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ABSTRACT - The droplet spectrum is a crucial factor in optimizing herbicide efficacy and minimizing spray drift. This study evaluated the effects of working pressure (100 to 600 kPa) and six adjuvants on droplet size, both in the absence and presence of herbicides, using an air-induction nozzle (TTI 110015VP) and a particle analyzer. Higher working pressures reduced droplet size—measured as $Dv_{0.1}$, $Dv_{0.5}$ (volume median diameter), and $Dv_{0.9}$, representing the diameters at which 10%, 50%, and 90% of the total spray volume consists of droplets of that size or smaller—and increased the volume percentage of fine droplets (V_{100}), regardless of the adjuvant or herbicide. Adjuvants influenced the droplet spectrum, with Xtend Protect1 producing the lowest relative span, indicating greater droplet size uniformity. A significant interaction between herbicides and adjuvants was observed, underscoring the need for a comprehensive analysis of these variables to optimize application quality. The addition of adjuvants and herbicides to the spray solution altered the correlations between droplet spectrum variables, emphasizing the importance of considering multiple factors in application decisions. Selecting the appropriate working pressure and adjuvant, along with a thorough analysis of the droplet spectrum, is essential for effective weed control, reducing spray drift, and ensuring environmental, applicator, and consumer safety.

Keywords: Droplet size; drift control; application efficiency; relative span

INTRODUCTION

The direct influence of sprayed droplet size on deposition, coverage, and spray drift makes it a key factor in herbicide application[1]. Coarser droplets, while less prone to drift, can result in insufficient coverage and increased runoff[2]. Finer droplets, despite providing greater coverage, are more susceptible to drift and evaporation, thereby increasing the risk of damage to adjacent crops and environmental contamination[3]. The search for the desired droplet spectrum aims to achieve a balance between adequate target coverage and drift management[4,5].

Therefore, the decision-making in crop protection must be guided by a careful analysis of how working pressure and adjuvants influence herbicide formulations[6]. Such an analysis enables an accurate determination of the optimal spray solution composition and the most suitable working pressure to achieve the desired droplet spectrum[7], thereby optimizing application and maximizing weed control effectiveness. Viscosity-increasing adjuvants have been shown to improve drift management, primarily by reducing the proportion of droplets smaller than 100–200 μm[8]. Droplet size also influences Dicamba absorption, as coarser droplets are less likely to be retained on leaf surfaces, potentially affecting herbicide efficacy[9]. The incorporation of Silwet L-77, a surfactant, into a glyphosate formulation reduces the surface tension of the solution, resulting in smaller droplet sizes and increased leaf deposition[10,11].

The inherent characteristics of a herbicide formulation directly influence the properties of the mixture, affecting its droplet spectrum, deposition, and absorption[12]. Therefore, selecting an appropriate herbicide and its formulation must take into account the target weed, prevailing weather conditions, and current regulatory guidelines. The herbicide 2,4-D can drift over considerable distances, posing a risk of contaminating sensitive crops[13].

Optimizing the droplet spectrum requires an understanding of the interactions between working pressure, adjuvants, and herbicide formulation[14] to maximize target deposition, minimize spray drift, and achieve effective weed control while ensuring environmental sustainability[15]. The droplet spectrum directly influences deposition, drift, and target coverage and is, in turn, modulated by working pressure, adjuvants, and herbicide formulation[16].

Therefore, it is essential to understand the effects of adjuvants and herbicides in applications using very coarse to extremely coarse droplets. This comprehensive study provides novel insights into the multifactorial dynamics among working pressure, commercially available adjuvants, and specific herbicide formulations, utilizing a contemporary air-induction nozzle. This integrative approach addresses a critical knowledge gap by elucidating complex interactions not often explored simultaneously, thereby offering crucial guidance for optimizing application quality and environmental safety under diverse field conditions.

MATERIALS AND METHODS

The experiment was conducted in May 2024 at the Center of Excellence in Agricultural Mechanization (CEMA), part of the Institute of Agricultural Sciences at the Federal University of Uberlândia. Two experiments were designed to assess the effect of the herbicide spray solution on the droplet spectrum, with and without adjuvants, under different working pressures. Both experiments followed a completely randomized design with four replications, consistent with established practices in spray application studies to ensure statistical robustness.

Experiment 1 employed a factorial design with five adjuvant mixtures plus a control, tested under six working pressures (100, 200, 300, 400, 500, and 600 kPa), resulting in a total of 36 treatments. The six adjuvant treatments were:

- Contact WSP (Nitro, Sertãozinho, São Paulo, Brazil) at a concentration of 50 mL per 100 L (0.5 mL L-1 or 0.05% v/v);
- Kento Pulveriza (Kentô Agro, Jaboticabal, São Paulo, Brazil) at a concentration of 40 mL per 100 L (0.4 mL L-1 or 0.04% v/v);
- Agral (Syngenta Proteção de Cultivos Ltd., Paulínia, São Paulo, Brazil) at a concentration of 30 mL per 100 L (0.3 mL L-1 or 0.03% v/v);
- Fighter NG (De Sangosse, Ibiporã, Paraná, Brazil) at a concentration of 150 mL per 100 L (1.5 mL L-1 or 0.15% v/v);
- Xtend Protect1 (Bayer S.A., Belford Roxo, Rio de Janeiro, Brazil) at a concentration of 1,000 mL per 100 L (10 mL L-1 or 1.0% v/v); and
- Pure water (control).

