

Modulation of the droplet spectrum by working pressure, adjuvants, and herbicides

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Editors:

Ricardo Alcántara de la Cruz
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Submitted: July 15th, 2025.

Accepted: November 13th, 2025.

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 $D_{v0.1}$, $D_{v0.5}$ (volume median diameter), and $D_{v0.9}$, 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 ProtectI significantly reducing $D_{v0.9}$. However, the lowest relative span, indicating greater droplet size uniformity, was achieved by different adjuvants depending on the working pressure. 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 droplet size spectrum is a crucial factor in optimizing herbicide efficacy and minimizing spray drift. Coarser droplets, while less prone to drift, can result in insufficient coverage and increased runoff.^(1,2) Conversely, finer droplets provide greater coverage, but are more susceptible to drift and evaporation, thereby increasing the risk of damage to adjacent crops and environmental contamination.⁽³⁾ The search for an ideal droplet spectrum aims to balance adequate target coverage with effective drift management.^(4,5)

Decision-making in crop protection requires a careful analysis of the influence of working pressure, adjuvants, and herbicide formulations on the spray solutions composition.^(6,7) Working pressure, for instance, directly affects the atomization process; in air-induction nozzles, increasing pressure generally reduces droplet size and increases the proportion of fine droplets.⁽⁸⁾ Adjuvants, in turn, modify physicochemical properties such as surface tension and viscosity, directly impacting the droplet spectrum and drift potential, for example, viscosity-increasing adjuvants can reduce the fraction of droplets smaller than 100–200 μm ,⁽⁹⁾ while surfactants decreasing surface tension results in smaller droplet and increased foliar deposition.^(10,11) Furthermore, the intrinsic characteristics of each herbicide formulation, such as the volatility of 2,4-D, also influence the mixture's properties and, consequently, deposition and absorption, posing a risk like contaminating sensitive crops through drift.^(12,13)

Given the multifactorial nature of pesticide application, optimizing the droplet spectrum requires a deep understanding of the interactions among these variables to maximize target deposition, minimize drift, and ensure effective weed control with environmental sustainability.⁽¹⁴⁻¹⁶⁾ While studies have explored isolated components, the combined dynamics among working pressure, commercial adjuvants, and specific herbicide formulations, especially with the use of modern air-induction nozzles that produce coarse to ultra-coarse droplet spectra, represents a critical knowledge gap. Therefore, this study aimed to evaluate the effects of working pressure (100 to 600 kPa), different adjuvants, and the presence/absence of herbicides on the droplet spectrum (Dv0.1, Dv0.5, Dv0.9, relative Span, and V_{100}), using an air-induction nozzle (TTI 110015VP), to provide insights for optimizing application quality and environmental safety.

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. Experiment 1 evaluated the impact of adjuvant-water solutions under different working pressures, while Experiment 2 investigated herbicide-adjuvant-water solutions. Both experiments followed a completely randomized design with four replications, consistent with established practices in spray application studies.

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⁽⁸⁾ – but often lack a detailed description of their composition.

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, Iporã, 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).

Experiment 2 included a total of 21 combinations. The working pressure was set at 300 kPa and adjuvant concentrations were identical to those described in Experiment 1. The experiment utilized a 4 (herbicides) x 5 (adjuvant treatments). The five adjuvant treatments include the four commercial adjuvants (Contact WSP, Kento Pulveriza, Agral, Fighter NG) and a pure water control, as listed in Experiment 1. An additional, non-factorial benchmark treatment, Dicamba + Xtend Protect1, was also included, reflecting a widely adopted commercial application practice for dicamba-based herbicides.

For Experiment 2, commercial herbicide 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), Flumizim 500 SC (500 g a.i. L⁻¹), and Zapp QI 620 (620 g a.e. L⁻¹). 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 dimetilamina (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);
- Flumioxazina (Flumizim 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).

