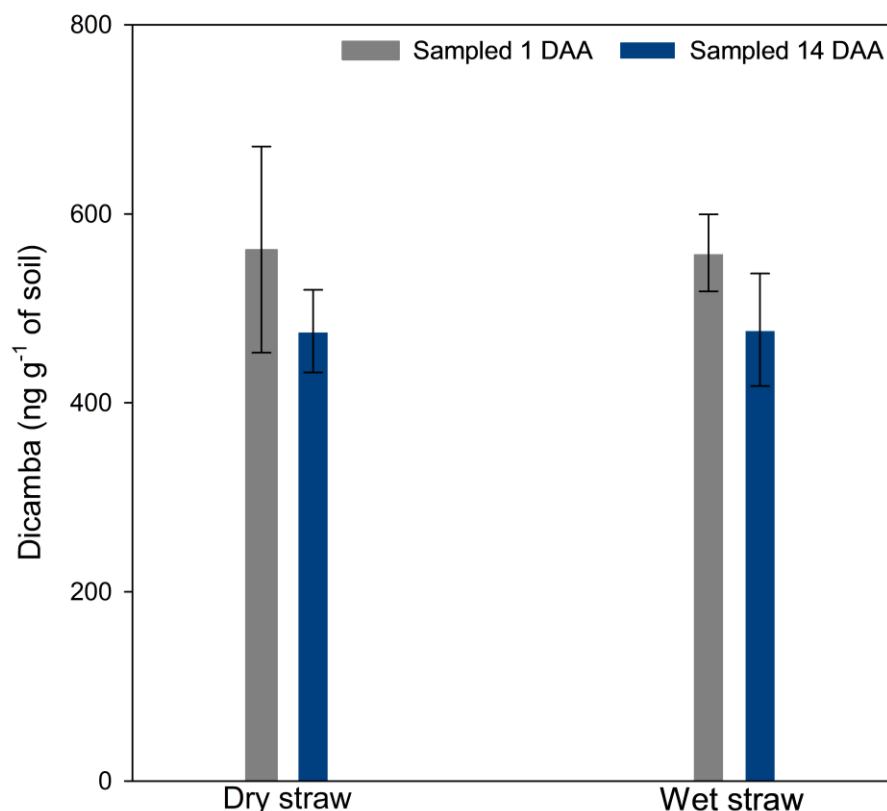


**Figure 7.** Dicamba availability in the soil when sprayed in dry and wet maize straw sampled 1 and 14 days after the application.

#### 4. Discussion

Dicamba is known as a highly soluble herbicide and has a low  $K_{ow}$  [26], which is why it can be easily released from the maize straw surface and reach the soil, where it will be available for plant uptake, explaining why more than half of the dicamba sprayed in study 1 was released after 20 mm of rainfall (Figure 1). Other herbicides as highly soluble as dicamba, such as sulfentrazone [14], metribuzin [6], amicarbazone [4], tebuthiuron [5], imazapic, and sulfentrazone [31], have also been shown to be easily released from crop residues after 20–30 mm of rainfall. The presence of surfactants in glyphosate formulation might have played a role in dicamba release from straw.

Evaluating dicamba leaching in no-till and conventional till systems, Hall and Mumma [32] found that the straw offers a physical barrier, but also retains dicamba in the surface. Gazola et al. [33] showed that rainfall simulation 1 day after dicamba DGA salt application released 54.8% of the chemical, while 15 days after the application, 44.6% of dicamba was released. Mundt et al. [30] observed that in field conditions, the maximum concentration of dicamba released from the straw to the soil occurred with 10 mm of rainfall 7 days after the application. Once dicamba is reported to have great mobility in the soil, the concentration and location in the soil will likely be determined by the rainfall during the season [34].

There are several factors influencing the availability of the herbicide in the soil, such as its physicochemical characteristics (solubility, herbicide formulation), rainfall after spraying, and degradation [11,12,35]. The photodegradation of a herbicide molecule occurs when the wavelengths are between 290 to 400 nm; once below 290 nm it is absorbed by the ozone layer and does not reach the Earth's surface, and when higher than 400 nm there is not enough energy to break the molecules, and dicamba maximum light absorbance occurs with wavelengths between 228 and 280 nm [26,36,37]. Thus, it is not likely that dicamba release was lower in longer drought periods because of photodegradation.

