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Effect of pesticide and other crop protection product mixtures on dicamba volatilization

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Dicamba is an important tool for managing hard-to-control weeds in Brazil. Its use has increased, especially with the adoption of dicamba-tolerant crops, making the implementation of best management practices essential to ensure safe herbicide application, whether alone or in combination with other products. This study evaluated the volatilization of dicamba (diglycolamine salt – DGA) applied alone or in tank mixtures with glyphosate potassium salt (GK), a volatility reducer (VR), and various commercial crop protection products, over corn straw under controlled conditions. Volatilized dicamba was collected for 24 h at 40 °C and quantified by LC−MS/MS (LOD = 0.09 ng mL^{-1}, LOQ = 0.39 ng mL^{-1}). The VR consistently reduced dicamba vapor losses by up to 90%, regardless of the mixture. Most tank mixes did not increase volatility relative to DGA + GK + VR, except for combinations with glufosinate ammonium and mesotrione + atrazine, which increased volatilization by 49% and 43%, respectively, compared to DGA + GK + VR, though still ~70% lower than dicamba applied alone. These increases were likely related to ammonia release and interactions with amine groups, rather than pH differences. Findings demonstrate that VRs are effective for mitigating dicamba volatilization even in complex mixtures, but certain combinations require caution. Results provide practical guidance for tank-mix decisions and support the adoption of best practices to reduce volatility-related drift in dicamba-based weed control.

KEYWORDS

no-tillage systems, diglycolamine salt, tank mixture, volatility reducer, liquid chromatography tandem-mass spectrometry (LC-MS/MS)

1 Introduction

Pesticide application is a critical component of integrated crop protection programs and directly affects the success of crop establishment and long-term productivity. To optimize operational efficiency, it is common for farmers to mix multiple formulated products in the same spray tank, these include herbicides, insecticides, fungicides, and other active ingredients combined with adjuvants or even fertilizers to enhance performance or reduce application costs (Gazziero, 2015; Costa et al., 2020). In weed management, especially for hard-to-control species, tank mixtures are essential to broaden the spectrum of control and to manage herbicide-resistant weeds more effectively and sustainably. By combining herbicides with different modes of action, these mixtures allow broader-spectrum control, improve performance against resistant weed biotypes, and help delay the evolution of herbicide resistance. This is particularly important in Brazilian agriculture, where resistance to multiple herbicide groups, such as EPSPS inhibitors and ALS inhibitors, is increasingly reported in species like *Conyza* spp. and *Amaranthus* spp. under tropical no-tillage systems (Heap, 2025).

Among the chemical tools available, dicamba is a selective, post-emergence auxin-mimicking herbicide (WSSA Group 4) with systemic action (Carbonari et al., 2022b). It is widely adopted in genetically engineered dicamba-tolerant crops and has become a key alternative for controlling glyphosate-resistant broadleaf species, such as *Conyza* spp., *Amaranthus* spp., and *Ipomoea* spp (Flessner et al., 2015; Osipe et al., 2017; Soltani et al., 2020). Dicamba is often used in combination with glyphosate or other herbicides to supplement or replace traditional glyphosate-based weed control programs (Osipe et al., 2017; Carbonari et al., 2022b). However, the herbicide's high potential for volatilization poses a significant risk of off-target movement and injury to sensitive crops (Carbonari et al., 2022a, b; Antuniassi et al., 2024).

In response to widespread dicamba drift incidents, such as the 1,411 and 605 injury complaints investigated in Missouri in 2017 and 2018, respectively, and the 1,500 complaints recorded by the Illinois Department of Agriculture between 2017 and 2022, and more than 3,500 reports nationwide in 2021, regulatory agencies imposed stricter use restrictions, culminating in limited sales and distribution for the 2024 season (Bradley, 2017, 2018; USEPA, 2021, 2024; Shipman, 2023; Dhanda et al., 2025). In Brazil, dicamba is recommended primarily for pre-plant desiccation. For non-tolerant crops such as cotton and soybean, a minimum interval between application and planting must be observed. In contrast, for dicamba-tolerant cultivars, application is also permitted post-sowing, provided it occurs before crop emergence (Carbonari et al., 2022a; Monsanto do Brasil, 2024).This underscores the importance of adopting best management practices to ensure the safe application of the herbicide, whether applied alone or in tank mixtures (Behrens and Lueschen, 1979; Mueller and Steckel, 2019; Sharkey et al., 2021).