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 – $D_{v0.1}$, volume median diameter ($D_{v0.5}$ or VMD), $D_{v0.9}$, 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 (V_{100}) – 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 $D_{v0.1}$, $D_{v0.5}$, 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 ($D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, and V_{100} in Experiment 1; $D_{v0.9}$ and V_{100} 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 version 4.3.1.⁽²⁰⁾

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	Monoetanolamina, urea, Monoammonium Phosphate, Modified Polyether Trisiloxane	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™1	Non-ionic surfactants	Dicamba drift and volatility reducer

* As provided by manufacturer

RESULTS

In Experiment 1, only the relative span variable met the assumptions of normality and homogeneity after the Box–Cox transformation. The variables $D_{v0.1}$, VMD, $D_{v0.9}$, 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.

$D_{v0.1}$, VMD, $D_{v0.9}$, 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: $D_{v0.1}$ reduced by 51.9% (from 446 μm to 214 μm), VMD by 40.6% (from 942 μm to 559 μm), and $D_{v0.9}$ by 35.3% (from 1328 μm to 860 μm). Conversely, the percentage of fine droplets (V_{100}) increased significantly by 525% (from 0.171% to 1.069%) (Table 2).

$D_{v0.1}$, VMD, and V_{100} were not significantly influenced by adjuvants. However, adjuvants had a significant effect

on $D_{v0.9}$, with mean values compared using Dunn’s test at a 5% significance level. The Xtend Protect1 adjuvant reduced $D_{v0.9}$ by 24.3% and 23.0% compared to water and Contact WSP, respectively. This finding is particularly relevant when considering Xtend Protect1’s status as a widely recognized industry benchmark for dicamba drift and volatility reduction. The other adjuvants produced similar results (Table 3).

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, among the treatments that yielded the lowest relative span values, Contact WSP was observed at 100 and 200 kPa, Kento Pulveriza at 300 kPa, Agral at 500 kPa, and Fighter NG at 600 kPa. At 400 kPa, no significant difference was observed among the adjuvants (Table 4).

Table 2. Effect of working pressure on the droplet spectrum

Pressure (kPa)	$D_{v0.1}$ (μm)	VMD (μm)	$D_{v0.9}$ (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
$P^{\text{-normality}}$	2.3×10^{-7}	1.2×10^{-6}	6.3×10^{-13}	1.2×10^{-3}
$P^{\text{-homogeneity}}$	4.7×10^{-3}	4.8×10^{-3}	2.2×10^{-16}	2.2×10^{-16}
$P^{\text{-Kruskal-Wallis}}$	2.2×10^{-16}	2.2×10^{-16}	2.2×10^{-16}	2.2×10^{-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

Table 3. Behavior of $D_{v0.9}$ in the presence of adjuvants

Adjuvant	$D_{v0.9}$ (μm)
Water	1122a
Contact WSP	1111a
Kento	1022ab
Agral	1002ab
Fighter NG	985ab
Xtend Protect1	903b
$P^{\text{-normality}}$	6.3×10^{-13}
$P^{\text{-homogeneity}}$	2.2×10^{-16}
$P^{\text{-Kruskal-Wallis}}$	1.5×10^{-3}
CV (%)	20.3

Means followed by the same letter do not differ, according to Dunn’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).

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 Flumizina 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 Flumizina in the absence of adjuvants (Table 5).

Table 4. 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
$P^{\text{adjuvant} \times \text{working pressure}}$	8.8×10^{-12}					
$P^{\text{normality}}$	0.060					
$P^{\text{homogeneity}}$	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.

