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CROP PRODUCTION

Droplet spectrum characteristics and drift potential of different droplet classes and spray volumes application of atrazine with nicosulfuron

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ABSTRACT: In this research, the Volumetric Median Diameters (VMDs), Relative Span (RS), percentage of droplets with a diameter smaller than 100 µm (V100), and percentage ofdrift (% drift) of four droplet classes (Fine, Medium, Coarse, and Very Coarse) were analyzedin two spray volumes (77 L.ha^{-1}and 144 L.ha^{-1}) employinga tank-mix of atrazine and nicosulfuron herbicides (2500 + 15 gaiha^{-1}), usingParticle/Droplet Imaging Analyze (PDIA) and wind tunnel techniques. The experiments were performed under Completely Randomized Design, in a 4 × 2 factorial scheme (droplet classes × sprayvolumes). Data underwent analysis of variance and Tukey's test at 5%, and the correlation between variables was computedconsidering Pearson's coefficient at 1% and 5%. The VMD of all droplet classes was considerably distinct in the two spray volumes. In both application spray volumes, the minimum VMD for the Coarsedropletclass classification was not attained. The highest means of RS were detectedin the spray volume of 77 L.ha^{-1}. All treatments demonstratedsignificant differences in the analysis of V100 and % drift, with the highest means observed in the Fine droplet (144 L.ha^{-1}) and Medium (77 L.ha^{-1}). A negative correlation existed between VMD × V100 and VMD × % drift and a positive correlation between V100 × % drift in the two spray volumes. RS was negatively correlated with VMD and positively with V100 and % drift, in the spray volume of 77 L.ha^{-1}. In the spray volume of 144 L.ha^{-1}, the correlation between RSand VMD, V100, and % drift was insignificant.
Key words: application technology, droplet size, wind tunnel, PDIA.

Características do espectro de gotas e potencial de deriva de diferentes classes de gotas e volumes de aplicação da mistura de atrazine com nicosulfuron

RESUMO: Nesta pesquisa foram avaliados os Diâmetros Medianos Volumétricos (DMVs), Amplitude Relativa (AR), percentual de gotas com diâmetro menor que 100 µm (V100) e porcentagem de deriva (% deriva) de quatro classes de gota (Fina, Média, Grossa e Muito Grossa) em dois volumes de aplicação (77L.ha^{-1}e 144L.ha^{-1}) utilizando a mistura dos herbicidas atrazine e nicosulfuron (2500 + 15 gi.a. ha^{-1}), utilizando os métodos de PDIA e de túnel de vento. Os experimentos foram realizados sob o delineamento inteiramente casualizado, no esquema fatorial 4 × 2 (classes de gota × volumes de aplicação), com cinco repetições. Os dados foram submetidos à análise de variância e ao teste de Tukey a 5%, e a correlação entre as variáveis calculada considerando o coeficiente de Pearson a 1% e 5%. O DMV de todas as classes de gotas foi significativamente diferente nos dois volumes. O DMV mínimo para a classificação da classe de gota Grossa não foi atingido nos dois volumes de aplicação. As maiores médias de AR foram observadas no volume de 77 L.ha^{-1}. Todos os tratamentos apresentaram diferenças significativas na análise de V100 e % deriva com as maiores médias observadas nas classes de gota Fina (144 L.ha^{-1}) e Média (77 L.ha^{-1}). Verificou-se correlação negativa entre DMV × V100 e DMV × % deriva e correlação positiva entreV100 × % deriva nos dois volumes. No volume de 77 L.ha^{-1} a AR correlacionou-se negativamente com o DMV e positivamente com V100 e % deriva. No volume de 144 L.ha^{-1} a correlação entre AR e DMV, V100 e % deriva não foi significativa.
Palavras-chave: tecnologia de aplicação, tamanho de gota, túnel de vento, PDIA.

INTRODUCTION

Weed competition is a significant limiting factor in crop yield, particularly among ecophysiologically similar species with the application of herbicides, majorly tank-mix such as atrazine and nicosulfuron in sub-doses, one of the forms of management (MARTINS et al., 2018; JORDÃO et al., 2021). Nevertheless, the inappropriate application of pesticides can cause soil contamination, water and adjacent areas, and one of the methods to minimize these risks is to employ knowledge of application technology, particularly concerning parameters such as droplet size and spray volume (ANTUNIASSI & BOLLER, 2019).

