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Predictive Modelling of the Droplet Size Distribution in Swirl Nozzles under Varying Operating Parameters

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ABSTRACT

Droplet size distribution is a critical parameter in liquid atomization because it governs spray coverage, evaporation rate, mixing efficiency, and overall process performance. Predicting droplet-size characteristics remains challenging due to the complex interactions among centrifugal forces, liquid-sheet instability, and operating conditions in swirl nozzles. This study presents a predictive modelling approach for estimating droplet size distribution under varying operating parameters. The significance of the model is directly linked to the combined effects of the selected operating parameters, spray pressure, exit orifice diameter, swirl chamber length-to-diameter ratio, and nozzle spraying height, which were systematically varied to evaluate their influence on droplet size distribution. The model evaluation yielded a p-value of 0.0079 and an F-value of 9822.41 at a 95% confidence level, indicating that variations in these parameters collectively have a statistically significant effect on spray characteristics.The predicted R2 of 0.9430 is in reasonable agreement with the adjusted R2 of 0.9999. The model exhibited excellent fit and predictive capability, as evidenced by an R^2 of 1.0000, adjusted R^2 of 0.9999, and predicted R^2 of 0.9430. The relatively close agreement between the adjusted and predicted R^2 values supports the model's robustness, while the low coefficient of variation (CV = 0.0255%) indicates high precision and reproducibility. Overall, the model effectively accounted for the variation in droplet size distribution. Results indicate that increased operating pressure produces finer droplets, whereas nozzle geometry significantly influences distribution uniformity. Thepredictive model provides a useful tool for spray system design and optimization, reducing reliance on extensive experimental testing and enhancing spray efficiency in practical applications

INTRODUCTION

Swirl nozzles are widely used in industrial, agricultural, and environmental applications that require efficient liquid atomization, including crop spraying, spray drying, combustion, wastewater treatment, and effluent dispersion. Their popularity is attributed to their simple construction and ability to produce finely atomized sprays with good spatial distribution (Ma *et al*., 2024; Hu *et al*., 2025). In pressure-swirl nozzles, liquid enters a swirl chamber where rotational motion is generated before exiting through a small orifice, producing either a hollow-cone or a full-cone spray depending on the nozzle design.

The atomization performance of swirl nozzles is largely determined by spray characteristics such as droplet size distribution, spray cone angle, spray height, and spray coverage, which directly influence mass transfer, chemical deposition, and overall process efficiency (Lefebvre and McDonell, 2017). These characteristics are affected by both operating conditions and nozzle geometry.

Operating pressure controls liquid velocity and swirl intensity, while geometric parameters such as orifice diameter, swirl chamber length-to-diameter ratio, and spray height govern internal flow development and droplet formation (Rashad *et al*., 2016; Lee *et al*., 2010; Lefebvre and McDonell, 2017).

The complex interaction among centrifugal forces, viscous effects, and surface tension makes spray formation highly nonlinear, limiting the ability of empirical observations alone to accurately predict spray behaviour (Bayvel and Orzechowski, 1993). Consequently, predictive modelling has become an important tool for establishing quantitative relationships between nozzle operating conditions and spray characteristics, thereby reducing experimental costs and supporting nozzle design optimization (Montgomery, 2017; Myers *et al*., 2016).

Although advances in experimental techniques and Computational Fluid Dynamics (CFD) have improved the understanding of spray atomization, many existing models remain computationally demanding or applicable only to specific nozzle configurations (Lefebvre and McDonell, 2017). Therefore, developing robust and practical predictive models remains essential for improving nozzle performance and spraying efficiency. This study focuses on modelling droplet size distribution in agricultural swirl nozzles by evaluating the combined effects of operating pressure, nozzle geometry, exit orifice diameter, and spray height.

METHODOLOGY

Materials and Equipment

The materials and equipment used for this study included a Nikon 750 JP 24.3-megapixel digital camera capable of producing high-resolution images with excellent detail, dynamic range, and continuous shooting of up to 6.5 frames per second for capturing experimental observations. A tripod stand was employed to provide stable and secure support for the camera during image acquisition. A specially designed test rig was utilized to evaluate the operational performance and capabilities of the swirl nozzles under controlled conditions. The swirl nozzles served as the primary experimental components for determining the emergent flow characteristics, including flow rate, pressure distribution, spray shape, direction, and velocity. Water was used as the test fluid throughout the experiment due to its suitability and availability for evaluating hydraulic performance.