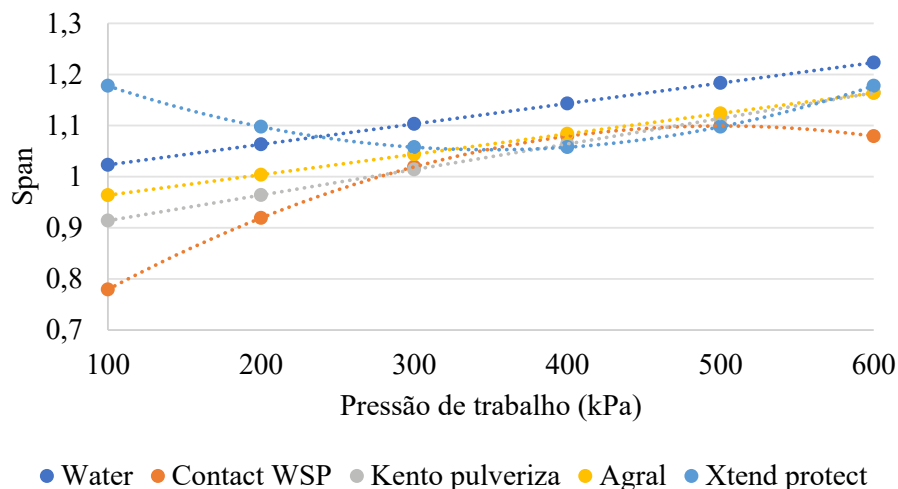


Figure 1. Relative span of the droplet spectrum as a function of working pressure.

Table 5. $D_{v0.1}$ behavior after adding adjuvants to herbicide mixtures

Adjuvant	$D_{v0.1}$ (μm)			
	Dicamba	2,4-D	Flumizim	Glyphosate
None	307aA α	264bA α	207cC α	216cD α
Fighter NG	321aA β	273bA α	281bB α	281bB α
Contact WSP	315bA α	262cA α	346aA β	276cB α
Kento	323aA β	264bA α	280bB α	338aA β
Agral	262bB α	232cB α	364aA α	240cC α
Dicamba + Xtend Protect1	342 β			
$P^{\text{herbicide x adjuvant}}$	0.000			
$P^{\text{adds x factorial}}$	0.000			
$P^{\text{normality}}$	0.189			
$P^{\text{homogeneity}}$	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

Table 6. VMD behavior after adding adjuvants to the herbicide mixture

Adjuvant	VMD (μm)			
	Dicamba	2,4-D	Flumizim	Glyphosate
None	758aA β	747bA β	713cB β	605dE α
Fighter NG	682bD α	699aC β	652cE α	652cC α
Contact WSP	678bE α	666cE α	688aC α	655dB α
Kento Pulveriza	690aC β	686aD α	666aD α	690aA β
Agral	752bB β	704cB β	794aA α	647dD α
Dicamba + Xtend Protect1	729 β			
$P^{\text{herbicide x adjuvant}}$	0.000			
$P^{\text{adds x factorial}}$	1×10^{-4}			
$P^{\text{normality}}$	0.167			
$P^{\text{homogeneity}}$	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

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 Flumizim spray solutions and 147 μm between Flumizim and Glyphosate in the presence of Agral (Table 6).

Except for Agral, the addition of adjuvants reduced $D_{v0.9}$. 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 7).

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–Flumizim mixture produced

the most uniform spectrum, while glyphosate applied without adjuvants was among the treatments that resulted in the highest heterogeneity (Table 8).

In Experiment 1, which analyzed the effects of adjuvants and working pressure, all variables exhibited strong correlations. $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ 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 $D_{v0.1}$, VMD, and $D_{v0.9}$ particularly between $D_{v0.9}$ and relative span (Figure 2a). In Experiment 2, the correlations between all variables were weaker. In Experiment 2, $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ exhibited positive correlations with one another. Conversely, $D_{v0.1}$ showed a negative correlation with both relative span and V_{100} . A positive correlation was observed between relative span and V_{100} (Figure 2b).

Table 7. Effect of adding adjuvants on droplet size and drift risk

Adjuvant	D _{v0.9} (µm)	v100 (%)
None	1134a	0.205ab
Fighter NG	1002b	0.150ab
Contact WSP	1016b	0.090a
Kento	1035b	0.075a
Agral	1137a	0.215b
P ⁻ normality	0.094	0.006
P ⁻ homogeneity	6.5 × 10 ⁻³	0.005
P ⁻ 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).