Commercial formulations were used at their respective field-recommended doses, with their active ingredient concentrations detailed as follows: Xtendicam (570 g a.e. L-1), Aminol 806 (806 g a.e. L-1), Flumizin 500 SC (500 g a.i. L-1), and Zapp QI 620 (620 g a.e. L-1).

Experiment 2 included a total of 21 treatments, with the working pressure set at 300 kPa and adjuvant concentrations identical to those described in Experiment 1. A factorial design was used, incorporating four herbicides and five spray mixtures, along with an additional commercially used spray mixture (Dicamba + Xtend Protect1), which was included as a benchmark reflecting a widely adopted commercial application practice for dicamba-based herbicides. The herbicides were:

- Dicamba (Xtendicam, Bayer S.A., Belford Roxo, Rio de Janeiro, Brazil) at 1.160 g acid equivalent ha-1 (equivalent to 2.04 L product ha-1);

- 2,4-D (Aminol 806, Adama Brasil S/A, Londrina, Paraná, Brazil) at a dose of 836 g of acid equivalent ha-1 (equivalent to 1.04 L product ha-1);
- Flumizin (Flumizin 500 SC, Iharabras S.A. Indústrias Químicas, Sorocaba, São Paulo, Brazil) at a dose of 187 g of active ingredient ha-1 (equivalent to 0.374 L product ha-1); and
- Glyphosate (Zapp QI 620, Syngenta Proteção de Cultivos, São Paulo, Brazil) at a dose of 2,450 g of acid equivalent ha-1 (equivalent to 3.95 L product ha-1).

Adjuvant composition information is limited, as manufacturers primarily provide details on their stated functional characteristics (Table 1). In the Brazilian market, some products are labeled with broad descriptors such as "multifunctional" or "performance accelerator"—indicating multiple functions (Hewitt, 2024)—but often lack a detailed description of their composition.

Table 1. Adjuvants used in the experiments to assess the effect of the herbicide spray solution on the droplet spectrum under different working pressures

Commercial adjuvant	Composition*	Stated functional characteristics*
Contact WSP	Acrylic polymer	Greater penetration of active ingredients; greater leaf coverage (wetting); improved droplet spreading; efficient against spray drift; does not alter mixture pH; reduced foaming
Kento Pulveriza	Vegetable oil	Adhesive that promotes increased absorption of products in the mixture; highly efficient spreader; decreases surface tension; increases electrical conductivity; reduces spray drift; anti-foam; breaks down the waxy layer, increasing plant uptake
Agral	Nonyl phenoxy poly (ethyleneoxy) ethanol	Enhanced foliar absorption of herbicides; greater penetration of systemic fungicides and insecticides; decreased burning risks
Fighter NG	Mixture of non-ionic surfactants	Improves droplet deposition on target; anti-foaming action; reduces drift losses; improves uniformity and droplet spectrum; increases coverage area
Xtend Protect^{TM}1	Non-ionic surfactants	Dicamba drift and volatility reducer

*As provided by manufacturer

The application was performed in a T9000 spray chamber (Tecnal Equipamentos Científicos, Piracicaba, São Paulo, Brazil)[17], which allows for precise control of working pressure, boom height, and application speed while maintaining a consistent application rate.

Droplet spectrum variables—Dv0.1, volume median diameter (Dv0.5 or VMD), Dv0.9, AR (the relative span of the droplet spectrum, where lower values indicate more uniform droplet distribution), and the percentage of the applied volume composed of droplets with a diameter below 100 μm (v100)—were measured using a p15 laser particle analyzer (Oxford Lasers, Didcot, Oxfordshire, UK) positioned inside the spray chamber. A TTI 110015VP air-induction flat spray nozzle (TeeJet Technologies, Glendale Heights, Illinois, USA) was used for the applications. The nozzle was equipped with a 100-mesh sieve and positioned 0.4 m from the optical beam of the laser particle analyzer, according to ASABE Standard S572.3[18].

The p15 analyzer was configured to measure 10,000 droplets per application within the 10–2,500 μm range. The nozzle position relative to the image capture remained consistent throughout the experiment, with adjustments made to align it with the center of the application jet[19].

Weather conditions inside the spray chamber were monitored using an ITWH1080 portable weather station (Instrutemp, Belenzinho, São Paulo, Brazil). The average temperature and relative humidity during the test were 24°C and 72%, respectively, with no wind.