Experimental Procedure

Fabrication of swirl nozzles

Swirl nozzles were designed and fabricated with varying geometric configurations, particularly swirl chamber length-to-diameter (L/D) ratios of 0.25, 0.5, and 1.0, alongside interchangeable exit orifice diameters of 1, 2, 3, and 4 mm. These configurations were selected to evaluate the influence of internal flow characteristics on atomization performance.

Experimental setup

The experimental setup was mounted on a calibrated spray test rig equipped with a pressure regulation system capable of delivering fluid at controlled pressures of 100, 150, 200, and 250 kPa. Spray experiments were conducted at varying nozzle heights of 40, 60, and 80 cm to capture the effect of spray development distance on droplet dispersion.

Distilled water was used as the working fluid to ensure consistency in physical properties. During each experimental run, spray images were captured using a high-resolution digital camera (24.3 MP) positioned perpendicular to the spray axis against a uniform black background to enhance droplet visibility. Image acquisition was performed under controlled lighting conditions to minimize shadow and reflection effects.

Experimental Image Analysis

The captured images were processed using Python-based image analysis techniques. Pre-processing steps included grayscale conversion, noise reduction using Gaussian filtering, and image enhancement. Droplet segmentation was carried out using Otsu's thresholding method, followed by morphological operations to refine droplet boundaries. Edge detection and contour extraction techniques were applied to identify individual droplets, from which geometric parameters such as droplet diameter and projected area were computed. These measurements were used to determine droplet size distribution metrics, including Volumetric Median Diameter (VMD) and frequency distribution profiles.

Design of Experiment

A statistical experimental design based on a D-optimal factorial scheme was employed to systematically vary the independent variables: orifice diameter (A), spray pressure (B), swirl chamber L/D ratio (C), and spray height (D), as also used by Mansor *et al*. (2022). The response variable, droplet size distribution, was quantified using derived parameters from Volume Mean Diameter (VMD) and distribution spread.

Modelling and Model Development

A mathematical model was developed using regression analysis to establish the relationship between the key operating parameters, exit orifice diameter, spray pressure, swirl chamber length-to-diameter ratio, and spray height, and to predict Droplet Size Distribution (DSD).

Regression equation for modelling spray characteristics

This study adopts an experimental-computational approach to develop a predictive model for Droplet Size Distribution (DSD) in swirl nozzles under varying operating parameters. The methodology integrates nozzle design, controlled experimentation, image processing, and statistical modelling.

A second-order polynomial regression model was employed to describe the relationship between the response and the independent variables, as commonly used in response surface methodology (Montgomery, 2017). The regression equation between the response variable Y and the independent variables X is presented in Equation 1:

$$y = \beta_0+\beta_1x_1+\beta_2x_2+\beta_3x_3+\beta_4x_4+\beta_{11}x_1^2+\beta_{22}x_2^2+\beta_{33}x_3^2 + \beta_{44}x_4^2+\beta_{12}x_1x_2 +\beta_{13}x_1x_3 +\beta_{14}x_1x_4+\beta_{23}x_2x_3+\beta_{24}x_2x_4+ \beta_{34}x_3x_4 + \varepsilon \quad (1)$$

Where:

y = computed value of the dependent variable

x_1, x_2, x_3, x_4= independent variables

β_0= intercept (predicted value of $y$when all $x_i = 0$)

$\beta_1, \beta_2, \beta_3, \beta_4$= coefficients for the linear effects of each independent variable

$\beta_{11}, \beta_{22}, \beta_{33}, \beta_{44}$= coefficients for quadratic terms of each variable

$\beta_{12}, \beta_{13}, \beta_{14}, \beta_{23}, \beta_{24}, \beta_{34}$= coefficients for two-factor interaction terms

ε= random error term, accounting for variability not explained by the model

Validation of the Developed Model

Model validation was performed by comparing predicted values with experimental results under selected operating conditions. Additionally, diagnostic plots such as residual analysis and parity plots were used to assess model accuracy and reliability. The developed model was then used to identify optimal operating conditions for achieving desirable droplet size distribution and spray uniformity.

RESULTS AND DISCUSSION

The model shows the relationship or effects of the respective independent variables, such as exit orifice (A), operating pressure(B), swirl chamber length, diameter ratio(C), and height of spraying

(D), on the DSD. The relationships between the combinations of the independent variables and the response variables were also established for each. Analysis of Variance (ANOVA) was employed to evaluate the significance of the developed models and their individual terms. The F-value and p-value were used to determine statistical significance at a 95% confidence level. Model adequacy was assessed using the coefficient of determination (R^2), adjusted R^2, predicted R^2, and lack-of-fit tests. Only statistically significant terms were retained in the final reduced models to improve predictive reliability and avoid overfitting (Kuhn and Johnson, 2019; James *et al*., 2021).