Table 8. Relative span of the droplet spectrum in the presence of adjuvants to the herbicide mixture

Adjuvant	Relative span			
	Dicamba	2,4-D	Flumizín	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	1.20cBa
Kento	1.02aAβ	1.15bAα	1.15bCβ	0.98aAβ
Agral	1.19bBα	1.23bAα	0.99aABβ	1.40cCα
Dicamba + Xtend Protect1	1.05β			
P ⁻ herbicide x adjuvant	0.000			
P ⁻ adds x factorial	0.003			
P ⁻ normality	0.110			
P ⁻ 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 Dunnett tests at 5% probability

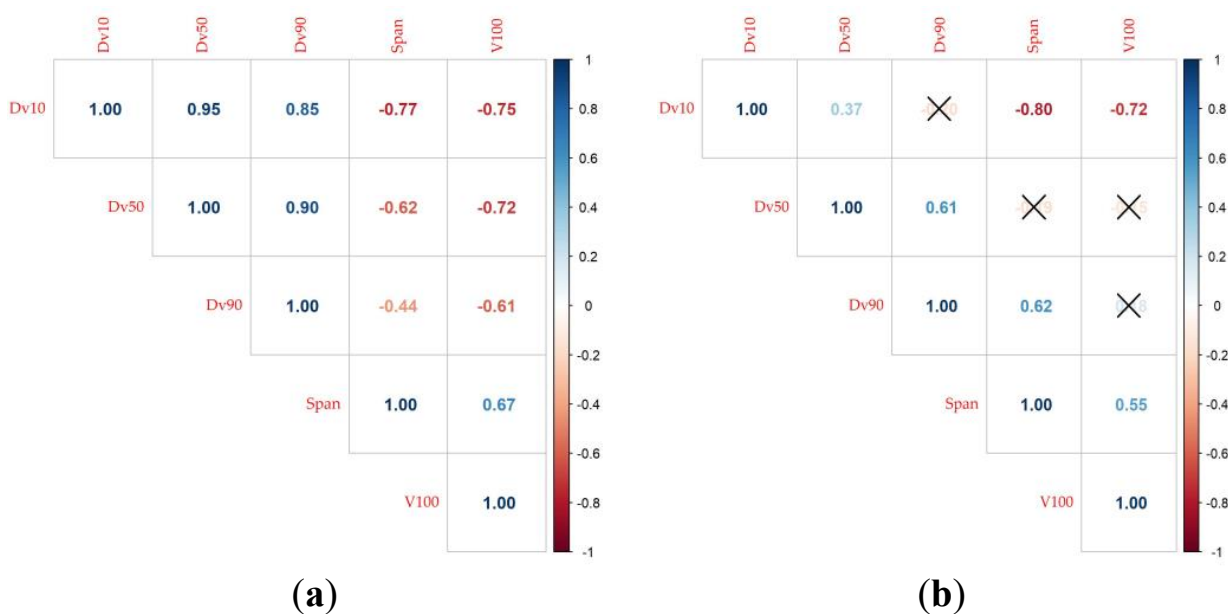


Figure 2. Correlation matrix: (a) Adjuvant and working pressure assay, and (b) herbicides in the presence of adjuvant assay.

DISCUSSION

Increasing in working pressure from 100 kPa to 600 kPa induced significant and progressive reductions in $Dv_{0.1}$, VMD, and $Dv_{0.9}$ droplet diameters, accompanied by a notable increase in the percentage of fine droplets (V_{100}) (Table 2). The transition from 300 to 400 kPa exerted the most pronounced effect on droplet size reduction. This behavior is consistent with previous observations that higher pressures, while reducing droplet size, can compromise coverage under certain conditions and are influenced by air entrainment within the droplets.^(19,21) The greater influence of pressure on VMD and $Dv_{0.9}$, compared to $Dv_{0.1}$, reflects the proportion of droplets in each size class of the spectrum and their interaction with leaf surfaces.^(8,22,23) The V_{100} fraction, directly proportional to the increase in pressure, is critical for herbicides with volatilization potential, such as Dicamba, increasing the risk of drift and damage to adjacent crops.^(24,25) Correct nozzle selection is, therefore, essential to mitigate these impacts. The TTI 110015VP nozzle, at 100 and 200 kPa, produced ultra-coarse droplets, and at 300 to 400 kPa, extremely coarse droplets, classifications that were maintained even at 500 and 600 kPa, demonstrating its intrinsic characteristic of generating a coarse droplet spectrum.⁽²⁶⁾