Residual normality (Shapiro–Wilk test) and homogeneity of variance (Bartlett test) were assessed for all variables in both experiments. Variables that met the assumptions for analysis of variance (ANOVA), which included the relative span in Experiment 1 and Dv0.1, Dv0.5, and relative span in Experiment 2 (after Box–Cox transformation where applicable), were analyzed using ANOVA. For variables that did not meet these assumptions, even after transformation (Dv0.1, Dv0.5, Dv0.9, and v100 in Experiment 1; Dv0.9 and v100 in Experiment 2), non-parametric Kruskal–Wallis tests were conducted. Post-hoc comparisons for significant ANOVA results were performed using Tukey's test, while Dunn's test was used for significant Kruskal–Wallis results, both at a 5% significance level. Comparisons involving the predefined 'extra treatment' were conducted using Dunnett's test at a 5% significance level. Additionally, Pearson correlation matrices were applied to all variables to explore inter-variable relationships. Statistical analyses were conducted using RStudio software[20].

RESULTS

In Experiment 1, only the relative span variable met the assumptions of normality and homogeneity after the Box–Cox transformation. The variables $Dv_{0.1}$, VMD, $Dv_{0.9}$, and V_{100} did not achieve normality or homogeneity, even after Box–Cox transformation. Consequently, the sources of variation—adjuvant and working pressure—were analyzed separately using the Kruskal–Wallis test. When significant differences were detected, comparisons were made using Dunn's test at a 5% significance level.

$Dv_{0.1}$, VMD, $Dv_{0.9}$, and V_{100} were significantly influenced by working pressure. An increase in working pressure from 100 to 600 kPa resulted in substantial decreases in droplet size: Dv0.1 reduced by 51.9% (from 446 μm to 214 μm), VMD by 40.6% (from 942 μm to 559 μm), and Dv0.9 by 35.3% (from 1328 μm to 860 μm). Conversely, the percentage of fine droplets (V100) increased significantly by 525% (from 0.171% to 1.069%) (Table 1).

Table 1. Effect of working pressure on the droplet spectrum

Pressure (kPa)	$Dv_{0.1}$ (μm)	$Dv_{0.5}$ (μm)	$Dv_{0.9}$ (μm)	V_{100} (%)
100	446a	942a	1328a	0.171a
200	358a	764ab	1108ab	0.222ab
300	287ab	672bc	999bc	0.441bc
400	261bc	637cd	954cd	0.642cd
500	235cd	595de	897de	0.813de
600	214d	559e	860e	1.069e
ρ-normality	$2.3x10^{-7}$	$1.2x10^{-6}$	$6.3x10^{-13}$	$1.2x10^{-3}$
ρ-homogeneity	$4.7x10^{-3}$	$4.8x10^{-3}$	$2.2x10^{-16}$	$2.2x10^{-16}$
ρ-Kruskal–Wallis	$2.2x10^{-16}$	$2.2x10^{-16}$	$2.2x10^{-16}$	$2.2x10^{-16}$
CV (%)	31.6	20.8	20.3	60.0

Means followed by the same letter in the column do not differ, according to Dunn's test at 5% probability

$Dv_{0.1}$, VMD, and V_{100} were not significantly influenced by adjuvants. However, adjuvants had a significant effect on $Dv_{0.9}$, with mean values compared using Dunn's test at a 5% significance level. The Xtend Protect1 adjuvant reduced $Dv_{0.9}$ by 24.3% and 23.0% compared to water and Contact WSP, respectively. The other adjuvants produced similar results (Table 2).

Table 2. Behavior of $Dv_{0.9}$ in the presence of adjuvants

Adjuvant	$Dv_{0.9}$ (µm)
Water	1122a
Contact WSP	1111a
Kento	1022ab
Agral	1002ab
Fighter NG	985ab
Xtend Protect1	903b
ρ-normality	$6.3\text{x}10^{-13}$
ρ-homogeneity	$2.2\text{x}10^{-16}$
ρ-Kruskal-Wallis	$1.5\text{x}10^{-3}$
CV (%)	20.3

Means followed by the same letter do not differ, according to Dunn's test at 5% probability.

There was an interaction between adjuvants and working pressure in the response variable relative span, which measures the relative span of the droplet spectrum. Consequently, Tukey's test was applied at a 5% significance level for adjuvants, treated as a qualitative variable, while linear and polynomial models were applied to working pressure, considered a quantitative variable. Adjuvants affected relative span differently across various working pressures. Specifically, the lowest relative span values were associated with Contact WSP at 100 and 200 kPa, Kento Pulveriza at 300 kPa, Agral at 500 kPa, and Fighter NG at 600 kPa. At 400 kPa, there was no significant difference between the adjuvants (Table 3).