Volatilization occurs when the pesticide converts to vapor and moves away from the treated area. This process is influenced by several factors, including temperature, humidity, wind speed, spray pH, product formulation, and application practices such as tank mixing and nozzle type (Behrens and Lueschen, 1979; Henry et al., 2021; Sharkey et al., 2021). Dicamba has a vapor pressure of 1.67 mPa at 20°C, a Henry's law constant of 5.05 x 10^{-5} Pa m³ mol^{-1} at 25°C and water solubility of 250,000 mg L^{-1} (Heap, 2025), making it prone to vapor losses, especially under tropical conditions. Newer low-volatility formulations, such as diglycolamine salt (DGA) and N,N-bis(3-aminopropyl)methylamine (BAPMA), have shown significantly lower volatility compared to older formulations like dimethylamine salt (DMA) (Mueller et al., 2013; Mueller and Steckel, 2019; Carbonari et al., 2022a; Antuniassi et al., 2024). Nonetheless, even advanced formulations may volatilize under certain conditions, and the selection of tank mix partners, based on pH compatibility, volatility, and formulation types, is crucial to minimize unintended volatilization (Egan and Mortensen, 2012; Ou et al., 2018).

Some studies indicate that increased dicamba volatility may be associated with a decrease in spray solution pH (Mueller and Steckel, 2019). As pH decreases, hydrogen ions become more readily available, facilitating the formation of dicamba acid, which is more prone to volatilization (Abraham, 2018). However, there is no clear consensus regarding a direct relationship between lower pH and increased dicamba volatility (Sharkey et al., 2020; Carbonari et al., 2022a). Carbonari et al. (2022a) observed that dicamba mixtures with glyphosate in diammonium and ammonium salt formulations exhibited higher volatility than the mixture with potassium salt glyphosate, despite having different spray solution pH values of 6.4, 3.72, and 4.7, respectively.

Current understanding of dicamba volatility is underpinned by a robust scientific framework, which includes field quantification methodologies (Riter et al., 2020; Sall et al., 2020; Antuniassi et al., 2024) and studies correlating field findings with controlled environment experiments to isolate variables (Carbonari et al., 2020, 2022a, 2022b; Taylor, 2021). Collectively, these works provide the foundation for modeling the fate and transport of this herbicide in the environment (Das, 2019). Despite these advances, the focus has been predominantly on dicamba applied alone or in simple mixtures with glyphosate. The influence of more complex tank mixtures, a standard agricultural practice, on volatilization potential remains a critically underexplored area.

Despite widespread tank mixing practices in tropical agriculture, data on their effects on dicamba volatilization are scarce. This study aimed to evaluate the volatilization of dicamba (diglycolamine salt – DGA) when combined with other pesticides commonly used in crop protection programs for managing pests and weeds in soybean cropping systems.

2 Materials and methods

The experiment was conducted twice, sequentially between 2022 and 2023, under controlled laboratory conditions at the Núcleo de Pesquisas Avançadas em Matologia (NUPAM), Faculty of Agricultural Sciences, São Paulo State University (UNESP), Botucatu, Brazil. A completely randomized design was used, with

three replications per treatment. Treatments consisted of the application of dicamba (diglycolamine salt – DGA) alone or in tank mixtures with other crop protection products (Tables 1, 2). Application rates followed the label recommendations for each product, representing doses that are commonly used under field conditions in soybean cropping systems in Brazil.

The different spray solutions (treatments) were applied to corn straw fragments measuring 6 × 8 cm, with the edges covered by 1 cm on each side at the time of application, resulting in a useful spray area of 35 cm². The straw was manually collected from a commercial corn field during the R6 phenological stage (BBCH 89), with a moisture content of 7% at the time of application. No sterilization was performed in order to preserve the natural surface characteristics, but the material was cleaned to remove dust and impurities. Applications were performed using a spray simulator with velocity and pressure control, equipped with a spray boom consisting of four TTI 110015 nozzles (TeeJet, Springfield, IL, USA), spaced 0.5 m apart and positioned 0.5 m above the application target. The application was carried out at a pressure of 3.0 bar and a speed of 3.6 km h⁻¹, producing extremely coarse droplets with a spray volume of 200 L ha⁻¹, which reflects the typical rates used in field applications of post-emergence herbicides in Brazil (Alves et al., 2021; Spricigio et al., 2021; Carvalho et al., 2023).