In Experiment 1, the addition of adjuvants to aqueous solution demonstrated the capacity to modulate the droplet spectrum, especially $Dv_{0.9}$ and relative span. Xtend Protect1 was the most effective in reducing $Dv_{0.9}$, aligning with its characteristic as a drift and volatility reducer for Dicamba (Table 3). Contact WSP had a minimal effect, while Kento, Agral, and Fighter NG showed intermediate effects, which can benefit coverage but increase the risk of drift depending on conditions.⁽²⁷⁾ The uniformity of the droplet spectrum, as measured by relative span, was influenced by the interaction between adjuvants and working pressure. Among the treatments that yielded the lowest relative span values, Contact WSP was observed at 100 and 200 kPa, Kento Pulveriza at 300 kPa, Agral at 500 kPa, and Fighter NG at 600 kPa. At 400 kPa, no significant difference was observed among the adjuvants (Table 3). Although some adjuvants have similar effects on $Dv_{0.1}$, VMD, and $Dv_{0.9}$ individually, they can improve the relative span. No interaction was observed between the adjuvant type and working pressure on droplet size, refuting the idea that finer droplets always result in greater deposition⁴. Selection must balance application efficiency, coverage, and drift risk.^(28,29)

Experiment 2, focusing on spray solutions with herbicides and adjuvants, revealed that adjuvants with anti-drift properties tend to increase droplet size, with the exception of Agral.⁽³⁾ Increasing $Dv_{0.1}$ to 100-150 μm is desirable to reduce the relative span⁸. The Dicamba + Xtend Protect1 mixture stood out for its anti-drift and anti-evaporation properties, with a $Dv_{0.1}$ of 342 μm , VMD of 729 μm , and a relative span of 1.05, positioning itself as an effective benchmark in maintaining coarser droplets and a narrow spectrum to mitigate drift and volatilization⁽³⁰⁾ (Tables 5, 6, 8). VMD, as a standard reference for droplet size, was influenced by all tested adjuvants.^(31,32) Dicamba formulations without adjuvants showed the highest VMD, while pure glyphosate resulted in a 25.3% lower VMD, which is attributed to the chemical compositions and physico-chemical properties of the mixtures.⁽³³⁾ The lack of detailed descriptions of adjuvant composition in this study limits a complete elucidation of the mechanisms involved, suggesting future research. All adjuvants, except Agral, reduced $Dv_{0.9}$, bringing the $Dv_{0.1}$, $Dv_{0.5}$, and $Dv_{0.9}$ percentiles closer together, a primary benefit for spectrum uniformity.⁽³⁴⁾ Agral, in turn, did not demonstrate a significant anti-drift effect, resulting in the highest proportion of V_{100} , which, although still low with the TTI 110015VP nozzle, indicates a higher drift risk.⁽¹⁹⁾

The analysis of the results reiterates that VMD alone is insufficient for a complete evaluation of application quality. It is imperative to consider $Dv_{0.1}$, $Dv_{0.9}$, relative span, and v_{100} for a holistic understanding of the droplet spectrum and its impacts on drift, coverage, and efficiency. The inclusion of adjuvants and herbicides alters the correlations between droplet spectrum variables, evidencing multifactorial complexity. In Experiment 1 (pressure and adjuvants), the weakest correlation was between $Dv_{0.9}$ and relative span, while VMD showed a strong negative correlation with relative span and V_{100} . In Experiment 2 (herbicides and adjuvants), the weakest correlation occurred between $Dv_{0.1}$ and $Dv_{0.5}$. The negative correlation between $Dv_{0.1}$ and relative span in both experiments emphasizes the importance of $Dv_{0.1}$ in determining spectrum uniformity.⁽³⁵⁾ The interaction between working pressure, adjuvants, and herbicides shapes the droplet spectrum and influences application efficiency by modifying the liquid sheet behavior.⁽²⁷⁾ Optimizing these parameters, considering specific application conditions and the inherent characteristic of the nozzle (such as the TTI 110015VP, which generates coarse

to ultra-coarse droplets), is crucial for maximizing control, minimizing drift, and ensuring environmental sustainability.