Table 3. Relative span of the droplet spectrum in the presence of adjuvants and different working pressures

Adjuvant	Working pressure (kPa)					
	100	200	300	400	500	600
Water	1.01bc	1.03b	1.17c	1.14a	1.17b	1.20b
Contact WSP	0.77a	0.91a	1.04ab	1.10a	1.09ab	1.13ab
Kento	0.91b	0.96ab	0.98a	1.07a	1.11ab	1.13ab

Agral	0.99bc	0.96ab	1.02ab	1.08a	1.08a	1.15ab
Fighter NG	1.05c	1.02b	1.05ab	1.06a	1.10ab	1.11a
Xtend Protect1	1.20d	1.03b	1.10bc	1.08a	1.12ab	1.21b
ρ-adjuvant x working pressure	8.8×10^{-12}					
ρ-normality	0.060					
ρ-homogeneity	0.580					
CV (%)	4.2					

Means followed by the same letter in the column do not differ, according to Tukey's test at 5% probability

Regarding adjuvants, Fighter had no significant effect on the relative span as pressure increased. However, adjustments in working pressure had differential effects on Contact WSP and Xtend Protect1. For Contact WSP, relative span increased between 400 and 450 kPa, whereas for Xtend Protect1, the opposite trend was observed. The relative span could be modeled linearly for the other three adjuvants: water, Kento Pulveriza, and Agral. These results indicate that the droplet spectrum exhibited greater homogeneity at lower working pressures (Figure 1).

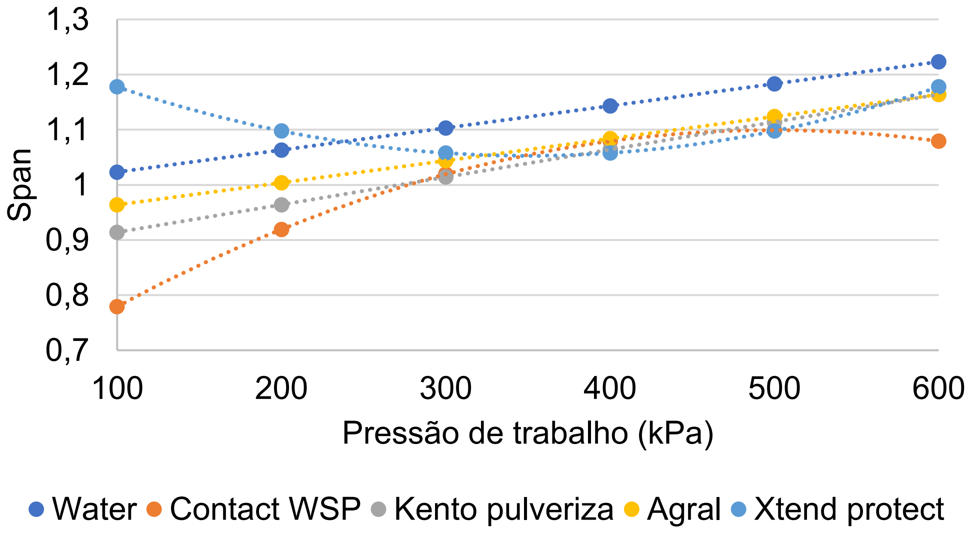


Figure 1. Relative span of the droplet spectrum as a function of working pressure
Water – $y = 0.0004x + 0.9832$; $R^2 = 0.80$
Contact WSP – $y = -2E\text{-}06x^2 + 0.002x + 0.5992$; $R^2 = 0.98$
Kento Pulveriza – $y = 0.0005x + 0.864$; $R^2 = 0.97$
Agral – $y = 0.0004x + 0.9238$; $R^2 = 0.87$
Xtend Protect1 – $y = 2E\text{-}06x^2 - 0.0014x + 1.2977$; $R^2 = 0.74$

Agral was the only adjuvant that reduced Dv$_{0.1}$ when added to Dicamba and 2,4-D spray solutions compared to formulations without adjuvants, decreasing droplet size by 17.2% and 13.7%, respectively. In contrast, mixtures containing Flumizin and Glyphosate showed increases of 43.1% and 36.1% in this variable when Contact WSP and Kento Pulveriza were added, respectively. The extra treatment produced 15.7% and 40.4% coarser droplets compared to Dicamba and Flumizin in the absence of adjuvants (Table 4).

Table 4. Dv$_{0.1}$ behavior after adding adjuvants to herbicide mixtures

Adjuvant	Dv$_{0.1}$ (µm)			
	Dicamba	2,4-D	Flumizin	Glyphosate
None	307aAα	264bAα	207cCα	216cDα
Fighter NG	321aAβ	273bAα	281bBα	281bBα
Contact WSP	315bAα	262cAα	346aAβ	276cBα
Kento	323aAβ	264bAα	280bBα	338aAβ
Agral	262bBα	232cBα	364aAα	240cCα
Dicamba + Xtend Protect1	342β			
ρ-herbicide x adjuvant	0.000			
ρ-adds x factorial	0.000			
ρ-normality	0.189			
ρ-homogeneity	0.059			
CV (%)	3.5			

Means followed by the same lowercase letters in the row, uppercase letters in the column, and Greek letters with the extra treatment letter do not differ according to the Tukey and Dunnet tests at 5% probability

The addition of adjuvants reduced VMD in mixtures containing Dicamba or 2,4-D. However, all adjuvants differed in terms of VMD when combined with herbicides. The greatest differences observed were 128 µm between Kento and Agral in Flumizin spray solutions and 147 µm between Flumizin and Glyphosate in the presence of Agral (Table 5).

