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DOI: https://doi.org/10.1590/1807-1929/agriambi.v30n9e304968 ORIGINAL ARTICLE

Low-volume electrostatic aerial spraying in eucalyptus: Application performance[1]

Pulverização aérea eletrostática em baixo volume em eucalipto: Desempenho da aplicação

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HIGHLIGHTS:

Electrostatic spraying maintained droplet density and coverage with a threefold reduction in spray volume.
Droplet spectrum and coverage uniformity were equivalent between electrostatic and hydraulic systems.
Reduced spray volume increased operational efficiency without compromising application quality.

ABSTRACT: Eucalyptus cultivation has high economic importance in Brazil, and the efficiency of phytosanitary management depends on the operational quality of spray applications. In this context, reducing spray volume without compromising application quality remains a challenge for aerial spraying. Therefore, this study evaluated whether low-volume electrostatic aerial spraying can maintain application quality indicators compared to the conventional hydraulic nozzle system in commercial eucalyptus plantations in southern Brazil. Two field experiments were conducted using an aircraft equipped with hydraulic nozzles (30 L ha^{-1}) and an electrostatic spray boom (10 L ha^{-1}). Application quality was assessed using water-sensitive papers to quantify droplet density, coverage, and volumetric median diameter at different canopy positions. Spray deposition was determined by dye recovery from leaves collected in the upper, middle, and lower canopy strata. Despite the threefold reduction in spray volume, no significant differences were observed between the application systems for droplet density and coverage. The hydraulic system resulted in greater deposition in the upper canopy, whereas no differences were observed between the application systems in the middle and lower strata. The electrostatic system provided a more uniform deposition distribution throughout the canopy while maintaining equivalent application quality with lower spray volume, greater operational efficiency, and lower cost per hectare.

Key words: spray solution volume, dye deposition, coverage area

RESUMO: O cultivo de eucalipto possui elevada relevância econômica no Brasil, e a eficiência do manejo fitossanitário depende da qualidade operacional das aplicações. Nesse contexto, a redução do volume de calda, sem comprometer a qualidade da pulverização, representa um desafio para a aplicação aérea. Assim, este estudo avaliou se a pulverização aérea eletrostática em baixo volume mantém os indicadores de qualidade de aplicação em comparação ao sistema convencional com pontas hidráulicas em povoamentos comerciais de eucalipto no sul do Brasil. Dois experimentos de campo foram conduzidos utilizando uma aeronave equipada com pontas hidráulicas (30 L ha^{-1}) e barra eletrostática (10 L ha^{-1}). A qualidade da aplicação foi avaliada por meio de papéis hidrossensíveis, quantificando densidade de gotas, cobertura e diâmetro mediano volumétrico em diferentes posições do dossel. A deposição foi determinada pela recuperação de corante em folhas coletadas nos estratos superior, médio e inferior do dossel. Apesar da redução de três vezes no volume de calda, não foram observadas diferenças significativas entre os sistemas de aplicação para densidade de gotas e cobertura. O sistema hidráulico apresentou maior deposição no estrato superior, enquanto não houve diferenças entre os sistemas de aplicação nos estratos médio e inferior. O sistema eletrostático apresentou distribuição mais homogênea da deposição ao longo do dossel, mantendo qualidade de aplicação equivalente com menor volume de calda, maior eficiência operacional e menor custo por hectare.

Palavras-chave: volume de calda, deposição de corante, área de cobertura

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Introduction

The efficiency of phytosanitary product application is a central topic in agricultural engineering, particularly in large-scale production systems, where the rational use of inputs is directly associated with the operational performance of spray applications. Aerial spraying strategies that reduce spray volume have proven effective in optimizing input use and increasing process efficiency while maintaining application functionality (Safaeinezhad et al., 2025).

Technological advances in these systems have been associated with improved spray deposition and reduced drift losses, contributing to greater technical and economic sustainability of operations (Chen et al., 2025). Complementarily, the optimization of operational parameters enhances spraying efficiency and reduces total application time, reinforcing the role of application technology in large-scale systems (İnan & Karci, 2025).