A second-order polynomial model was developed to predict DSD as a function of the selected nozzle operating parameters. The model accounts for the individual (linear), curvature (quadratic), and combined (interaction) effects of exit orifice diameter, spray pressure, swirl chamber length-to-diameter ratio, and spray height on the resulting droplet distribution pattern. This formulation allows for a more realistic representation of the nonlinear behaviour typically observed in spray atomization processes. The variables were expressed in coded form to ensure uniform scaling and to enhance the reliability of the regression analysis. The adequacy of the model was evaluated using analysis of variance (ANOVA) at a 95% confidence level.

Predictive modelling was carried out using Response Surface Methodology (RSM). A second-order polynomial regression model of the form in Equation 2 was fitted to the experimental data, where y represents the droplet size distribution response and x represents the coded independent variables. Model adequacy was evaluated using analysis of variance (ANOVA), coefficient of determination (R^2), adjusted R^2, predicted R^2, and lack-of-fit tests at a 95% confidence level ($p \leq 0.05$).

Influence of Parameters on DSD

The results of experiments conducted to model the effect of operating conditions on spray characteristics are presented in Table 1.

Table 1: Experimental matrix and results of spray characteristics

			Factor			Response
Std	**Run**	**A (mm)**	**B (kPa)**	**C**	**D (cm)**	**DSD**
5	1	4	100	0.5	40	1.44
12	2	1	200	0.25	40	1.56
13	3	3	150	0.5	60	1.53
7	4	4	200	0.25	60	1.56
2	5	3	100	0.25	40	1.56
1	6	3	250	1	60	1.57
9	7	4	200	1	40	1.53
8	8	1	100	1	40	1.57
10	9	1	100	0.25	80	1.56
11	10	4	100	1	60	1.53
3	11	4	150	0.25	60	1.57
4	12	1	150	1	80	1.59
6	13	1	250	0.5	80	1.57

A: Orifice diameter; B: Spray pressure; C: L/D ratio; D: Spray Height; DSD: Droplet size distribution

Effect of Nozzle Orifice Diameter on DSD

Figure 1 illustrates the effect of nozzle orifice diameter on droplet size distribution. The Figure shows that droplet size distribution initially increased sharply as the orifice diameter increased from 1 mm to 2 mm, reaching a maximum of 1.5642, and decreased with further increases in orifice size. This nonlinear pattern indicates that orifice diameter strongly influences droplet uniformity, with medium-sized orifices producing the widest spread of droplet sizes, while both smaller and larger orifices yield narrower distributions (Hua *et al*., 2022). The initial rise in droplet size distribution at 2 mm suggests that intermediate orifice diameters generate sprays with more heterogeneous droplet spectra (Creech *et al*., 2015). The finding from this study is in line with the findings of Nuyttens *et al*. (2007) that nozzle geometry and orifice size significantly affect atomization, leading to variations in droplet uniformity. Similarly, Balsari *et al*. (2019) observed that medium orifices often produce a broad mix of fine and coarse droplets due to unstable liquid sheet breakup, thereby increasing the width of the droplet spectrum. In contrast, the reduction in droplet size distribution at larger orifices (3 and 4 mm) indicates improved uniformity, likely because larger openings reduce shear forces and promote the formation of more consistent droplet sizes. This agrees with the work of Hilz and Vermeer (2013)that larger nozzle sizes typically generate coarser but more uniform droplets, reducing variability in droplet distribution. Smaller orifices (1 mm) also showed relatively low droplet size distribution values, consistent with studies by Matthews *et al*. (2014), which emphasized that fine nozzles, while producing smaller droplets, tend to have narrower droplet spectra due to more controlled atomization.