Following application, the targets were left undisturbed for 10 minutes to dry in a laboratory room at 22°C. The straw fragments were then transferred to individual collection cartridges and placed into a closed-loop vapor collection system made of PVC tubing with an internal diameter of 20 mm, as described by Carbonari et al. (2020). The system included inlets to accommodate 24 cartridges and was connected to a vacuum pump via a 3 mm internal-diameter hose, operating at an airflow rate of 100 mL min⁻¹, measured at the beginning and end of the 24-hour collection period to ensure consistency throughout the experiment. The system was maintained in a chromatographic oven at a constant temperature of 40°C, a temperature selected to simulate worst-case field conditions for dicamba volatilization under tropical scenarios. Each cartridge was sealed with a cap containing a 3 mm diameter opening to allow airflow, and the outlet end was fitted with two PVDF filters (0.20 µm pore size, 25 mm diameter) (Chromafill Xtra, MN, Düren, Germany) installed in series to ensure high-efficiency vapor capture, with the second filter serving primarily as a control to confirm capture efficiency, as dicamba was virtually undetectable at this stage (Figure 1).

After the 24-hour, dicamba was extracted from the straw, the inner walls of the cartridges, and the filters using a methanol:water solution (25:75 v/v) (Carbonari et al., 2022a; Antuniassi et al., 2024). To extract the dicamba deposited on the straw, the samples were placed in centrifuge tubes containing 40 mL of the extraction solution and subjected to an ultrasonic bath for 30 minutes (Elmasonic P, Siegen, Germany). The cartridges were rinsed with 10 mL of the methanol: water solution to remove any dicamba residues adhered to the walls. In both procedures, the resulting extracts were filtered using 0.45 µm Millipore syringe filters and transferred to 2 mL vials. The amount of volatilized dicamba was determined by individually rinsing the filters with 1.5 mL of the extraction solution.

TABLE 1 Pesticides and other crop protection products and application rates used in the experiment.

Active ingredient[1]	Formulation class[2]	Pesticide class	Dose
dicamba (DGA)	SL	Herbicide	720 g ae ha⁻¹
glyphosate	SL	Herbicide	960 g ae ha⁻¹
acetic acid - potassium acetate (VR)	SL	Adjuvant	1.0% (v/v)
saflufenacil	WG	Herbicide	35 g ai ha⁻¹
glufosinate ammonium	SL	Herbicide	700 g ai ha⁻¹
chlorimuron-ethyl	WG	Herbicide	20 g ai ha⁻¹
flumioxazin	SC	Herbicide	60 g ai ha⁻¹
carfentrazone	EC	Herbicide	30 g ai ha⁻¹
diclosulan	WG	Herbicide	35.028 g ai ha⁻¹
imazethapyr	SL	Herbicide	100 g e.a ha⁻¹
s-metholaclor	EC	Herbicide	1920 g ai ha⁻¹
mesotrione + atrazine	SC	Herbicide	75 + 750 g ai ha⁻¹
lambda-cyhalothrin	CS	Insecticide	7.5 g ai ha⁻¹
zeta-cypermethrin	EC	Insecticide	35 g ai ha⁻¹
methomyl	SL	Insecticide	215 g ai ha⁻¹
flubendiamide	SC	Insecticide	33.6 g ai ha⁻¹
nonylphenoxy poly (ethyleneoxy) ethanol (NPE)	SL	Adjuvant	0.5% (v/v)
orange peel oil	SL	Adjuvant	0.15% (vv)
methyl soybean oil ester	EC	Adjuvant	0.5% (v/v)
mineral oil	EC	Adjuvant	0.5% (v/v)
ADJ35	SL	Adjuvant	0.075% (v/v)

[1]Formulated products registered and marketed in Brazil. DGA, digicolamine salt dicamba (Xtendcan® - Bayer); Glyphosate, glyphosate potassium salt (Roundup Transorb R® - Bayer); VR, volatility reducer - XtendProtect® (added in tank mixture) (Bayer); saflufenacil, Heat® - BASF, glufosinate ammonium (Finale® - Bayer); chlorimuron-ethyl, (Classic® – FMC); flumioxazin (Sumissoya® – Sumitomo); Carfentrazone, (Aurora® – FMC); diclosulan (Spider® – Corteva); imazethapyr, (Pivot® – BASF); s-metolachlor, (Dual Gold® – Syngenta); mesotrione + atrazine, (Calaris® – Syngenta); lambda-cyhalothrin, (Karate® – Syngenta); zeta-cypermethrin, (Mustang® – FMC); Methomyl, (Lannate® - Corteva); flubendiamide, (Belt® – Bayer); nonylphenoxy poly(ethyleneoxy) ethanol - non-ionic surfactant (NPE) (Agral® – Syngenta); orange peel oil (Wetcit Gold® - Oroagri); methyl soybean oil ester (Aureo® - BASF); mineral oil (Assist® – BASF); ADJ35 (tall oil alkyl ethoxylated, adjuvant under development - Bayer). [2]EC, emulsifiable concentrate; SL, soluble concentrate; CS, capsule suspension; WG, Water-Dispersible Granules; SC, Suspension Concentrate.