In the majority of available spray nozzles models, the droplet formation process is conditioned by the passage of a pressurized solution through a

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small orifice, leading to the formation of a thin liquid sheet, which becomes unstable and disintegrates into droplets of different sizes (MATTHEWS et al., 2014). Factors such as operating pressure and the physical properties of the solution can influence this outcome; although, the droplet size is conditioned to the nozzle (LOPES & REIS, 2020).

Droplets with diameters smaller than 100 µm have a great possibility of drifting, being more susceptible to evaporation or wind drag before reaching the target (MATTHEWS et al., 2014), with numerous research showing an association between the volume of droplets with a smaller diameter than 100 µm (V100) and the drift volume (STAINIER et al., 2006; ANTUNIASSI et al., 2014; CHEN et al., 2020). The need to utilize smaller droplets appears when opting for application in decreased spray volumes, to compensate for the lower coverage levels provided by decreased spray volumes, considering that spray volume and coverage are directly correlated parameters (ANTUNIASSI & BOLLER, 2019; SANTOS-JÚNIOR et al., 2022).

The drift occurrence can affect the environment, human health, and the efficacy of the application, especially of herbicides such as atrazine, which is extensively employed to control weeds in crops such as corn, sugarcane, and sorghum, with a considerable persistence time in the environment, often being detected in quantities that surpass the limits provided by regulatory agencies (CARVALHO et al., 2017; URSELER et al., 2022).

Additionally, herbicide drift can both impact sensitive crops in crop fields close to treated areas and weed plant communities on the margins of crop fields, which may damage the management of these species in the long term as a result of the development of resistance to these pesticides via recurrence exposure of these species at under-doses (VIEIRA et al., 2020).

Following the above-mentioned assumptions, the objective of this investigation was to validate the characteristics of the droplet spectrum by Particle/Droplet Image Analysis (PDIA) and the drift potential in the wind tunnel of different spray nozzles (droplet classes), in two spray volumes employing a tank-mix of atrazine and nicosulfuron herbicides.

MATERIALS AND METHODS

The evaluation of the droplet spectra and the examination of the drift potential of the treatments were performed at the NEMPA - "Núcleo de Ensaio de Máquinas e Pneus Agroflorestais" at the Experimental Farm Lageado, of the College of Agricultural Sciences - UNESP, Botucatu/SP.

The experiments were performed in a completely randomized design, in a 4 × 2 factorial scheme (Fine, Medium, Coarse, and Very Coarse droplet classes × spray volumes of 77L.ha^{-1}and 144 L.ha^{-1}), with five repetitions, utilizing the ADGA 01 flat fannozzles, Fine droplet; AD 01, Medium droplet; ST 01, Coarse dropletand AD-IA 007, Very Coarse droplet, for a spray volume of 77 L.ha^{-1} at operating pressures of 200; 200; 200; and 350kPa respectively, and the XR 110015 types, Fine droplet; TT 110015, Medium droplet; AIXR 110015, Coarse droplet and AIXR 11002, Very Coarse droplet for the spray volume of 144 L.ha^{-1}, at operating pressures of 310; 310; 310; and 180 kPa, respectively.

The droplet spectrum analysis was conducted employing the VisiSize P15 system (Oxford Lasers, Imaging Division, Oxford, U.K.), which computes via image, the size of particles in real-time (PDIA), considering as a trial plot the approximate amount of ten thousand droplets (KASHDAN et al., 2003), sampled at the application distance of 0.5 m.

The assessment of drift potential was performed in a wind tunnel (ISO/DIS 22856-1, 2005), comprising of capturing the drift produced by spraying on artificial targets (nylon wires), at three meters from the spray nozzle, under wind at a speed of 2.5 ms^{-1}, for 10 seconds, with the experimental plot containing five wires. Spraying was carried out under meteorological conditions of 22 ± 3ºC and air relative humidity of 46 ± 6% and regulated by a digital thermo-hygrometer.

The tank-mix solution employed in both experiments was atrazine (AclamadoBR®, SC) and nicosulfuron (Nico®, OD) at 2500 and 15 g a.i. ha^{-1}, with the addition of the dye marker Brilliant Blue FCP (Brastokio®) at 6 gL^{-1}. The dye marker was added only in the drift potential evaluation experiment.