Table 5. Dv$_{0.5}$ behavior after adding adjuvants to the herbicide mixture

Adjuvant	Dv$_{0.5}$ (µm)			
	Dicamba	2,4-D	Flumizin	Glyphosate
None	758aAβ	747bAβ	713cBβ	605dEα
Fighter NG	682bDα	699aCβ	652cEα	652cCα
Contact WSP	678bEα	666cEα	688aCα	655dBα
Kento Pulveriza	690aCβ	686aDα	666aDα	690aAβ
Agral	752bBβ	704cBβ	794aAα	647dDα

Dicamba + Xtend Protect1	729β
ρ-herbicide x adjuvant	0.000
ρ-adds x factorial	1×10^{-4}
ρ-normality	0.167
ρ-homogeneity	0.124
CV (%)	2.6

Means followed by the same lowercase letters in the row, uppercase letters in the column, and Greek letters with the extra treatment letter do not differ according to the Tukey and Dunnet tests at 5% probability

Except for Agral, the addition of adjuvants reduced $Dv_{0.9}$. The most significant reduction, 13.2%, was observed with Fighter NG compared to the absence of adjuvants. Agral resulted in a higher fraction of finer droplets (V_{100}), increasing the probability of spray drift (Table 6).

Table 6. Effect of adding adjuvants on droplet size and drift risk

Adjuvant	$Dv_{0.9}$ (μm)	V_{100} (%)
None	1134a	0.205ab
Fighter NG	1002b	0.150ab
Contact WSP	1016b	0.090a
Kento	1035b	0.075a
Agral	1137a	0.215b
ρ-normality	0.094	0.006
ρ-homogeneity	6.5×10^{-3}	0.005
ρ-Kruskal-Wallis	0.237	0.007
CV (%)	7.9	90.3

Means followed by the same letter in the column do not differ significantly (Dunn's test, $p > 0.05$).

Droplet spectra became more uniform with the addition of adjuvants to all herbicide spray solutions, except for those containing 2,4-D, where no significant difference was observed. The Contact WSP–Flumizin mixture produced the most uniform spectrum, while the most heterogeneous mixture occurred when glyphosate was applied without adjuvants (Table 7).

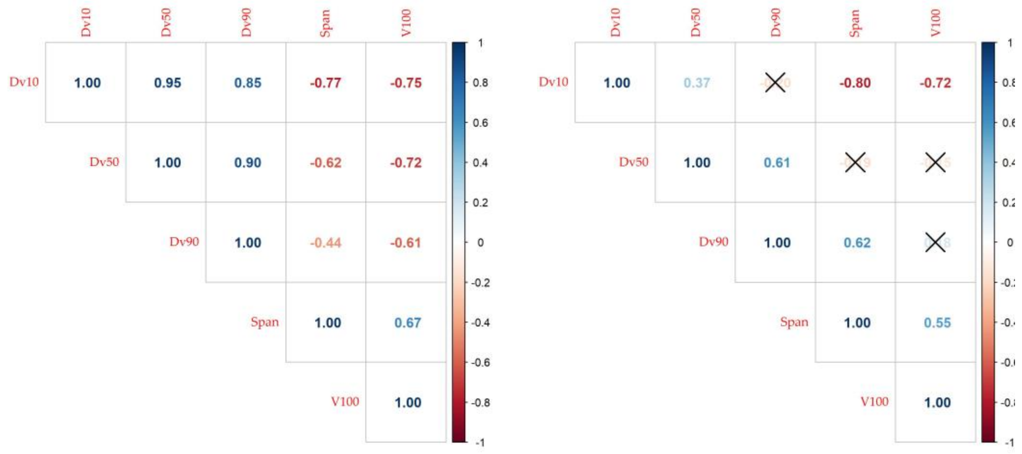
Table 7. Relative span of the droplet spectrum in the presence of adjuvants to the herbicide mixture

Adjuvant	Relative span

	Dicamba	2,4-D	Flumizin	Glyphosate
None	1.13aBβ	1.19aAα	1.32bDα	1.41bCα
Fighter NG	1.01aAβ	1.16bAα	1.04aBβ	1.04aAβ
Contact WSP	1.01bAβ	1.13cAβ	0.93aAα	1.20cBα
Kento	1.02aAβ	1.15bAα	1.15bCβ	0.98aAβ
Agral	1.19bBα	1.23bAα	0.99aABβ	1.40cCα
Dicamba + Xtend Protect1	1.05β			
ρ-herbicide x adjuvant	0.000			
ρ-adds x factorial	0.003			
ρ-normality	0.110			
ρ-homogeneity	0.234			
CV (%)	5.5			