Dicamba was analyzed using a liquid chromatography–tandem mass spectrometry (LC-MS/MS) system composed of a high-performance liquid chromatograph (Prominence UFLC, Shimadzu, Kyoto, Japan) equipped with two LC-20AD pumps, a SIL-20AC autoinjector, a DGU-20A5 degasser, a CBM-20A controller system, and a CTO-20AC oven. The chromatograph was coupled to a Triple Quad 4500 mass spectrometer (Applied Biosystems, Foster City, CA, USA). Chromatographic analyses were

TABLE 2 Treatments used to evaluate dicamba volatilization when applied alone or in combination with other crop protection products listed in Table 1, along with the corresponding pH values of the spray solutions.

	Treatments	Solution pH
1	Dicamba diglycolamine sal (DGA)	7.06
2	DGA + glyphosate potassium salt (GK)	4.7
3	DGA + volatility reducer (VR)	6.65
4	DGA + GK + VR	5.24
5	DGA + GK + VR + saflufenacil + ADJ 35	5.38
6	DGA + GK + VR + glufosinate ammonium + ADJ 35	5.12
7	DGA + GK + VR + flumioxazin + mineral oil	5.4
8	DGA + GK + VR+ carfentrazone + mineral oil	5.39
9	DGA + GK + VR + diclosulan	5.39
10	DGA + GK + VR + imazethapyr	5.43
11	DGA + GK + VR+ mesotrione + atrazine + mineral oil	5.24
12	DGA + GK + VR + chlorimuron-ethyl + mineral oil	5.42
13	DGA + GK + VR + lambda-cyhalothrin	5.3
14	DGA + GK + VR + zeta-cypermethrin	5.28
15	DGA + GK + VR + methomyl	5.32
16	DGA + GK + VR + flubendiamide	5.29
17	DGA + GK + VR + s-metholaclor	5.39
18	DGA + GK + VR + methyl soybean oil ester	5.38
19	DGA + GK + VR + NPE	5.4
20	DGA + GK + VR + orange peel oil	5.43
21	DGA + GK + VR + ADJ 35	6.00

performed with a C18 column (Phenomenex Gemini 5 - C18RP 110Å) using an injection volume of 20 uL, with 5 mM ammonium acetate (Avantor Performance Materials, Inc., Center Valley, PA, USA) in water and 5 mM ammonium acetate in methanol (Merck KGaA, Darmstadt, Germany). The flow rate used was 1.0 mL min^{-1}, and the ratio of the solvents was gradually increased from the 80:20 (methanol/water) to the 95:5 range from 0 to 4 min, maintained at 95:5 range from 4 to 10 min, and returned to the initial condition. The total running time was 12 min. The retention time of dicamba in this system was 5.68 min. The electrospray ionization source (ESI) was used in the negative mode. Eight concentrations of the dicamba analytical standards with a certified purity level of 99.9% (Sigma Aldrich, St Louis, MO, USA) were used to construct the calibration curve. The limit of quantification (LOQ) and detection (LOD) for dicamba ware 0.39 and 0.09ng ml^{-1}, respectively, determined according to ICH guidelines. Dicamba was monitored at unit resolution in multiple reaction monitoring (MRM) mode at m/z 218.749 −174.7 with a confirmatory transition at m/z 218.749 −174.7.

The data obtained in duplicate were independently subjected to analysis of variance (ANOVA) using the F-test at a 5% significance level, followed by the application of the residual variance homogeneity test (Fmax) (Hattley, 1950). Upon confirmation of homogeneity between experiments, the data were pooled into a single dataset with six replicates and subjected to a new ANOVA. When significant differences among treatments were confirmed, means were compared using the t-test (LSD) at a 5% significance level, employing the Sisvar software (Sisvar®, Lavras, MG, Brazil) (Ferreira, 2014).

3 Results and discussion

The addition of the volatility-reducing agent (VR) to the spray solution was effective at lowering levels of volatilized dicamba, both when DGA was applied alone and when combined with other pesticides (Table 3). When dicamba (DGA) was applied alone, the total amount volatilized was 0.51 ± 0.072 g ha^{-1}, whereas the addition of the VR reduced this value to 0.05 ± 0.010 g ha^{-1}, an approximately 90% reduction (Table 3). To contextualize this value (DGA alone), it represents approximately 0.07% of a typical applied rate of 720 g ae ha^{-1}. This falls within the range of off-site losses measured in large-scale field studies. For example, Sall et al. (2020) reported dicamba fluxes from 0.023 to 0.302% of the applied rate (median 0.08%) across diverse environmental conditions.