The evaluated factors of the droplet spectrum were the volumetric diameters of 10%, 50%, and 90% [$DV_{0.1}$; Volume Median Diameter (VMD); and $DV_{0.9}$ respectively], percentage of droplets smaller than 100 µm (V100) and Relative Span (RS), were calculated by Equation (1): (1), where RS = Relative Span (dimensionless); $DV_{0.1}$,VMD and $DV_{0.9}$ = diameter (µm) at which 10%, 50%, and 90% of the droplet volume are contained in droplets at or below that diameters, respectively (FERGUSON et al, 2015).

The drift potential was quantified by spectrophotometry, reading solutions collectedfrom washing the nylon threads with 150 mL of deionized water at a wavelength of 630 nm, by a spectrometer (Shimadzu UV-2600) linked to a computer, with the reading data processed by the UVProbe software, which compares the readings absorbance solutions with the absorbance of a known concentration solution, hence obtaining the estimate of the percentage of drift (% drift) of each treatment.

For the variables VMD, V100, RS, and % drift, analysis of variance (ANOVA) and the Tukey test at 5% probability were carried out to compare means, employing the *ExpDes.pt* package in the R software (FERREIRA et al., 2018).

The means of findings for all examinations were compared by confidence interval with 95% probability (95% CI). Correlation matrices were built between the variables VMD, V100, % drift, and RS using the *psych* package in the R software (REVELLE, 2020),given Pearson's correlation coefficient at 1% and 5% probability.

RESULTS AND DISCUSSION

Both the droplet class factor and the spray volume factor, and their interactions, were significant ($P < 0.01$) in the evaluated variables, except for the spray volume in relation to the % drift (Table 1). Hence, the droplet class factor was divided into the spray volume factor and vice versa.

In table 2, it is possible to observe, considering the VMD, that the treatments varied considerably among themselves regarding droplet size both within and between the evaluated volumes, except for the Very Coarse droplet, which did not show a significant difference between the spray volumes. Evaluating the droplet classes in the spray volumes of 77 L.ha^{-1}and 144 L.ha^{-1}, the VMDs observed for the Coarse droplet class (257.97 µm and 334.43 µm, respectively) were below the VMD amplitude for the Coarse droplets classification (341 — 403 µm), fitting into the medium droplets class (236 – 340 µm) (ANSI/ASABE S572.1, 2009). The highest VMD value for the Fine droplet class was validated in the spray volume of 77 L.ha^{-1} (210.75 µm), and the highest VMD values for the Medium and Coarse droplets were confirmed in the spray volume of 144 L.ha^{-1} (264.61 µm and 334.43 µm, respectively) (Table 2).

The outcomes of droplet size is a complex product of various variables, with emphasis on the interaction between the nozzle type (orifice size and technological design) and the physical properties of the spray solution, including surface tension and viscosity, and it occurs irrespective of the active ingredients (HEWITT et al., 2008; FERGUSON et al., 2015; BUTTS et al., 2019; LOPES & REIS, 2020). Pesticides with SC-type formulations (the predominant type in the solution used in this research) may lower the VMDs of droplet spectra even offering a rise in the solution viscosity (physical property considered correlated with the improvement in droplet size) (SCHAMPHELEIRE et al., 2009; CARVALHO et al., 2017).

VMD reduction to the point of failing to meet the classification of the Very Coarse droplet class was also detected in the AD-IA nozzle, at an operating pressure of 3.1 bar, for an application volume of 65 L.ha^{-1} (COSTA et al., 2020). Such observations in the literature demonstrated that the usage of pesticides formulated in SC can decrease the VMDs of some nozzle types, corroborating with what was observed in this research for the Course droplet class. Nevertheless, general application guidelines suggested that systemic herbicides, such as atrazine and nicosulfuron, do not need a high level of coverage to be effective and can be used with Coarse droplets compared to contact herbicides, which achieve better when applied with Fine droplets (BUTTS et al., 2018), being shown by ANSI/ASABE S572.1

Table 1 - Analysis of variance (ANOVA) with *Fc* values for Volume Median Diameter (VMD), Relative Span (RS), percentage of droplets smaller than 100 µm (V100), and percentage of drift.