CONCLUSIONS

This study elucidated the complex modulation of the droplet spectrum by working pressure, adjuvants, and herbicides in applications with a TTI 110015VP air-induction nozzle, offering crucial insights for optimizing application and environmental safety. Increases in working pressure consistently reduced droplet size (Dv0.1, VMD, Dv0.9) and elevated the proportion of fine droplets (V_{100}), directly impacting the balance between coverage and spray drift risk. The adjuvant type markedly influenced the spectrum; while Xtend Protect1 promoted a more uniform spectrum by reducing Dv0.9, Agral increased drift risk due to a higher v_{100} . The significant interaction between herbicides and adjuvants underscores the need for careful selection, tailored to each formulation, to maximize control efficacy and safety. Furthermore, isolated VMD evaluation is insufficient; parameters such as Dv0.1, Dv0.9, relative span, and V_{100} are essential for a comprehensive understanding of the droplet spectrum and for optimizing applications. The inclusion of adjuvants and herbicides also altered the correlations between droplet spectrum variables, reinforcing the importance of a multifactorial analysis in each application scenario.




DATA AVAILABILITY STATEMENT



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





ACKNOWLEDGMENTS, FINANCIAL SUPPORT, AND FULL DISCLOSURE



This research was partially funded by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Finance Code 001, and Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG), APQ-00434-24.

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REFERENCES

- Butts TR, Virk SS, Kouame KB. Droplet size, velocity, and spray coverage from a magnetic-assisted sprayer. *Biosyst Eng.* 2024;245:1-11. Available from: <https://doi.org/10.1016/j.biosystemseng.2024.06.010>
- Godinho JD Júnior, Vieira LC, Ruas RA, Carvalho A Filho, Faria VR, Deus PI. Spray nozzles, working pressures, and use of adjuvant in reduction of 2,4-D herbicide spray drift. *Planta Daninha.* 2020;38:1-7. Available from: <https://doi.org/10.1590/S0100-83582020380100070>
- Silva CL, Cunha JP, Alvarenga CB, Zampiróli R. Interface Properties and droplet spectra as a function of adjuvants and spray nozzles. *AgriEngineering.* 2025;7:116. DOI: 10.3390/agriengineering7040116. Available from: <https://doi.org/10.3390/agriengineering7040116>
- Prado EP, Guerreiro JC, Ferreira-Filho PJ, Nascimento V, Ferrari S, Galindo FS, Funichello M, et al. Performance of spray nozzles and droplet size on glufosinate deposition and weed biological efficacy. *Crop Prot.* 2024;177:106560. Available from: <https://doi.org/10.1016/j.cropro.2023.106560>
- Griesang F, Spadoni AB, Ferreira PH, Ferreira MC. Effect of working pressure and spacing of nozzles on the quality of spraying distribution. *Crop Prot.* 2022;151:105818. Available from: <https://doi.org/10.1016/j.cropro.2021.105818>
- Li X, Chen L, Tang Q, Li L, Cheng W, Hu P, Zhang R. Characteristics on the spatial distribution of droplet size and velocity with difference adjuvant in nozzle spraying. *Agronomy.* 2022;12:1960. Available from: <https://doi.org/10.3390/agronomy12081960>
- Milanowski M, Subr A, Combrzynski M, Rózanska-Boczula M, Parafiniuk S. Effect of adjuvant, concentration, and water type on the droplet size characteristics in agricultural nozzles. *Appl Sci.* 2022;12:5821. Available from: <https://doi.org/10.3390/app12125821>
- Hewitt AJ. Adjuvant use for the management of pesticide drift, leaching, and runoff. *Pest Manag Sci.* 2024;80:2649-59. Available from: <https://doi.org/10.1002/ps.8255>
- Creech CF, Kruger GR, Oliveira M, Easterly A. Reduced adsorption of dicamba spray droplets on leaves as droplet size increases. *Weed Technol.* 2024;1-32. Available from: <https://doi.org/10.1017/wet.2024.34>
- Appah S, Asante EA, Ayambire CA. Analogous charging effect of surfactant-pesticide spray jet on droplet characteristics and deposition on hydrophobic leaf surfaces. *Eur J Agric Food Sci.*