In the presence of glyphosate potassium salt (GK), dicamba volatilization was also reduced from 0.34 ± 0.042 g ha^{-1} (DGA + GK) to 0.10 ± 0.018 g ha^{-1} when the VR was added, representing a 70% reduction relative to DGA + GK and 80% relative to DGA alone (Table 3). These findings confirm the effectiveness of the VRA in mitigating dicamba volatilization even in complex spray mixtures. Other studies have reported the effectiveness of volatility-reducing agents in reducing the concentration of dicamba vapor, even in less volatile formulations and when mixed with glyphosate (Abraham, 2018; Carbonari et al., 2020, 2022a). Carbonari et al. (2022a), when studying the volatilization of dicamba in mixtures with glyphosate from different formulations, observed that mixtures with ammonium and diammonium glyphosate salts led to a significant increase in dicamba volatilization.

Previous studies have established robust frameworks for quantifying dicamba volatility under field and controlled conditions. Riter et al. (2020) developed and validated an active air-sampling approach coupled with aerodynamic and integrated horizontal-flux models for field applications, and this framework was applied across 23 trials by Sall et al. (2020) revealing substantial variability driven by formulation, weather, and soil. Taylor (2021) further compared field versus controlled-environment responses, underscoring the roles of temperature and relative humidity. Our results extend this body of work by quantifying how specific commercial tank mixes, used with a volatility-reducing agent under tropical conditions, alter dicamba vapor losses.

Antuniassi et al. (2024) investigated the volatilization behavior of dicamba DGA salt formulated with a volatility-reducing agent at six field sites located in tropical regions of Brazil. Their findings
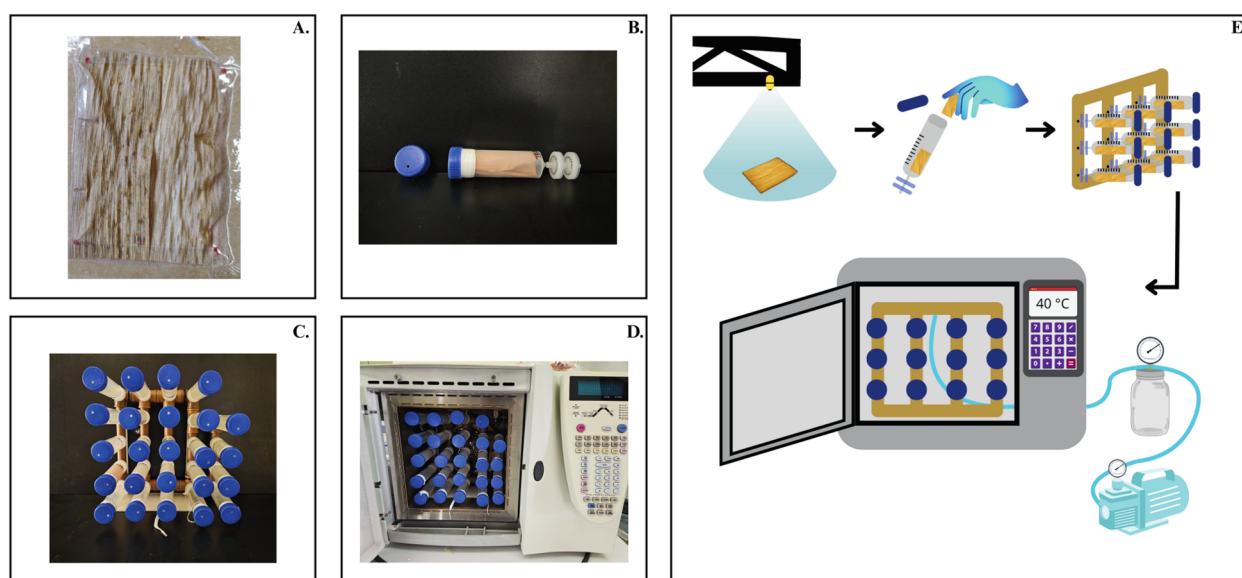
FIGURE 1
Experimental setup for dicamba volatilization assessment using corn straw under controlled conditions. **(A)** Fragment of corn straw (useful area of 35 cm²) used as deposition target (35 cm²). **(B)** Collection cartridge assembled with straw fragments and outlet filters. **(C)** Cartridge holder with 24 units prepared for vapor collection. **(D)** Chromatographic oven set at 40°C containing the vapor collection system. **(E)** Schematic representation of the experimental procedure: application on straw, cartridge assembly, system installation in the closed-loop vapor chamber.