Variation sources	---Variables---			
	VMD	RS	V100	Drift
Droplet class (a)	36437.72**	28.62**	4761.16**	1040.68**
Spray volume (b)	1030.03**	2209.57**	506.54**	0.514
a × b	2389.56**	32.54**	1455.79**	308.27**
CV (%)	0.56	1.03	3.23	5.34

"**": significant at 1% by the *F* test.

Table 2 - Means[1] comparison between the variables Volume Median Diameter (VMD), Relative Span (RS), percentage of droplets smaller than 100 µm (V100), and percentage of drift.

Spray volume (Lha^{-1})	----------Dropletclass----------			
	Fine	Medium	Coarse	VeryCoarse
	----------VMD (µm)----------			
77	210.75 Da	235.44 Cb	257.97 Bb	417.77 A
144	168.74 Db	264.61 Ca	334.43 Ba	419.37 A
	----------RS----------			
77	1.44 Aa	1.41 Ba	1.36 Ca	1.37 Ca
144	1.18 Bb	1.22 Ab	1.21 Ab	1.17 Bb
	----------V100 (%)----------			
77	7.56 Ab	6.24 Ba	5.03 Ca	2.14 Da
144	15.74 Aa	5.67 Bb	3.25 Cb	1.72 Db
	----------Drift (%)----------			
77	4.49 Bb	7.20 Aa	2.83 C	1.58 D
144	7.55 Aa	4.38 Bb	2.80 C	1.56 D

[1]Means followed by different uppercase letters in the row and lowercase in the column differ by Tukey's test at 5% probability.

(2009), for post-emergent systemic herbicides VMDs between 341and 403 µm (Coarse droplet) (Table 2).

Regarding the RS of the analyzed treatments, the highest mean in the Fine droplet (1.44) wasdiscoveredin the spray volume of 77 L.ha^{-1}, which varies statistically from the Medium (1.41), Coarse (1.36), and Very Coarse droplet class (1.37), which displayed no difference among each other. In the spray volume of 144 L.ha^{-1}, the highest RS means were detectedin the Medium (1.22) and Coarse (1.21) droplet classes, which did not vary amongst themselves, followed by the Fine (1.18) and Very Coarse droplet class (1.17), which were also not significantly different (Table 2).

Comparing the treatments between the application volumes for RS, all treatments in the spray volume of 77 L.ha^{-1}exhibitedvalues greater than those shown by the treatments in the spray volume of 144 L.ha^{-1}. As the RS articulates how uniform it is the droplet spectrum, the higher its value, the larger the size range of the sprayed droplets, the lower the uniformity and, thus, the lower the spraying quality (MADUREIRA et al. 2015, MARTINS et al. 2021), it is then confirmed, that the most heterogeneous droplet spectra were noted in the smaller spray volume treatments (Table 2).

Following the changes observed in the VMD, the variance in the RS between the spray volumes have a plausible justification for the interaction between the spray solution and the nozzle type. The pesticide concentration in the solution is higher in the spray volume of 77 L.ha^{-1}, which may have influenced the physical characteristics of the solution in a more accentuated way, directly influencing the shear pattern at the droplet formation (CUNHA et al., 2003), aiding a more heterogeneous droplet spectrum.

It is necessary to accomplish the best possible performance from the nozzle for a high-quality pesticide application, especially concerning the RS, implying that, when choosing a spray nozzle, give preference to those that perform with greater droplet homogeneity, with a lower volume of droplets prone to drift and providing good target coverage (MARTINS et al., 2021).

Comparing the V100 between the droplet classes, it is validated, for the two application spray volumes, considerable differences between the means of all treatments. In the spray volume of 77 L.ha^{-1}, the highest mean was observed in the Fine (7.56%), followed by the Medium (6.24%), Coarse (5.03%), and Very Coarse droplet class (2.14%). In the spray volume of 144 L.ha^{-1} the same trend was noted, with the highest mean found in the Fine (15.74%), followed by the Medium (5.67%), Coarse (3.25 %), and Very Coarse droplet class (1.72%). Higher means of V100 were observed in the spray volume of 77 L.ha^{-1}, except for the Fine droplet class, which showed the highest means in the spray volume of 144 L.ha^{-1} (Table 2).