Spray volume represents one of the main bottlenecks in aerial spraying, as it directly affects application efficiency, costs, and logistics (Liu et al., 2023). High spray volumes increase operational time, fuel consumption, and losses, thereby reducing overall process efficiency. Thus, reducing spray volume without compromising application quality becomes a technical necessity, especially in low-volume systems, in which uniform target coverage is a determining factor. In this context, standardized tools, such as water-sensitive papers and tracers, are widely employed to assess spray quality (He et al., 2024). These evaluation methods are particularly important for comparing and validating emerging spray technologies designed to enhance deposition and coverage.

Among the available systems, electrostatic spraying stands out, as it is based on the attraction between electrically charged droplets and plant surfaces, a mechanism that promotes spray adhesion to the target and can improve the efficiency of the applied product (Schroder & Loeck, 2006). Although comparisons between hydraulic nozzle systems and electrostatic booms have been reported for agricultural crops, such as cotton (Silva, 1997), their application in forest crops remains poorly explored, highlighting gaps in application technology studies.

Eucalyptus stands out both for its economic importance and for the complexity of its canopy architecture. Brazil is the world's leading producer of short-fiber pulp derived from species of the genus Eucalyptus (IBA, 2024). However, plantation productivity depends on efficient phytosanitary management, particularly in response to pests such as the bronze bug *Thaumastocoris peregrinus* (Carpintero & Dellapé, 2006) (Hemiptera: Thaumastocoridae), which has caused significant damage. Under these conditions, chemical control is widely adopted (Machado et al., 2016), and aerial spraying represents a viable operational alternative for large areas, with efficiency dependent on equipment type and the quality of spray coverage achieved (Mewes et al., 2013).

In this context, the objective of this study was to evaluate whether, in eucalyptus crop management, electrostatic aerial spraying with reduced spray volume maintains application quality when compared with the conventional hydraulic nozzle system. For this purpose, indicators such as droplet density (drops cm^{-2}), coverage area (cm^2), and volumetric median diameter were evaluated on water-sensitive papers, in addition to the deposition of Brilliant Blue dye in different canopy strata and the spray solution compatibility in aerial spraying systems equipped with hydraulic nozzles and electrostatic booms.

Material and Methods

The first stage of the experiment was dedicated to evaluating the physicochemical stability of the spray solutions, considering that the reduction in application volume in the electrostatic system results in higher concentrations of spray components compared with the conventional volume of 30 L ha^{-1}. At this stage, assessments of stability, compatibility, foam formation, and precipitation were performed for the spray solutions used in field applications, following the correct mixing order, with the water added first, followed by the insecticide, and finally, the adjuvant. Table 1 presents the phytosanitary products used in the analyses, as well as the corresponding application rates, which were proportionally adjusted to maintain the same concentrations and spray volumes adopted in the field experiment, considering the preparation of 0.5 L of spray solution for the laboratory evaluations.

The analytical methodology was based on an adaptation of the technical standard ABNT NBR 13875:2014, following complementary technical references, such as ABNT NBR 13073:2019 for the cleaning and preparation of glassware in agricultural product assays, ABNT NBR 13074:2004 for the preparation of standard water for the tests, ABNT NBR 13075:1994 for the proper handling of phytosanitary products in the laboratory, and ABNT NBR NM ISO 3310-1 (2010) for the correct use of test sieves. The evaluation was based on visual analysis performed at 0, 1, 5, 10, and 30 min after spray solution preparation, with scores assigned from 1 to 5 according to a scale adapted from the Brazilian Center of Bioaeronautics (n.d.), as presented in Table 2. The experimental procedure and the visual evaluation criteria are schematically illustrated in Figure 1.

Table 1. Description of phytosanitary products and adjusted application rates for analysis

Treatments	Description	Spray volume	Dose per 0.5 L
1	Sperto® + Magic Oil®	10 L ha^{-1}	6 g + 5 mL
2	Sperto® + Magic Oil®	30 L ha^{-1}	2 g + 5 mL

Table 2. Visual parameters for spray solution evaluation after preparation

Degree	Condition	Recommendation
1	Immediate separation	Do not apply
2	Separation after 1 min	Do not apply
3	Separation after 5 min	Continuous agitation
4	Separation after 10 min	Continuous agitation
5	Perfect stability	No restrictions