revealed that dicamba volatilization peaked within the initial hours following application, then declined sharply around 20 hours post-application. The cumulative mass loss of dicamba was minimal, averaging 0.15 ± 0.08% of the applied dose. Furthermore, the mean in-field airborne concentration (38.66 ± 9.52 ng m⁻³) represented only 28% of the No Observed Adverse Effect Concentration (NOAEC) of 138 mg m⁻³, established by the U.S. Environmental Protection Agency (USEPA - United States Environmental Protection Agency, 2018), which represents the most sensitive threshold reported without observable adverse effects. This threshold has also been confirmed as protective in field-scale studies, where even the worst-case scenarios estimated 24 h average dicamba concentrations below 51 ng m⁻³ at 1 cm above ground level, highlighting the low likelihood of off-target injury when application best practices are followed (Sall et al., 2020). This is particularly relevant for assessing the risk of off-target exposure in susceptible crops at typical canopy heights.

Overall, the addition of other crop protection products to the spray solution DGA + GK + VR did not increase the concentration of volatilized dicamba, except for mixtures with glufosinate ammonium + ADJ35 (0.155 ± 0.028 g ha⁻¹ and mesotrione + atrazine + mineral oil (0.149 ± 0.039 g ha⁻¹), which increased by 49% and 43%, respectively (Figure 2; Table 3). However, when compared to the isolated dicamba application (0.515 ± 0.072 g ha⁻¹), the vapor produced in these mixtures was reduced by approximately 70% (Table 3). Therefore, even with mixtures that have the potential to increase dicamba volatilization, the use of the volatility-reducing agent effectively minimizes these losses,

although its efficacy is lower compared to the DGA + VR and DGA + GK + VR applications (Table 3; Figure 2).

The increased volatilization of dicamba, specifically in the mixture with glufosinate, may be related to the interaction of dicamba with ammonia. Although the glufosinate ammonium herbicide and its metabolites are non-volatile (Takano and Dayan, 2020), tank mixtures of dicamba with ammonia-based products can result in increased volatilization levels, as seen in mixtures with ammonium glyphosate salt and diammonium salt (Carbonari et al., 2022a). In the case of the mixture with mesotrione + atrazine, it is challenging to provide explanations for dicamba volatilization based solely on the chemical structure of other agents used in the mixture with dicamba (Sharkey et al., 2020; Sharkey and Parker, 2024). However, the interaction with the amine groups of these herbicides, whether secondary or primary, could lead to complex interactions and contribute to the increased volatilization of dicamba, since the amines in dicamba salts themselves may have characteristics that affect volatilization (Sharkey et al., 2020).

When comparing treatments with similar pH values but different added components, it becomes evident that pH alone does not explain the volatilization patterns observed. For example, DGA + GK + VR presented a pH of 5.24 and resulted in volatilization losses of 0.104 ± 0.018 g ha⁻¹. In contrast, DGA + GK + VR + glufosinate ammonium and DGA + GK + VR + mesotrione + atrazine showed comparable pH values (5.12 and 5.24, respectively) but volatilization increased by approximately 50% (0.155 ± 0.028 g ha⁻¹ and 0.149 ± 0.039 g ha⁻¹, respectively) compared to treatment DGA + GK + VR (Tables 2, 3). This

TABLE 3 Volatilized dicamba (g ha⁻¹) after isolated application and in mixture with other phytosanitary products.

	Treatments	Volatilized dicamba (g ha^{-1})
1	Dicamba diglycolamine sal (DGA)	0.515 ±* 0.072
2	DGA + glyphosate potassium salt (GK)	0.338 ± 0.042
3	DGA + volatility reducer (VR)	0.053 ± 0.010
4	DGA + GK + VR	0.104 ± 0.018
5	DGA + GK + VR + saflufenacil + ADJ 35	0.025 ± 0.009
6	DGA + GK + VR + glufosinate ammonium + ADJ 35	0.155 ± 0.028
7	DGA + GK + VR + flumioxazin + mineral oil	0.020 ± 0.013
8	DGA + GK + VR+ carfentrazone + mineral oil	0.032 ± 0.025
9	DGA + GK + VR + diclosulan	0.019 ± 0.008
10	DGA + GK + VR + imazethapyr	0.027 ± 0.021
11	DGA + GK + VR+ mesotrione + atrazine + mineral oil	0.149 ± 0.039
12	DGA + GK + VR + chlorimuron-ethyl + mineral oil	0.021 ± 0.009
13	DGA + GK + VR + lambda-cyhalothrin	0.025 ± 0.008
14	DGA + GK + VR + zeta-cypermethrin	0.083 ± 0.027
15	DGA + GK + VR + methomyl	0.075 ± 0.033
16	DGA + GK + VR + flubendiamide	0.028 ± 0.004
17	DGA + GK + VR + s-metholaclor	0.037 ± 0.007
18	DGA + GK + VR + methyl soybean oil ester	0.021 ± 0.005
19	DGA + GK + VR + NPE	0.044 ± 0.008
20	DGA + GK + VR + orange peel oil	0.035 ± 0.006
21	DGA + GK + VR + ADJ 35	0.045 ± 0.007