Means followed by the same lowercase letters in the row, uppercase letters in the column, and Greek letters with the extra treatment letter do not differ according to the Tukey and Dunnet tests at 5% probability

In Experiment 1, which analyzed the effects of adjuvants and working pressure, all variables exhibited strong correlations. Dv$_{0.1}$, Dv$_{0.5}$, and Dv$_{0.9}$ exhibited a strong positive correlation with one another, as did relative span with V$_{100}$. Relative span and V$_{100}$ showed a strong negative correlation with Dv$_{0.1}$, VMD, and Dv$_{0.9}$ particularly between Dv$_{0.9}$ and relative span (Figure 2a). In Experiment 2, the correlations between all variables were weaker. In Experiment 2, Dv0.1, Dv0.5, and Dv0.9 exhibited positive correlations with one another. Conversely, Dv0.1 showed a negative correlation with both relative span and V100. A positive correlation was observed between relative span and V100 (Figure 2b).



(a) (b)

Figure 2. Correlation matrix: (a) Adjuvant and working pressure assay, and (b) herbicides in the presence of adjuvant assay.

DISCUSSION

Increasing pressure in 100 kPa increments resulted in reductions in $Dv_{0.1}$ by 88, 71, 26, 26, and 21 µm. The reductions in VMD were more pronounced, measuring 178, 92, 35, 42, and 36 µm. For $Dv_{0.9}$, droplet size decreased by 220, 109, 45, 57, and 37 µm with each 100 kPa increment. The transition from 300 to 400 kPa had the most pronounced effect on droplet size[11]. Similarly, Cauwer et al.[19] reported that increasing working pressure in air induction nozzles reduced droplet size but compromised coverage. Conversely, Faggion & Antuniassi,[21] found that increasing working pressure increased the volume of air captured inside droplets.

Pressure increases had a greater effect on VMD and $Dv_{0.9}$ than on $Dv_{0.1}$. This behavior is influenced by the proportion of droplets in each size class of the spectrum[8,22], as this number affects droplet behavior on leaf surfaces[23], influencing absorption or subsequent runoff. This phenomenon is a consequence of increased droplet fractionation with rising pressure, which reduces their ability to retain initial kinetic energy[15], leading to the formation of a greater proportion of finer droplets.

The effect on V_{100} was directly proportional to the increase in working pressure. When applying herbicides (selective or non-selective), it is crucial to minimize this droplet fraction. For herbicides with volatilization potential (e.g., Dicamba), the V_{100} droplet fraction can cause significant impacts. Therefore, selecting the appropriate nozzle is essential for achieving the recommended droplet spectrum. Incorrect nozzle selection can lead to spray drift, the effects of which may become evident days after application in perennial crops[24] and manifest in various ways in affected plants. In annual crops, Dicamba and 2,4-D, whether applied alone or in combination with other pre- or post-emergent herbicides, can reduce seed vigor and germination, as observed in soybean crops[25].

The TTI 110015VP nozzle produces ultra-coarse droplets at 100 and 200 kPa, extremely coarse droplets at 300 and 400 kPa, and very coarse droplets at 500 and 600 kPa[26]. The droplet classifications were compared with the S572.3 standard[18], and the spectrum obtained at 100, 200, 300, and 400 kPa matched the TP 65 15-SS and TP 65 10-SS reference nozzles (TeeJet Technologies, Glendale Heights, Illinois, USA) at 100 and 120 kPa, respectively[18]. However, at 500 and 600 kPa, the droplet classification remained extremely coarse.

The results indicate that adjuvants can influence droplet size ($Dv_{0.9}$) during spraying. Xtend Protect1 appears to be the most effective in reducing droplet size at the $Dv_{0.9}$ percentile. This aligns with its stated functional characteristic as a dicamba drift and volatility reducer, suggesting its composition effectively modifies the spray solution to narrow the droplet size range, which can mitigate drift risk, whereas Contact WSP has a minimal effect compared to pure water. The remaining adjuvants (Kento, Agral, and Fighter NG) exhibited intermediate effects. This reduction in droplet size can be beneficial for increasing spray coverage and narrowing the droplet size range; however, depending on the application conditions, it may also increase the risk of spray drift. The effect of adjuvants on the droplet spectrum is influenced by droplet size due to shifts in the stability of the liquid sheet Yang et al.[27] before droplet formation.

Increasing the droplet size with a TTI 110015VP nozzle is challenging due to its inherently coarse droplet spectrum (high, extreme, or ultra-coarse). In this case, reducing droplet size may be more beneficial for improving the relative span of the application. Therefore, it is more advantageous to incorporate adjuvants with adhesive, spreading, or wetting properties, as not all adjuvants are designed to increase droplet size[8]. At 100 and 200 kPa, Contact WSP produced the most uniform droplet spectrum. This effect is consistent with its reported properties of improved droplet spreading and efficient drift control, which is likely to contribute to a more homogeneous droplet distribution at lower pressures. However, at 300, 500, and 600 kPa, the most uniform spectrum was achieved with the addition of Kento, Agral, and Fighter NG adjuvants, respectively.