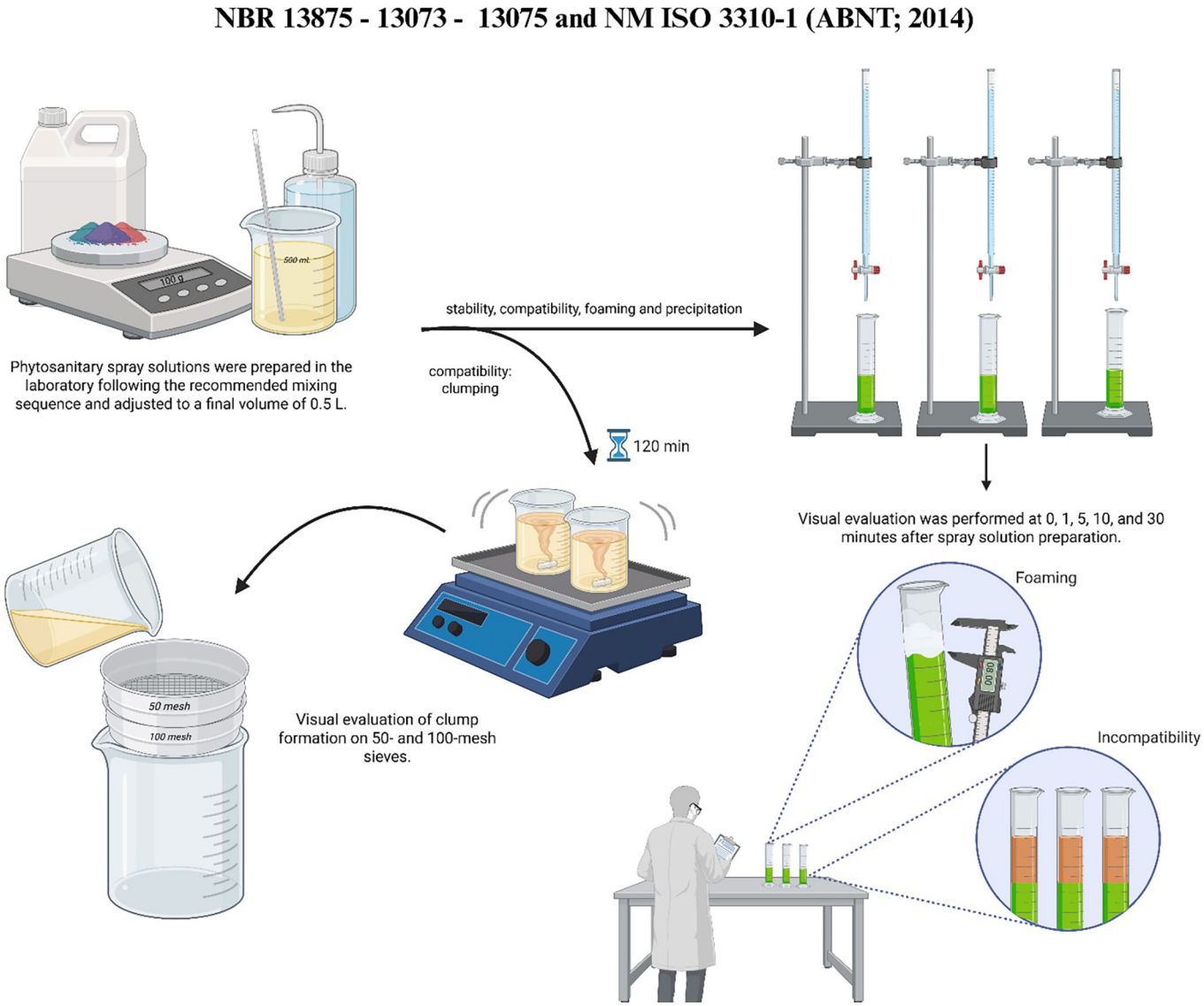
Source: Adapted from the Brazilian Center of Bioaeronautics (2006)

Field experiments were conducted in commercial plantations of *Eucalyptus benthamii* Maiden & Cambage during the 2023 and 2024 growing seasons in the state of Rio Grande do Sul, Brazil. The study was structured as two field trials conducted in different locations and years. Evaluations were carried out considering the application system - A (hydraulic vs. electrostatic) and canopy strata (D) as factors in a factorial scheme (A × D, resulting in eight treatment combinations distributed in a randomized complete block design with four replicates, conducted in distinct areas but with similar operational characteristics, aiming to compare application quality between the systems.