*The value followed by ± represents the value of the confidence interval at a 5% significance level.
Application on corn straw.

outcome reinforces that, under the conditions tested, pH reduction was not directly correlated with lower dicamba volatility. Instead, the presence of glufosinate ammonium likely contributed to increased vapor losses through the release of ammonia, while the mesotrione + atrazine mixture may have influenced dicamba protonation via interactions with their amine groups. Future studies are needed to isolate and test these interactions directly. Specifically, in the mixture with glyphosate, correlating dicamba volatilization with the chemical structure becomes even more complex due to the number of hydrogen-bonding sites, including a carboxylic group, a secondary amine group, as well as a phosphonate group (Sharkey et al., 2020). Solid crystals of glyphosate and ammonium glyphosate are reported to have up to

eight and ten intermolecular hydrogen bonds per glyphosate molecule, respectively (Knuuttila et al., 1979; Sagatys et al., 2000). Thus, it is possible that these groups disrupt the hydrogen bonds formed between dicamba and amines in the absence of glyphosate, resulting in increased dicamba volatilization (Sharkey et al., 2020).

In a study aimed at elucidating the factors contributing to dicamba volatilization with amine salts, Sharkey and Parker (2024) found that increasing proportions of neutral dicamba relative to the anion were correlated with higher volatilization from residues prepared with DMA, DGA, and BAPMA. However, this correlation was not observed with other amines (e.g., IPA), suggesting that additional secondary factors associated with the amines should be considered in explaining dicamba volatilization.

The additional properties of amines that may impact dicamba protonation include the number of amine groups (e.g., multiple amine groups in the case of BAPMA), the type of amine (e.g., primary amine IPA vs secondary amine DMA), and the ability to form complex bonding networks, as the strength of the hydrogen bond between the amine and dicamba can influence the effect of the amine on dicamba volatilization (Sharkey et al., 2020). Specifically, dicamba is more extensively deprotonated by amines containing additional polar groups (e.g., hydroxyl and ether groups in DGA), which may explain the contribution of these groups to suppressing dicamba volatilization (Sharkey et al., 2020). Thus, beyond the characteristics of different dicamba salts, mixing with other products can generate more complex interactions that affect dicamba volatilization.

Thus, beyond the characteristics of different dicamba salts, mixing with other products can generate more complex interactions that affect dicamba volatilization. These amine–dicamba interactions are often pH-dependent, as pH influences the equilibrium between neutral and ionic dicamba species. However, in the present study, treatments with similar pH values but different co-formulants (e.g., glufosinate ammonium vs. mesotrione + atrazine) exhibited markedly different volatilization patterns, indicating that pH alone was not the primary determinant of volatility under the tested conditions.

In the study conducted by Sharkey and Parker (2024), in addition to the characteristics related to dicamba amine salts, the authors investigated the interference of S-metolachlor in dicamba volatilization and observed that the herbicide did not affect dicamba protonation in the residues, which was consistent with its negligible effect on dicamba volatilization. These results are similar to those found in the present study, as the mixture of DGA + GK + VRA + S-metolachlor (T17) did not increase volatilization, whether compared to the isolated dicamba application (T1) or the DGA + GK + VRA mixture (T4) (Table 3; Figure 2).