Effect of Swirl Chamber L/D Ratio on DSD

The effect of the L/D ratio on droplet size

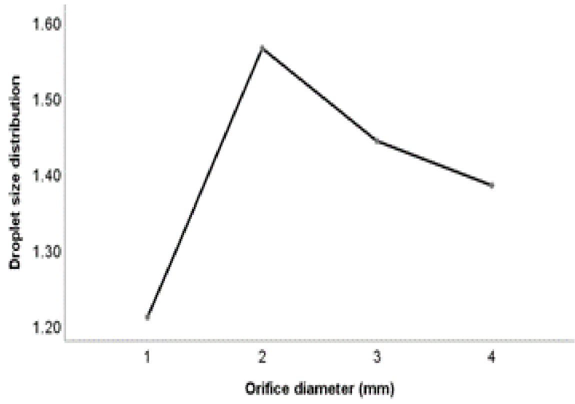

Figure 1: Effect of orifice diameter on the Droplet size distribution

distribution is illustrated in Figure 2. The Figure shows that the droplet size distribution increases sharply with increasing L/D ratio. The lowest value of 1.28 was obtained at an L/D ratio of 0.25, and the highest value of 1.45 was obtained at an L/D ratio of 1.0. The steep rise in the droplet size distribution from 0.25 to 0.5 indicates that the internal flow becomes more complex and turbulent at higher L/D ratios, leading to uneven breakup of the liquid sheet and greater variability in droplet formation (Ade *et al*., 2024).

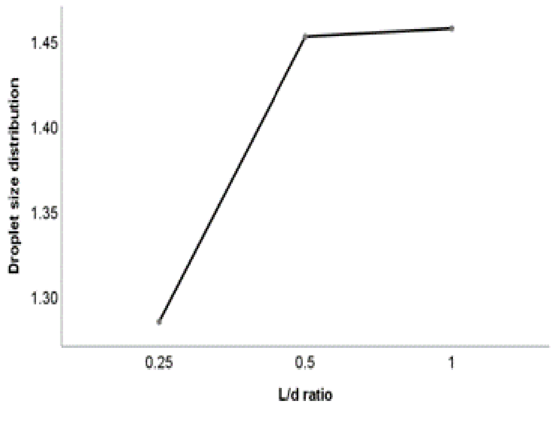

Figure 2: Effect of swirl chamber length/diameter ratio on droplet size distribution

This may be attributed to the longer flow path within the nozzle or channel, which can alter internal turbulence and breakup dynamics, promoting the formation of both fine and coarse droplets. These findings align with Nuyttens *et al*. (2007), that internal nozzle geometry significantly affects atomization performance.

The minimal increase in droplet size distribution beyond an L/D ratio of 0.5 results in little to no additional change in droplet size distribution, where further increases in length relative to diameter yield diminishing returns in terms of broadening the droplet distribution. This could point to a stabilization of internal flow patterns, resulting in a relatively consistent droplet spectrum. Matthews *et al*. (2014) similarly noted that beyond a certain threshold, further elongation of spray channels or nozzles does not necessarily improve atomization quality.

Effect of Spray Pressure on DSD

Figure 3 illustrates the variation of droplet size distribution (DSD) with spray pressure, revealing a non-linear relationship between the two variables. At a spray pressure of 100 kPa, the DSD is relatively low, indicating finer and more uniform droplets. As the pressure increases to 150 kPa, the DSD rises noticeably, suggesting a wider spread in droplet sizes and reduced uniformity.

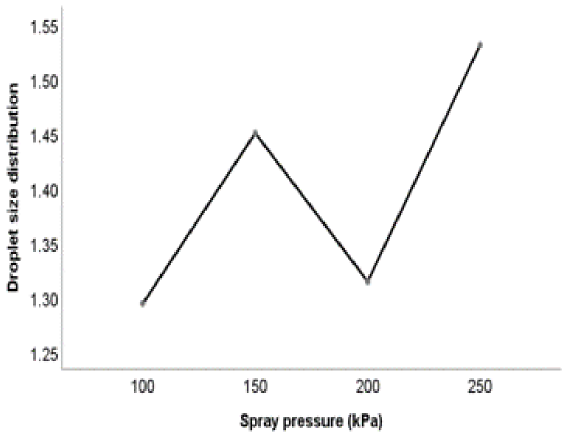

Figure 3: Effect of spraying pressure on the droplet size distribution

However, at 200 kPa, the DSD decreases again, implying an improvement in droplet uniformity at this intermediate pressure. Further increase in spray pressure to 250 kPa results in the highest DSD value observed, indicating a significant increase in droplet size variability. The trend demonstrates that droplet size distribution does not vary linearly with spray pressure but fluctuates due to the complex interaction of atomization dynamics, including turbulence and swirl intensity. The results indicate that moderate spray pressure, particularly around 200 kPa, may promote more uniform droplet formation, whereas excessively high pressure tends to increase dispersion and reduce spray consistency.