The contribution of adjuvants to relative span is influenced by working pressure. Although adjuvants have similar effects on $Dv_{0.1}$, VMD, and $Dv_{0.9}$ individually, they can enhance relative span. This aspect is crucial, as coverage—a key factor in evaluating application quality—is affected by droplet size[28]. Deposition is not solely determined by the droplet class produced during spraying[4]; other factors, such as nozzle type, relative span, and target characteristics, also play a fundamental role. Contact WSP produced the most uniform droplet spectrum, whereas Xtend Protect1 generated the most heterogeneous spectrum at 100 and 600 kPa, exhibiting behavior similar to pure water at 600 kPa.

The results of Experiment 1 indicated no interaction between adjuvant type and working pressure on the size of droplets generated by the TTI 110015VP nozzle. This finding helps to refute incorrect recommendations, particularly the misconception that finer droplets always lead to greater deposition on leaf surfaces[4]. Working pressure and adjuvants can influence droplet impact on leaves, affecting deposition, absorption, and loss through runoff into the soil[29]. These results suggest that the selection of adjuvant and working pressure should be carefully evaluated to optimize herbicide application, ensuring a balance between application efficiency, coverage, and the risk of spray drift.

In Experiment 2, $Dv_{0.1}$, VMD, and relative span exhibited a normal distribution of residuals and homogeneity of variance, eliminating the need for transformation. The interactions were statistically significant, and the factors were compared using Tukey's test at a 5% significance level. However, $Dv_{0.9}$ and V_{100} did not exhibit normality or homogeneity, even after applying a Box–Cox transformation. Therefore, they were analyzed separately using the Kruskal–Wallis test and, when significant, compared using Dunn's test at a 5% significance level. Differences between the extra treatment and the factorial treatment scheme were assessed using Dunnett's test at a 5% significance level.

Adjuvants with anti-drift properties generally promote an increase in droplet size[3] All adjuvants examined in this study, except for Agral, are recommended for this purpose. This effect was particularly evident when combined with hormonal herbicides such as Dicamba and 2,4-D. In Australia, $Dv_{0.1}$ is a droplet size parameter indicated on the labels of products intended for aerial application[8]. Increasing $Dv_{0.1}$ to approach 100–150 µm is desirable, as this brings its value closer to that of $Dv_{0.9}$, thereby reducing the relative span.

The anti-drift and anti-evaporative properties of the Dicamba + Xtend Protect1 spray mixture were evident, as indicated by its Dv0.1 of 342 µm (Table 4), Dv0.5 of 729 µm (Table 5), and a relatively low relative span of 1.05 (Table 7). These values distinctly position this formulation apart from corresponding herbicide treatments without adjuvants, highlighting its capacity to maintain coarser droplet sizes and a narrower droplet spectrum, which are crucial for mitigating drift and minimizing volatilization, consistent with observations by Vieira et al.[30].

The VMD, the standard reference for droplet size in applications, was influenced by all tested adjuvants[31,32]. Without adjuvants, the highest VMD value was observed with the Dicamba formulation, whereas glyphosate alone produced a VMD that was 25.3% lower. These results are attributed to the chemical composition and formulation of both adjuvants and herbicides, as well as the physicochemical properties of the spray mixture[33], particularly the inert substances in the formulations. This lack of detailed chemical composition for certain adjuvants limits full elucidation of the specific physicochemical mechanisms underlying their observed effects on the droplet spectrum. Future research incorporating fully characterized adjuvant compositions would provide deeper mechanistic insights into their interaction with spray solutions and aid product development.

All adjuvants, except Agral, reduced $Dv_{0.9}$. Consequently, they increased $Dv_{0.1}$ and decreased $Dv_{0.9}$ to varying degrees. An effective adjuvant should contribute to the uniformity of the droplet spectrum by minimizing both the relative span and V_{100} as much as possible[34]. In this study, the primary benefit of adjuvants was their ability to bring the $Dv_{0.1}$, $Dv_{0.5}$, and $Dv_{0.9}$ percentiles closer together.

The effect of adjuvants on the spray solution can either improve or reduce droplet spectrum uniformity. In general, $Dv_{0.1}$ increased with the addition of adjuvants, although no significant differences were observed between the various adjuvants or in the absence of adjuvants. A similar trend was observed for $Dv_{0.5}$ and $Dv_{0.9}$, particularly with Fighter NG, Contact WSP, and Kento Pulveriza, resulting in a more uniform application[1]. This can be attributed to the fact that adjuvants modify physicochemical properties, such as surface tension and viscosity, which in turn influence the droplet formation process[15].