Aerial application with hydraulic nozzles was performed in the municipality of Cachoeira do Sul, RS, Brazil, in an 8.6-year-old seed-origin stand, established over an area of 15 ha. The trees had a mean diameter at breast height (DBH) of 17.50 cm and an average height of 23.0 m. Application with the electrostatic boom was conducted in the municipality of São Gabriel, RS, in a 10-year-old clonal plantation covering an area of 16 ha, where trees showed a mean DBH of 20.08 cm and an average height of 29.6 m.

In both experiments, a randomized block design was adopted, with four blocks per experiment, with evaluations conducted on selected trees within each block. Each block contained four trees, totaling 16 experimental units per experiment. The application system constituted the treatment factor applied at the plot level, while canopy strata (upper third, middle third, one meter above the ground, and ground level) were evaluated as treatment factors in a 2 × 4 factorial scheme, with treatments defined by the combination of the levels of both factors. Data were analyzed using a linear mixed-effects model, considering application system (factor A), canopy strata (factor D), and their interaction (A × D) as fixed effects, while blocks were treated as random effects nested within each experiment (location/year).

The experiments were conducted with a focus on evaluating application quality indicators, such as droplet density, coverage area, volumetric median diameter, and spray distribution within the canopy, rather than comparing absolute deposition between different areas or growing seasons. Therefore, the comparison between application



1 - Preparation of phytosanitary spray solutions with adjustment to a final volume of 0.5 L; 2 - Determination of the physicochemical properties of the spray solutions using burettes; 3 - Visual assessment at different time intervals after preparation; 2.1 - Magnetic stirring of the spray solutions; 3.1 - Visual assessment of clump formation using sieves

Figure 1. Schematic representation of the methodology for evaluating the physicochemical compatibility of phytosanitary spray solutions

systems was based on their ability to maintain spray quality under contrasting spray volumes, representative of conventional hydraulic and low-volume electrostatic application technologies.

Aerial applications were carried out using manned agricultural aircraft of the Ipanema model, operating under commercial application conditions. The spraying systems evaluated corresponded to conventional application with hydraulic nozzles and low-volume application with an electrostatic boom, adopting spray volumes representative of each technology.

In the hydraulic nozzle experiment, an Ipanema 202A aircraft was used, equipped with D8 Core 45 (UniJet®, Spraying Systems Co., Wheaton, Illinois, USA) hollow-cone hydraulic nozzles, operating at a working pressure of 28 psi. The spray volume applied was 30 L ha^{-1}, a value commonly adopted in conventional aerial spraying to ensure application uniformity. The aircraft operated at an average flight height of approximately 4 m above the canopy, with a forward speed of 205 km h^{-1}.

In the electrostatic boom experiment, an Ipanema 201A aircraft was used, equipped with an electrostatic boom with a total length of 4.15 m, composed of ceramic nozzles model 05. The working pressure was 45 psi, and the spray volume adopted was 10 L ha^{-1}, characterizing a low-volume aerial application. Flight height and aircraft forward speed were kept similar to those used in the hydraulic nozzle experiment in order to minimize operational interference in the comparison of application quality.

The selection of spray volumes and spraying systems was based on the operational characteristics and the working principles of each technology. While the hydraulic nozzle system relies primarily on pressure-driven atomization and spray volume to ensure adequate coverage, the electrostatic system promotes droplet electrification, enhancing their attraction to and adhesion on plant surfaces, thereby enabling a reduction in applied volume without compromising spray quality indicators.

Spray deposition analysis was conducted with the objective of evaluating spray distribution across different canopy strata and identifying potential losses associated with the aerial application systems, and it was not used as an isolated criterion of application quality. For this assessment, Brilliant Blue (FD&C Blue No. 1) dye was added to the spray solution at a concentration of 1% (m v^{-1}), allowing deposit quantification through spectrophotometric analysis.