Effect of Spray Height on DSD

Figure 4 illustrates the effect of spray height on droplet size distribution. The Figure shows that droplet size distribution increases with increasing spray height to a maximum of 1.55 and then decreases with further increase in spray height.

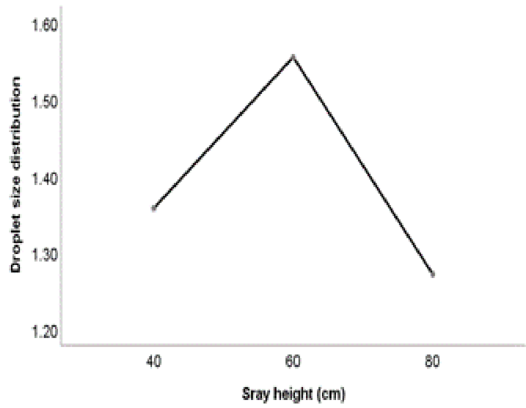

Figure 4: Effects of spraying heights on the Droplet size distribution

The highest value of 1. 55 was obtained at 60 cm spray height, while the minimum value of 1.2707 was obtained at 80 cm spray height. This trend suggests that spray height is crucial in determining the uniformity of droplet sizes, with mid-range heights leading to greater droplet heterogeneity. The initial increase in droplet size distribution from 40 to 60 cm spray height indicates that moderate spray heights can introduce more variability in droplet size. This may be due to the increased distance allowing droplets more time to interact with air currents, resulting in uneven breakup and secondary atomization. Balsari *et al*. (2019) noted that increasing spray height can enhance turbulence and drift potential, which may broaden the droplet spectrum. However, the subsequent sharp decrease in droplet size distribution at 80 cm spray height suggests improved droplet uniformity at higher spray heights. This could be attributed to better dispersion and gravitational settling of droplets, leading to a more homogeneous spray pattern. Hilz and Vermeer (2013) reported similar observations, where increased spray height allowed finer droplets to settle and distribute more evenly, reducing the width of droplet size distribution in the spray (SPAN).

Interactive Effect of Orifice Diameter, Spray Pressure, Length-diameter Ratio, and Spray Height on Droplet Size Distribution

Figure 5 illustrates the interactive effects of the operating parameters on droplet size distribution. Figure 5(a) shows the combined influence of orifice diameter and spray pressure on droplet size distribution. The response surface indicates that droplet size distribution initially increased with increasing orifice diameter and spray pressure, reaching a maximum at intermediate levels of both variables before declining slightly at higher values. This suggests the existence of an optimum combination of nozzle diameter and pressure that promotes the formation of more uniformly sized droplets. The elliptical contour pattern further confirms a significant interaction between these factors, indicating that the effect of spray pressure depends on the selected orifice diameter. Similarly, Figure 5(b) demonstrates the interaction between spray pressure and spray height. Droplet size distribution increased with both factors up to a peak region around the middle of the experimental range and then decreased slightly at higher spray pressures and spray heights. This behaviour may be attributed to improved atomization at moderate operating conditions, while excessive pressure and spray height encourage secondary droplet breakup and dispersion, leading to broader droplet size variations.

Figure 5(c) presents the interaction between the L/D ratio and spray height on droplet size distribution. The response surface reveals a pronounced curvature, indicating a strong interaction between the two variables. Droplet size distribution decreased initially with increasing L/D ratio before increasing again at higher values, while spray height generally contributed to larger distribution values. The minimum droplet size distribution was observed at moderate L/D ratios and lower spray heights, whereas higher spray heights combined with extreme L/D ratios produced larger droplet size distributions. The contour plot confirms the nonlinear relationship between these variables. Overall, the figures indicate that droplet size distribution is governed by complex interactions among nozzle geometry and operating conditions, with optimum performance occurring at moderate levels of spray pressure, spray height, and L/D ratio. These findings are consistent with recent studies, which have demonstrated that nozzle geometry, operating pressure, and spray height collectively influence droplet size distribution, atomization efficiency, and overall spray performance, Cerruto *et al.* (2021) reported that variations in nozzle design and operating pressure significantly affect droplet size distribution and spray uniformity, while Makhnenko *et al*. (2021) showed that liquid sheet breakup and droplet formation are controlled by the interaction between nozzle geometry and operating conditions. Similarly, Privitera *et al*. (2023) emphasized that optimizing nozzle dimensions and spraying parameters is essential for improving droplet uniformity, atomization quality, and application efficiency in agricultural spraying systems.