The estimation of drift potential can be analyzed by V100 (CUNHA et al., 2003; STAINIER et al., 2006; ANTUNIASSI & BOLLER, 2019), nevertheless, to minimize drift, other variablesmust be considered, including meteorological conditions at the application time, temperature below 30 ºC, air relative humidity above 50%, and wind speed between 3 and 10 kmh^{-1}, particularly when spraying smaller droplets (ANTUNIASSI & BOLLER, 2019).

Evaluating the % drift, there are substantial differences between all droplet classes. In the spray volume of 77 L.ha^{-1}, the highest mean of the % drift was noted in the Medium (7.20%), followed by the Fine (4.49%), Coarse (2.83%) and Very Coarse droplet class (1.58%). In the spray volume of 144 L.ha^{-1}, a different pattern was confirmed, with the highest mean observed in the Fine (7.55%), followed by the Medium (4.38%), Coarse (2.80%) and Very Coarse droplet class (1.56%) (Table 2). Comparing the spray volumes, it seems that the highest % drift was stimulated by the Fine droplet in the spray volume of 144 L.ha^{-1}, followed by the Medium droplet in the spray volume of 77 L.ha^{-1}, without considerable differences between Coarse and Very Coarse droplet classes among the analyzed spray volumes (Table 2). The trend of higher drift percentages for smaller droplet classes were estimated and has already been noted in other reports (STAINIER et al., 2006; CHEN et al., 2020).

Investigating the relationship between the response variables for the spray volume of 77 L.ha^{-1} (Figure 1), there was a moderate negative correlation between VMD × RS (-0.60), a strong negative correlation between VMD × drift (-0.71) and a very strong negative correlation between VMD × V100 (-0.97), implying that droplets with higher VMD offer lower V100, lower % drift, and greater homogeneity, validating the outcomes obtained by MADUREIRA et al. (2015) who observed an inversely proportional relationship between VMD and V100, examining the interaction between nozzles and different solutions. There exists a positive, strong, and significant correlation between RS × V100 (0.76) signifying that more heterogeneous spectra are likely to express greater volumes of droplets smaller than 100 µm, and also, a moderate positive correlation between RS × drift (0.60), demonstrating that, for the spray volume of 77 L.ha^{-1}, more heterogeneous droplet spectra were more inclined to drift. A strong, positive and significant correlation existed between V100 × drift

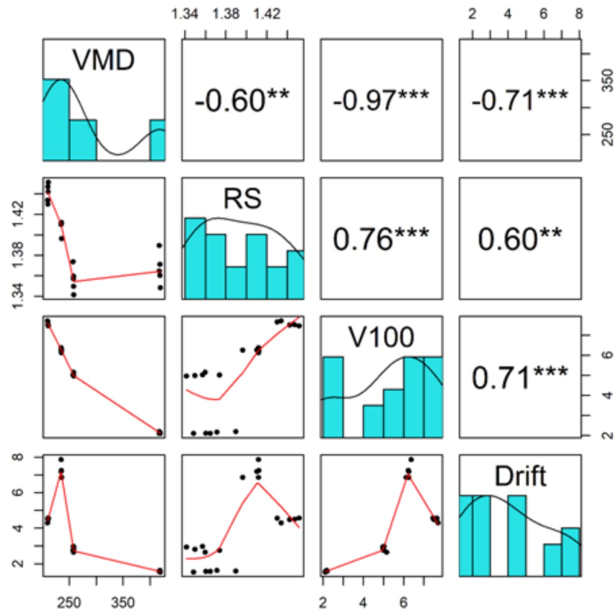

Figure 1 - Correlation matrix[1] between the variables Volume Median Diameter (VMD), Relative Span (RS), percentage of droplets smaller than 100 µm (V100), and percentage of drift for spray volume of 77 L.ha^{-1}.

[1]Diagonal: distribution histogram with density line; lower half: approximate polygonal scatterplots; upper half: correlation value between variables (*p*) with significance levels, with "**" and "***", corresponding to 5% and 1%, respectively, by Pearson's correlation.

(0.71). Such correlation data are extensively verified in the literature, specifically the positive correlation between V100 × drift (MADUREIRA et al., 2015; OLIVEIRA et al., 2015).