To quantify spray deposition at each canopy level from each tree, ten leaves were collected per canopy stratum (upper, middle, one meter above the ground, and ground level), representing subsamples used to estimate the response at each level of factor D (canopy strata). The collected leaves were placed in identified plastic bags and transported to the laboratory for analysis.

For dye extraction, each set of leaves was washed with 50 mL of distilled water under standardized manual agitation in order to solubilize the dye deposited on the leaf surface. The resulting solution was subjected to spectrophotometric reading at a wavelength of 470 nm, and the results were expressed as micrograms of dye per milliliter of solution (μg mL^{-1}).

Deposition data were used to interpret the spray distribution pattern among plant strata and to identify possible losses due to excessive deposition at the top of the canopy or on the ground, especially as a function of the spraying system employed.

The quality of aerial application was evaluated using water-sensitive papers, which were employed to quantify indicators related to droplet spectrum and distribution, such as droplet density, coverage area, and volumetric median diameter (VMD). This assessment aimed to compare the ability of the spraying systems to maintain application quality under contrasting spray volumes.

Water-sensitive papers were positioned at four locations representative of the vertical distribution of the spray: the upper third of the canopy, the middle third of the canopy, one meter above the ground, and at ground level. In each experimental unit (tree), two water-sensitive papers were placed at each canopy stratum, totaling eight papers per tree (two papers × four strata), characterizing subsamples within each experimental unit. Thus, the papers were used to estimate spray deposition at each level of the canopy. For each spraying system, four trees per block were evaluated, with blocks considered as replicates in the experimental design.

The papers were mounted on vertically positioned metal rods placed next to the trees. To avoid interference with the behavior of electrically charged droplets, particularly during application with the electrostatic boom, the metal rods were previously insulated with electrical tape, minimizing electrostatic attraction of the spray to the support.

After application, the water-sensitive papers were collected, identified, and scanned at high resolution. The resulting images were analyzed using DropScope® (SprayX, São Paulo, SP, Brazil) software version 2.11.8, coupled with a microcamera, which performed droplet impact counting, droplet diameter estimation, and calculation of the covered area on the paper surface.

Data obtained from the water-sensitive papers were used to characterize spray quality in the different plant strata and at ground level, allowing comparison between application systems in terms of droplet distribution uniformity and maintenance of application quality indicators, regardless of the spray volume employed.

Meteorological conditions during aerial applications were monitored in order to characterize the spraying environment and ensure that operations were carried out within suitable ranges for aerial application, minimizing environmental interference with application quality indicators.

In the hydraulic nozzle experiment, meteorological variables were obtained from the Caçapava do Sul, Rio Grande do Sul meteorological station (Costi Olivos). During the application, conducted in April 2023, the mean air temperature was 26.1 °C, relative air humidity was 61%, and wind speed ranged from 3.7 to 4.9 km h^{-1}.

For the electrostatic boom application, meteorological information was obtained from the São Gabriel, Rio Grande do Sul meteorological station (INMET, station A832). Spraying was carried out in March 2024, with a mean air

temperature of 25.05 °C, relative air humidity of 70.50%, and wind speed ranging from 1.7 to 3.6 km h^{-1}.

Applications were performed under meteorological conditions considered suitable for aerial spraying, and the recorded data were used to contextualize the results rather than being employed as experimental factors in the statistical analysis.

Data obtained from spray deposition and application quality evaluations were initially subjected to verification of the assumptions of residual normality and homogeneity of variances. Subsequently, the data were analyzed using a linear mixed-effects model, considering application system (factor A) and canopy strata (factor D), as well as their interaction (A × D), as fixed effects.

Experiments (location/year) and blocks nested within experiments were treated as random effects. When significant effects were detected, means were compared using Tukey's test ($p \leq 0.05$) based on estimated marginal means, allowing comparisons between application systems within each canopy stratum and between strata within each system. In contrast, physicochemical compatibility evaluations were assessed descriptively and were not subjected to statistical analysis. Statistical analyses were performed using R software, version 4.6.0.

Additionally, an economic assessment was conducted to compare the application technologies, based on operational costs per hectare obtained through a market survey with aerial spraying service providers. The survey included multiple providers to ensure representativeness, and the collected data were used to estimate average operational costs for each application method. A descriptive cost comparison approach was adopted to evaluate the economic feasibility of the systems in relation to their operational characteristics.