- 2024;6(1):45-50. Available from: [10.24018/ejfood.2024.6.1.757](https://doi.org/10.24018/ejfood.2024.6.1.757)
11. Basílio S, Furtado MR Júnior, Alvarenga CB, Vitória EL, Vargas BC, Privitera S, et al. Effect of adjuvants on physical-chemical properties, droplet size, and drift reduction potential. *Agriculture*. 2024;14:2271. DOI: [10.3390/agriculture14122271](https://doi.org/10.3390/agriculture14122271). Available from: <https://doi.org/10.3390/agriculture14122271>
 12. Ávila R Neto, Melo AA, Ulguim AR, Pedrosa RM, Barbieri GF, Luchese EF, et al. Mixtures of 2,4-D and Dicamba with other pesticides and their influence on application parameters. *Int J Pest Manag*. 2024;70(1):121-30. Available from: <https://doi.org/10.1080/09670874.2021.1959082>
 13. Noguera MM, Avila LA, Zimmer M, Becker R, Egewarth K, Camargo ER. Buffer zones for 2,4-D application nearby tobacco fields. *Cienc Rural*. 2022;52:e20210350. Available from: <https://doi.org/10.1590/0103-8478cr20210350>
 14. Hu P, Zhang R, Chen L, Li LL, Tang Q, Yan W, et al. Effect of polymer adjuvant type and concentration on atomization characteristics of nozzle. *Agriculture*. 2024;14:404. Available from: <https://doi.org/10.3390/agriculture14030404>
 15. Liao J, Luo X, Wang P, Zhou Z, O'Donnell CC, Zang Y, et al. Analysis of the influence of different parameters on droplet characteristics and droplet size classification categories for air induction nozzle. *Agronomy*. 2020;10:256. Available from: <https://doi.org/10.3390/agronomy10020256>
 16. Xue S, Han J, Xi Z, Lan Z, Wen RF, Ma X. Coordination of distinctive pesticide adjuvants and atomization nozzles on droplets spectrum evolution for spatial drift reduction. *Chin J Chem Eng*. 2024;66:250-62. Available from: <https://doi.org/10.1016/j.cjche.2023.10.001>
 17. Ferguson JC, Hewitt AJ, Eastin JA, Connell RJ, Roten RL, Kruger GR. Developing a comprehensive drift reduction technology risk assessment scheme. *J Plant Prot Res*. 2014;54:85-9. Available from: [https://journals.pan.pl/Content/89309/PDF/JPPR_54\(1\)_13_Ferguson.pdf](https://journals.pan.pl/Content/89309/PDF/JPPR_54(1)_13_Ferguson.pdf)
 18. American Society of Agricultural and Biological Engineers. ASABE S572.3: Spray nozzle classification by droplet spectra. ASABE; 2020.
 19. Cauwer B, Meuter I, Ryck S, Dekeyser D, Zwervaegher I, Nuyttens D. Performance of drift-reducing nozzles in controlling small weed seedlings with contact herbicides. *Agronomy*. 2023;13(5):1342. Available from: <https://doi.org/10.3390/agronomy13051342>
 20. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing; 2024. Available from: www.r-project.org.
 21. Faggion F, Antuniassi UR. Desempenho de pontas de pulverização quanto a indução de ar nas gotas. *Energia Agric*. 2010;25:72-82. Available from: <https://doi.org/10.17224/EnergAgric.2010v25n4p72-82>
 22. Yang W, Zhong W, Jia W, Ou M, Dong X, Zhang T, et al. The effect of oil-in-water emulsion pesticide on the evolution of liquid sheet rim disintegration and the spraying distribution. *Crop Prot*. 2024;177:106547. Available from: <https://doi.org/10.1016/j.cropro.2023.106547>