In the investigation between the response variables in the sprayvolume of 144 $L.ha^{-1}$ (Figure 2), the correlations between VMD × RS, RS × V100, and RS × drift were insignificant. The RS×drift correlation may display inconsistent findings and may be positive or negative, depending on the evaluation of other variables for a better understanding of the relationship between the droplet spectrum parameters and the % drift (ANTUNIASSI et al., 2014), as conducted in this study.

Very strong and significant negative correlations were corroborated between VMD × V100 (-0.93) and VMD × drift (-0.98), implying, following the same way as the spray volume of 77 $L.ha^{-1}$, that higher values of VMDexhibit lower percentages of droplets smaller than 100 μm, % drift, and greater homogeneity in the spray volume (Figure 2).

The relationship between V100 × drift was very strong and positive (0.97) in the spray volume of 144 $L.ha^{-1}$ (Figure 2). The positive correlation between these two parameters was anticipated because of the drift potential of finest droplets size, and for this same motive, there is a negative correlation between VMD × drift (-0.98), trends also noted by STAINIER et al. (2006); ANTUNIASSI et al. (2014) and CHEN et al. (2020). Comparing the magnitude of the correlation coefficients between the two spray volumes, particularly between VMD × drift and V100 × drift, stronger correlations were detected in the spray volume of 144 $L.ha^{-1}$, signifying that higher VMD values in the larger spray volume, affected the V100 and consequently the % drift.

In practical terms, the outcomes discovered in this investigation may be beneficial to monitor herbicide application operations in weed control programs. In the two spray volumes studied in this research, the use of the Very Coarse droplet class was the one that followed the application guidelines for systemic herbicides regarding VMD. As for the application quality, the spray volume of 144 $L.ha^{-1}$ displayed the greatest uniformity in the droplet spectra in all droplet classes studied and, droplet

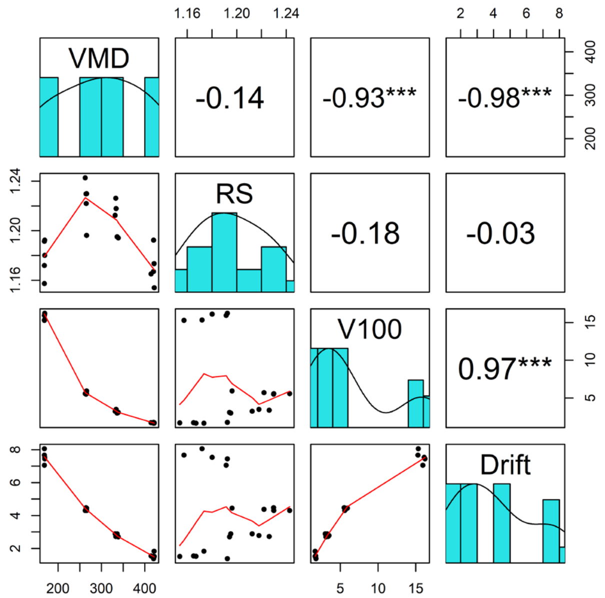

Figure 2 - Correlation matrix[1] between the variables Volume Median Diameter (VMD), Relative Span (RS), percentage of droplets smaller than 100 μm (V100), and percentage of drift for spray volume of 144$L.ha^{-1}$.

[1]Diagonal: distribution histogram with density line; lower half: approximate polygonal scatterplots; upper half: correlation value between variables (*p*) with significance levels, with “***” and “”, corresponding to 1% and 0% (not significant), respectively, by Pearson’s correlation.

uniformity is a relevant qualitative factor; although, no significant correlations were observed between the other variables.

CONCLUSION

The spray volume considerably affects the VMD, RS, and V100 parameters.

The correlation between the parameters VMD × V100 being negative and V100 × drift being positive, in the two examined spray volumes, shows that the use of spectra of droplets with higher VMDs offers lower % drift by decreasing the V100.

The application of a spray volume of 144 $L.ha^{-1}$ employing Coarse or Very Coarse droplet classes adequately approaches established qualitative factors concerning VMD, with lower RS and lower V100 compared to the spray volume of 77 $L.ha^{-1}$.

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DECLARATION OF CONFLICTS OF INTEREST

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to the conception and writing of the manuscript. All authors critically revised the manuscript and approved the final version.

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