Agral did not exhibit a significant anti-drift effect and, in several cases, did not differ from herbicides applied without adjuvants. As a result, it produced the highest V100, particularly compared to Kento Pulveriza. The V_{100} fraction was low when applied with the TTI 110015VP nozzle, which generates very coarse and extremely coarse droplets. Although this represents only a small fraction of the spectrum, adjuvants can help mitigate the risk of drift in these droplet categories. However, proper nozzle selection has a much greater impact on coverage and droplet size than adjuvant or herbicide addition to the spray mixture[19].

Field technicians have traditionally relied on VMD to assess adjuvant effects in agricultural applications. However, VMD alone is insufficient for a comprehensive analysis of the droplet spectrum; additional variables, including $Dv_{0.1}$, $Dv_{0.9}$, relative span, and V_{100}, should also be considered. These variables must be effectively communicated by researchers and extension workers to ensure they reach producers and field technicians.

In the context of crop protection, studies have shown that certain adjuvants can either increase or decrease droplet size, even when using TTI nozzles[32]. However, considering the relative span can lead to greater spectrum uniformity, which necessitates an understanding of $Dv_{0.1}$ and $Dv_{0.9}$ values. The present study confirms that droplet size was larger in the absence of adjuvants.

Adjuvant and herbicide addition to the spray solution altered correlations between droplet spectrum variables, emphasizing the need for field technicians to account for all factors influencing droplet size. In Experiment 1, where working pressure and adjuvants were the sources of variation, the weakest correlation was observed between $Dv_{0.9}$ and relative span. VMD exhibited a strong negative correlation with relative span and V_{100} (Rodrigues Neto et al., 2023). In Experiment 2, the weakest correlation was found between $Dv_{0.1}$ and $Dv_{0.5}$. These findings suggest that different sources of variation influence relationships between droplet spectrum variables.

The correlation between $Dv_{0.1}$ and relative span was strongly negative in both experiments, highlighting the significance of this droplet size percentile in determining spectrum uniformity[35]. This relationship is further reinforced by the correlation between $Dv_{0.1}$ and V_{100}. Ultimately, the interaction among working pressure, adjuvants, and herbicides shapes the droplet spectrum and can influence application efficiency by modifying spraying liquid sheet behavior[27]. Optimizing these parameters based on specific application conditions is crucial for maximizing control, minimizing drift, and ensuring environmental sustainability.

This study underscores the critical role of selecting appropriate adjuvants in combination with specific herbicides to optimize droplet size, thereby reducing spray drift and enhancing application efficiency, particularly for hormonal herbicides. The findings provide valuable insights for decision-making in weed management by considering both application efficiency and environmental safety. While the effects of adjuvants and working pressure (Experiment 1) on the droplet spectrum are relatively predictable, the introduction of different herbicides (Experiment 2) adds complexity, necessitating a more tailored approach for each situation. It is important to note that these findings are primarily specific to the TTI 110015VP air-induction nozzle, which inherently produces a coarse to ultra-coarse droplet spectrum. The behavior of these adjuvants, or other types, may differ significantly when used with nozzles designed to produce finer droplet categories, suggesting an area for future research to broaden the applicability of these insights.

CONCLUSIONS

Increasing the working pressure reduced droplet size ($Dv_{0.1}$, VMD, and $Dv_{0.9}$) and increased the volume percentage of fine droplets (V100), regardless of the adjuvant or herbicide used. This relationship is fundamental to achieving an optimal balance between coverage and spray drift risk. Adjuvant type directly influences the droplet spectrum, particularly $Dv_{0.9}$ and relative span. Xtend Protect1 reduced $Dv_{0.9}$ and provided a more uniform spectrum, whereas Agral increased drift risk due to a higher V_{100}. The choice of adjuvant depends on the herbicide, as their interaction affects droplet size and uniformity. This synergy influences both weed control effectiveness and environmental safety.

Evaluating VMD alone is insufficient for determining application quality. As demonstrated in this study, treatments with similar VMD values could exhibit differences in relative span and v100, impacting overall uniformity and drift potential. Therefore, Dv0.1, Dv0.9, relative span, and v100 must be considered to fully understand the droplet spectrum and its impact on spray drift, coverage, and application efficiency. The TTI 110015VP spray nozzle affects the droplet spectrum even with adjuvant addition. Selecting the appropriate nozzle while considering the target, weather conditions, and herbicide is crucial for optimizing application.

Adjuvant and herbicide inclusion alters correlations between droplet spectrum variables. In Experiment 1 (working pressure and adjuvants), the weakest correlation was between $Dv_{0.9}$

and relative span, while VMD exhibited a strong negative correlation with relative span and V_{100}. In Experiment 2 (herbicides and adjuvants), the weakest correlation was between $Dv_{0.1}$ and $Dv_{0.5}$. These shifts in correlation patterns indicate that different factors (working pressure, adjuvants, and herbicides) influence the droplet spectrum in distinct ways, underscoring the need for a comprehensive analysis tailored to each specific application scenario.

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DATA AVAILABILITY STATEMENT

All data supporting the results of this study are contained within this article.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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