 23. Ma J, Liu K, Dong X, Huang X, Ahmad F, Qiu B. Force and motion behaviour of crop leaves during spraying. *Biosyst Eng*. 2023;235:83-99. Available from: <https://doi.org/10.1016/j.biosystemseng.2023.09.012>
 24. Rubert J, Tarouco CP, Wesz AM, Bortolin ES, Reis CB, Ulguim AR. Simulated drift of 2,4-D and Dicamba in pecan (*Carya illinoensis* K. Koch) and olive trees (*Olea europaea* L.). *Cienc Florestal*. 2024;34:1-20. Available from: <https://doi.org/10.5902/1980509869073>
 25. Ceretta JM, Albrecht AJ, Albrecht LP, Silva AF, Yokoyama AS. Can pre and/or post-emergent herbicide application affect soybean seed quality? *Caatinga*. 2023;36:740-7. Available from: <https://doi.org/10.1590/1983-21252023v36n401rc>
 26. TeeJet Technologies. Catálogo 52-PT [Internet]. 2024 [cited 2024 Jul 1]. Available from: www.teejet.com.
 27. Yang W, Zhong W, Jia W, Ou M, Dong X, Zhang T, et al. Study on atomization mechanisms and spray fragmentation characteristics of water and emulsion butachlor. *Front Plant Sci*. 2023;14:1265013. Available from: <https://doi.org/10.3389/fpls.2023.1265013>
 28. He M, Qi P, Han L, He X. Study on spray evaluation: The key role of droplet collectors. *Agronomy*. 2024;14:305. Available from: <https://doi.org/10.3390/agronomy14020305>
 29. Xie Q, Song M, Wen T, Cao W, Zhu Y, Ni J. An intelligent spraying system for weeds in wheat fields based on a dynamic model of droplets impacting wheat leaves. *Front Plant Sci*. 2024;15:1420649. Available from: <https://doi.org/10.3389/fpls.2024.1420649>
 30. Vieira BC, Butts TR, Rodrigues AO, Schleier III JJ, Fritz BK, Kruger GR. Particle drift potential of glyphosate plus 2,4-D choline pre-mixture formulation in a low-speed wind tunnel. *Weed Technol*. 2020;34:520-7. Available from: <https://doi.org/10.1017/wet.2020.15>
 31. Liu Q, Shan C, Zhang H, Cancan C, Lan Y. Evaluation of liquid atomization and spray drift reduction of hydraulic nozzles with four spray adjuvant solutions. *Agriculture*. 2023;13:236. Available from: <https://doi.org/10.3390/agriculture13020236>
 32. Alves GS, Kruger GR, Cunha JP. Spray drift and droplet spectrum from Dicamba sprayed alone or mixed with adjuvants using air-induction nozzles. *Pesqui Agropecu Bras*. 2018;53:693-702. Available from: <https://doi.org/10.1590/S0100-204X2018000600005>
 33. Sijs R, Bonn D. The effect of adjuvants on spray droplet size from hydraulic nozzles. *Pest Manag Sci*. 2020;76:3487-94. Available from: <https://doi.org/10.1002/ps.5742>
 34. Rodrigues AD Neto, Ribeiro NA, Oliveira FA, Faria GA, Prado EP. Droplet spectrum characteristics and drift potential of different droplet classes and spray volumes application of atrazine with nicosulfuron. *Cienc Rural*. 2023;53:e20220509. Available from: <https://doi.org/10.1590/0103-8478cr20220509>
 35. Privitera S, Manetto G, Pascuzzi S, Pessina D, Cerruto E. Drop size measurement techniques for agricultural sprays: A state-of-the-art review. *Agronomy*. 2023;13:678. Available from: <https://doi.org/10.3390/agronomy13030678>