Results and Discussion

The results of the physicochemical compatibility analysis of the spray solutions indicated that reducing the application volume to 10 L ha^{-1}, with the consequent increase in the concentration of spray components, did not result in incompatibilities that would hinder aerial application (Table 3). At both evaluated volumes, adequate behavior was observed regarding stability, foam formation, and precipitation, provided that continuous agitation was adopted during spray solution preparation and application, as discussed for more concentrated spray solutions in agricultural spraying by Cunha & Alves (2009).

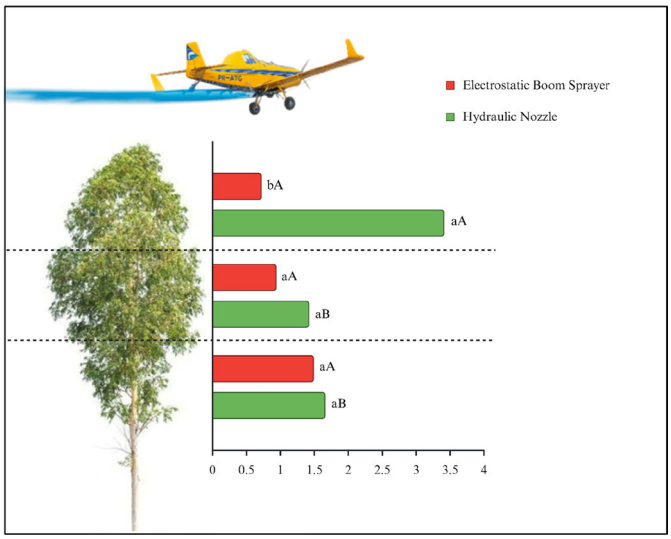
At the spray volume of 10 L ha^{-1}, greater initial foam formation was observed, as well as the occurrence of partial phase separation after longer resting periods, a characteristic associated with the higher concentration of both the product and the adjuvant in the spray solution. However, this separation was classified within acceptable operational limits according to the adopted evaluation scale and did not represent a restriction to application when recommendations for continuous agitation were followed.

At the spray volume of 30 L ha^{-1}, foam formation was less pronounced; however, adjuvant separation over time was also observed, indicating that the need for spray solution agitation is not exclusive to low-volume applications. Overall, the results demonstrate that the higher spray solution concentration in the electrostatic system does not compromise its physicochemical stability, thereby technically validating the execution of low-volume field applications (Tavares & Cunha, 2023).

A significant interaction between application system and canopy stratum was observed ($p = 0.0052$). As shown in Figure 2, spray deposition differed between application systems depending on the canopy position. In the upper canopy, the hydraulic nozzle system promoted greater dye deposition (3.42 µg mL^{-1}) compared to the electrostatic boom (0.73 µg mL^{-1}), representing an increase of approximately 4.5-fold and differing significantly between systems.

Table 3. Compatibility among products and foam formation over time after agitation at spray volumes of 10 and 30 L ha^{-1}

Spray volume (L ha^{-1})	Time of evaluation (min)	Foam formation (cm)	Degree of stability at the end of 30 min
10	0	2.8	4 Continuous agitation
	1	2.4	
	5	1.7	
	10	0.5	
	30	Foam ring	
30	0	Foam ring	3 Continuous agitation
	1	Foam ring	
	5	Foam ring	
	10	Foam ring	
	30	0	



Differences between application systems within each canopy stratum and among canopy strata within each application system were assessed by Tukey's test ($p \leq 0.05$) using estimated marginal means from a linear mixed model. Means followed by distinct lowercase letters indicate differences between application systems within each canopy stratum, whereas uppercase letters indicate differences among canopy strata within each application system

Figure 2. Dye concentration (µg mL^{-1}) in three canopy thirds of eucalyptus plants subjected to aerial spraying with an aircraft equipped with hydraulic nozzles and an electrostatic boom

In contrast, no differences between application systems were observed in the middle and lower canopy strata ($p = 0.6261$ and $p = 0.8645$, respectively), indicating similar performance of both technologies in these regions. Regarding the vertical distribution within each system, the hydraulic nozzle application resulted in higher deposition in the upper canopy compared to the middle and lower strata, whereas no significant differences among canopy strata were detected for the electrostatic system, indicating a more uniform distribution of spray along the plant profile.