In order to evaluate dicamba volatilization from mixtures with glyphosate, saflufenacil, and adjuvants, Ferreira et al. (2020) observed that the mixture of dicamba with potassium glyphosate salt and an adjuvant based on lecithin + propionic acid was more volatile and toxic to soybean plants. On the other hand, mixtures of dicamba with lecithin + soybean methyl ester + ethoxylated alcohol (D+F) and with potassium glyphosate + saflufenacil (D+R+H)
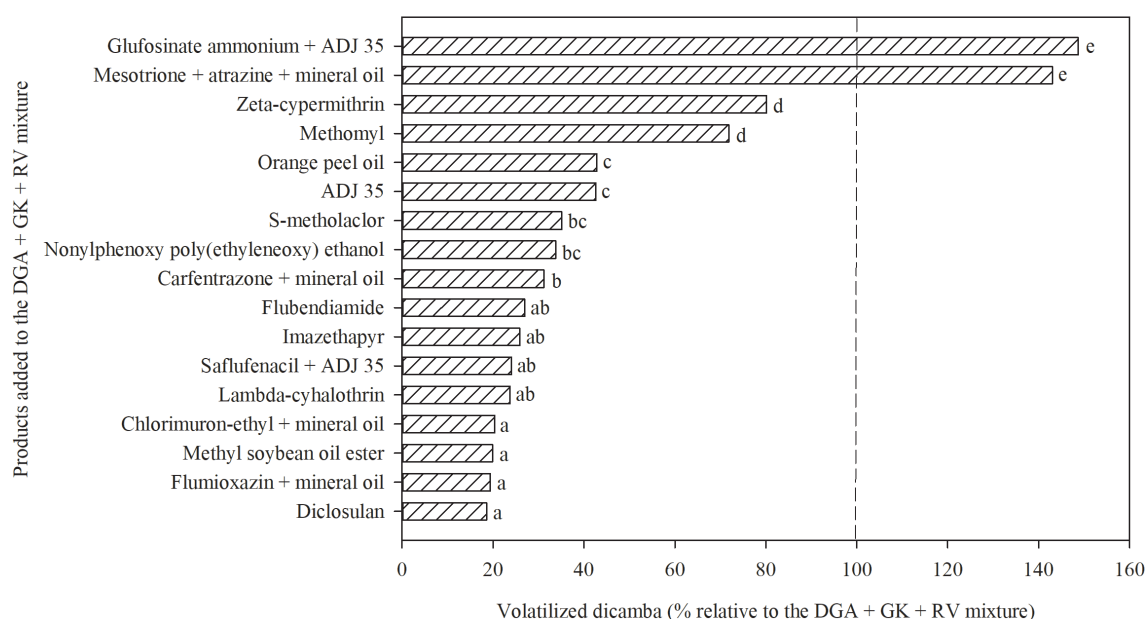
FIGURE 2

Percentage of volatilized dicamba after the addition of phytosanitary products to the dicamba (DGA) + glyphosate (GK) spray solution and volatility-reducing agent (VR). The vertical dashed line represents the reference percentage of volatilized dicamba from the DGA + GK + VR mixture. Means were compared using the t-test (LSD) at a 5% significance level. The doses of each product are described in Table 1.

showed low levels of injury to soybean plants. It is important to note that the authors did not quantify the volatilized dicamba production; instead, the assessments were based on the visual effects of dicamba on soybean plants. The experimental setup prevented particle drift, as treated soil was placed in sealed plastic chambers connected only by hoses that allowed gas exchange with separate chambers containing soybean plants. Therefore, the injury observed in soybean plants was attributable exclusively to dicamba vapor exposure, rather than to droplet drift or direct contact with the spray solution. Although the study did not quantify the amount of volatilized dicamba, the visual assessment of injury provides qualitative evidence supporting volatilization potential under different mixture scenarios.

4 Conclusions

Volatility reducers effectively lower dicamba vapor levels, achieving reductions of up to 90%. Even when other products are included in the spray solution, reductions of approximately 70% are still observed. However, mixtures containing glufosinate ammonium or mesotrione +atrazine increased dicamba volatilization compared to DGA + GK + RV alone. The influence of additional tank-mix components on dicamba vapor loss remains poorly understood and may involve complex chemical interactions. These findings underscore the need for further research to clarify these mechanisms and optimize tank-mix strategies. By improving understanding of these interactions, application practices can be refined to maximize weed control efficacy while minimizing off-target movement and potential environmental impacts.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

RC: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft. GG: Formal analysis, Methodology, Visualization, Writing – review & editing. MP: Formal analysis, Visualization, Writing – review & editing. HB: Formal analysis, Visualization, Writing – review & editing. DA: Formal analysis, Visualization, Writing – review & editing. RO: Formal analysis, Supervision, Visualization, Writing – review & editing. EV: Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Visualization, Writing – review & editing. CC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Supervision, Visualization, Writing – original draft.

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Conflict of interest

Authors MP, HB, DN, and RO were employed by Bayer CropScience.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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