Volatilization is another factor that can help in herbicide degradation, and the volatility of a chemical will vary according to the amount sprayed, temperature, humidity, chemical formulation, and sprayed surface [38]. Dicamba has low vapor pressure (1.67 mPa at 25 °C) and is considered to have a low volatility; however, it is a strong acid (pKa 1.87) formulated as a salt, and its acid form is volatile [23,25,26]. DGA salt dicamba sprayed has a higher volatility when sprayed in moist soil and a lower volatility when sprayed in dry soil and corn straw [10]; therefore, volatility probably did not interfere significantly in the leaching of dicamba from the straw to the soil, although it might have helped.

Another fact to consider is that the crop residue (corn straw) contains cellulose, hemicellulose, lignin, proteins, and soluble substances, which are a major fraction of organic carbon [39]. Physical disintegration as well as chemical degradation, such as of cellulose and lignin, over time, increase the surface area and additional binding surfaces for herbicide retentions [40], and these might be the reason why dicamba was not released from the straw to the soil in greater concentration after certain periods.

Maintaining straw and adopting a no-till system brings multiple benefits [41] and it also impacts weeds' behavior once it affects seed dormancy and germination [42], and also impacts the herbicide dynamics in the soil because it increases the soil organic matter and microbiological activity. Dicamba degradation is highly influenced by microbial activity [28] and Kah et al. [27] showed that, 50% of the dose sprayed degraded faster in soil with OC content than in soil with low OC content.

Dicamba has been shown in other studies to be efficient in controlling *B. pilosa* and plants from the *Ipomoea* genus when sprayed as a pre-emergent herbicide. Gazola et al. [33] found that dicamba salt DGA was effective in controlling multiple weed species, such as *Digitaria insularis*, *Conyza* spp., *B. pilosa*, *Amaranthus hybridus*, and *Eleusine indica* when sprayed directly in the soil as a PRE herbicide and the addition of straw improved the control efficacy of the cited weeds. Mundt et al. [30] evaluated weed control of *B. pilosa*, *Euphorbia heterophylla*, and *Ipomoea nil* with dicamba as a PRE herbicide, and the results showed 62.5% of weeds were controlled when dicamba was sprayed in the soil, with some improvement when corn straw was added.

Chang and Born [43] studied <sup>14</sup>C-dicamba uptake by leaves and root and found that the distribution pattern of dicamba was similar for both, being evenly distributed in the crops and accumulated in young leaves in the weeds studied, indicating that plants can absorb and translocate dicamba by roots as well. Corn and cucumber absorbed dicamba in the shoot and roots; however, when uptake occurred by the roots, the growth was more severely affected [44].

Some residual effects have also been reported for other weed species, such as for the genus *Amaranthus*, *Ambrosia trifida*, *Chenopodium album*, *Conyza canadensis*, and *Abutilon theophrasti* [45]. Another study showed that dicamba can be efficient as a PRE herbicide even though the studied species is dicamba-resistant. Ou et al. [46] had reduced *Kochia scoparia* (dicamba-resistant) density when dicamba was sprayed in PRE. Dicamba is a herbicide that controls only broadleaf species because grasses can rapidly metabolize it to non-phytotoxic compounds irreversibly [43].

The presence or absence of the straw can influence the dicamba that will be available for plant uptake in the soil, once the straw acts as a physical barrier, preventing the herbicide from reaching the soil and requiring rainfall for the herbicide to be released from the straw and reach the soil where it will have activity and work in weed control [3–6]. However, multiple studies have shown the effect that straw has on weed suppression. For example, Coelho et al. [47] tested straw from different cover crops (a mix of cover crop, black oat, and sunflower) and observed that the mix and black oat were very effective in reducing the number of weeds. As mentioned before, straw acts as a physical barrier for herbicides, but also as a physical barrier affecting light and temperature in the soil [48]. In this context, the no-till system can also be a tool for weed management and can be integrated with chemical control.

## 5. Conclusions

Up to 70% of dicamba was released from the straw after 20 mm of rainfall and the amount of straw did not influence these results, however, the longer the drought period, the less herbicide will be available to reach the soil. Dicamba sprayed as a PRE was able to control both weed species in this study regardless of the presence or absence of straw.

Dicamba is a POST-herbicide commonly used by farmers, especially in burndowns, and its residual effect might be a tool to extend the weed-free period during a crop season; however, extra attention is necessary when sprayed prior to planting sensitive crops, such as soybean.

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