At the spray volume of 30 L ha^{-1}, the higher deposition values observed in the upper canopy layers indicate a less uniform distribution along the vertical canopy profile, with a tendency for product concentration on the most exposed leaves. This pattern may favor runoff processes and increase losses to the soil, without a proportional increase in deposition in the lower layers, indicating that greater absolute deposition should not be interpreted in isolation as an indicator of higher application efficiency (Yao et al., 2021).

In contrast, the electrostatic system operating at low volume exhibited more balanced deposition values among the different canopy positions, even with a lower total applied volume. This behavior is associated with the action of the electric field on smaller droplets, which receive an electrical charge and are attracted to plant surfaces due to the electric potential difference between the droplets and the canopy, promoting their adhesion and a more homogeneous spray distribution (Sasaki et al., 2013). Electrostatic spraying systems have been described as more efficient in terms of deposition, highlighting their potential for more economical and effective applications, even at reduced spray volumes (Chaim, 2007).

Thus, the results indicate that reducing application volume, when associated with electrostatic technology, does not compromise spray deposition within the canopy and may promote a more uniform distribution along the vertical plant profile, corroborating previous findings for spraying systems aimed at optimizing deposition efficiency with lower spray volumes (Cunha & Alves, 2014).

Analysis of the water-sensitive papers indicated that, in general, the application systems exhibited similar spray quality patterns across the different plant strata, as shown in Table 4. No significant interaction between application system and canopy stratum was observed for droplet density ($p = 0.7969$), and the application systems did not differ statistically when evaluated in isolation ($p = 0.2061$). For droplet density (droplets cm^{-2}), canopy stratum had a significant effect ($p = 0.0030$), with higher values generally observed in the upper portions of the canopy, particularly in the upper third, while lower values were recorded in the lower strata and near ground level. This pattern was consistent for both application systems.

A similar pattern was observed for droplet-covered area. No significant interaction between application system and canopy stratum was detected ($p = 0.5111$), and the application systems did not differ statistically when evaluated in isolation ($p = 0.3752$). Thus, spray coverage was primarily influenced by canopy position ($p = 1.122 \times 10^{-5}$), with higher values observed in the upper and middle strata and reduced coverage in the lower canopy and at ground level. This distribution pattern was consistent between the hydraulic nozzle and electrostatic boom applications.

The joint interpretation of droplet density and covered area variables should be performed with caution, as there are no standardized thresholds defining optimal levels of these indicators in relation to the biological efficacy of the active ingredients used, as highlighted by Lopes et al. (2024).

Regarding VMD, a significant interaction between application system and canopy stratum was observed ($p = 0.00924$), indicating that the effect of the application system depended on canopy position. Higher VMD values were recorded for the hydraulic nozzle system in the upper third of the plants, differing significantly from the electrostatic boom ($p = 0.0010$).

In the remaining strata, no significant differences between application systems were detected ($p > 0.05$), although numerically higher values were also observed for the hydraulic system, particularly at ground level ($p = 0.0522$). These results indicate a predominance of coarser droplets in this system, whereas the electrostatic boom exhibited lower and more uniform VMD values across the different strata.

The relationship between droplet size and deposition pattern is consistent with the physical behavior described by Chen et al. (2020), who demonstrated that larger-diameter droplets are less susceptible to deflection by air currents and tend to deposit directly on more external surfaces. In contrast, in hydraulic nozzle applications, the predominance of larger droplets is associated with lower surface coverage and reduced penetration capacity in vegetation targets with denser canopies, limiting droplet retention within internal canopy regions.

This behavior has been previously described by Zhu et al. (2004) and Guler et al. (2007), who emphasized that larger droplets tend to exhibit lower coverage efficiency in complex vegetative structures. Conversely, smaller droplets remain suspended for longer periods, favoring penetration into the canopy interior and promoting more homogeneous coverage along the plant vertical profile, an effect enhanced by the microclimate within forest stands, which reduces droplet evaporation (Ru et al., 2023).

After evaluating the application quality of the two systems analyzed, the hydraulic nozzle and the electrostatic boom, a comparative analysis of the operational feasibility of the applications was conducted. Operational costs per hectare were estimated at US$ 53.92 for the hydraulic nozzle application and US$ 31.37 for the electrostatic boom application, based on a market survey conducted with three aerial spraying service providers, which reported similar values for each application modality.

The approximately 42% difference in cost per hectare is directly related to the operational requirements imposed by the higher spray volume used in the hydraulic nozzle application. The use of larger volumes reduces aircraft autonomy, increases refueling frequency, and consequently

Table 4. Droplet density, droplet-covered area, and volumetric median diameter (VMD) in four canopy strata of eucalyptus plants subjected to aerial spraying with an aircraft equipped with hydraulic nozzles and an electrostatic boom

Droplet density (droplets cm²)					
Application system	Canopy stratum				Mean
	Upper	Middle	One meter	Soil	
Hydraulic nozzle	7.04	7.38	3.90	4.09	5.60 a
Electrostatic boom	7.51	5.83	1.61	2.69	4.41 a
Mean	7.28 A	6.60 A	2.76 B	3.39 B	-
CV (%)			29.65		
Covered area (cm⁻²)					
Application system	Canopy stratum				Mean
	Upper	Middle	One meter	Soil	
Hydraulic nozzle	0.68	0.57	0.23	0.49	0.49 a
Electrostatic boom	0.51	0.48	0.09	0.16	0.31 a
Mean	0.60 A	0.53 A	0.16 B	0.33 AB	-
CV (%)			39.05		
VMD (μm)					
Application system	Canopy stratum				Mean
	Upper	Middle	One meter	Soil	
Hydraulic nozzle	352.8 aA	273.8 aA	198.6 bA	347.1 aA	293.1
Electrostatic boom	204.6 aB	231.1 aA	198.5 aA	260.3 aA	223.6
Mean	278.7	252.5	198.6	303.7	
CV (%)			11.85		

Means followed by distinct lowercase letters compare application systems within each canopy stratum, while uppercase letters compare canopy strata within each application system, according to Tukey's test ($p \leq 0.05$) based on estimated marginal means obtained from a linear mixed model; CV- Coefficient of Variation

increases the number of flights required to treat the same area (Caputti et al., 2025). This increase in the number of operational cycles results in lower operational efficiency (ha h^{-1}), longer total application time, and an increase in specific fuel consumption per hectare treated (Safaeinejad et al., 2025).

In contrast, the electrostatic boom application, by operating with a reduced spray volume, allows a larger area to be treated per refueling, reduces the number of flights, and optimizes the use of the aircraft's operational time. This condition results in higher operational efficiency, lower fuel consumption per unit area, and reduced logistical costs associated with aerial operations. Considering that the reduction in application volume did not compromise spray quality, the results indicate that the adoption of electrostatic technology represents a technically more efficient and economically more viable alternative for aerial applications in forest systems.

Conclusions

1. The phytosanitary spray solutions maintained adequate physicochemical compatibility even at higher concentrations, supporting the feasibility of low-volume aerial applications without compromising spray stability.

2. Aerial spraying with an electrostatic boom enabled the use of reduced spray volumes while maintaining comparable application quality parameters to the hydraulic nozzle system.

3. Electrostatic technology promoted a more uniform distribution of spray throughout the canopy, whereas the hydraulic nozzle system resulted in greater droplet deposition and larger droplet size in the upper canopy layers.

4. The electrostatic boom demonstrated operational advantages, including potential reductions in cost per hectare and increased aircraft productivity under the evaluated conditions.

Contribution of authors: All authors contributed to the conception, development, and writing of the manuscript. Norton B. Junior: experimental design, organization and acquisition of field data, and provision of the infrastructure for conducting the experiment. Fernanda M. Miranda: adaptation of the manuscript to the journal guidelines, final revision, investigation, and data interpretation. Thaís P. Roso, Adriano A. Melo, Manoel P. Zinelli, and Marcos Lenz: participation in all stages of the study, including experimental design, data collection, analysis, interpretation of results, manuscript writing, and critical revision. All authors approved the final version of the manuscript and assume responsibility for its content.

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