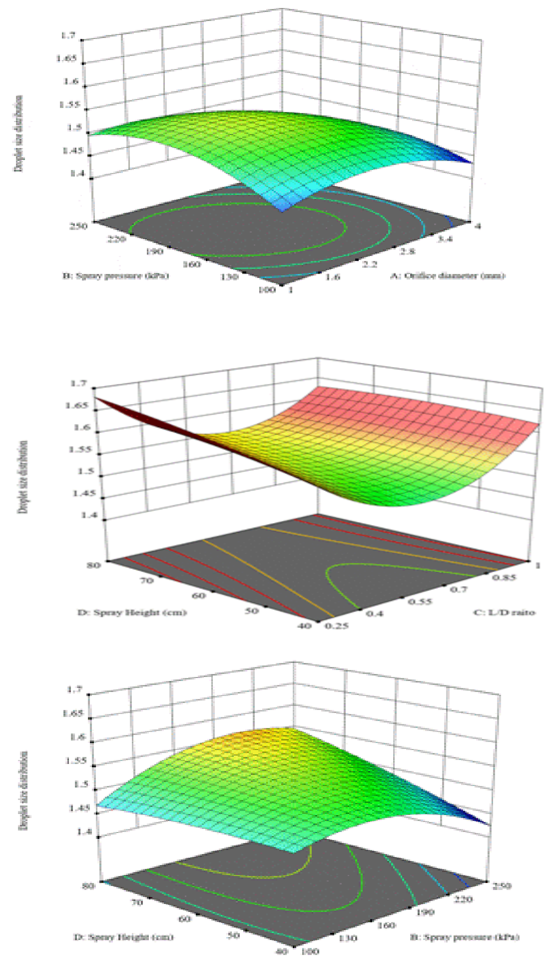

Figure 5: Interactive effect of (a) orifice diameter and spray pressure, (b) spray pressure and spray height and (c) L/D ratio on droplet size distribution

Table 2 presents the ANOVA results for the Reduced Quadratic model developed for droplet size distribution. The model was highly significant (F = 9822.41, p = 0.0079), indicating that the selected process variables adequately explained the variation in droplet size distribution. All the main factors, namely orifice diameter (A), spray pressure (B), L/D ratio (C), and spray height (D), significantly affected droplet size distribution ($p < 0.05$). Among these factors, orifice diameter (F = 15407.81) and spray height (F = 14457.70) exerted the strongest effects, while spray pressure and L/D ratio also contributed significantly. The interaction effects AB, BD, and CD were significant, indicating that the influence of one factor depended on the level of another. Furthermore, all quadratic terms (A^2, B^2, C^2, and D^2) were significant, confirming the existence of curvature in the response surface and suggesting that droplet size distribution responds nonlinearly to changes in the process variables. The L/D ratio quadratic term (C^2) recorded the highest F-value (38304.04), identifying it as the most influential curvature effect in the model.

Table 2: ANOVA for reduced quadratic model**:** Droplet size distribution

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0169	11	0.0015	9822.41	0.0079	significant
A-Orifice diameter	0.0024	1	0.0024	15407.81	0.0051	
B-Spray pressure	0.0001	1	0.0001	611.84	0.0257	
C-L/D ratio	0.0001	1	0.0001	712.03	0.0238	
D-Spray Height	0.0023	1	0.0023	14457.70	0.0053	
AB	0.0004	1	0.0004	2699.39	0.0123	
BD	0.0023	1	0.0023	14964.36	0.0052	
CD	0.0009	1	0.0009	5513.64	0.0086	
A^2	0.0013	1	0.0013	8451.00	0.0069	
B^2	0.0019	1	0.0019	12256.83	0.0058	
C^2	0.0060	1	0.0060	38304.04	0.0033	
D^2	0.0001	1	0.0001	369.11	0.0331	
Residual	1.563E-07	1	1.563E-07			
Cor Total	0.0169	12				
Fit Statistics						
Std. Dev.	0.0004		**R^2**	1.0000	**Adeq Precision**	395.0104
Mean	1.55		**Adjusted R^2**	0.9999		
CV. %	0.0255		**Predicted R^2**	0.9430		

The regression equation further explains the direction and magnitude of these effects. The negative coefficients of orifice diameter (-0.0271), L/D ratio (-0.0035), AB (-0.0188), CD (-0.0219), A^2 (-0.0425), B^2 (-0.0473), and D^2 (-0.0071) indicate that increasing these terms tends to reduce droplet size distribution, thereby promoting a more uniform spray. Conversely, spray pressure (+0.0045), spray height (+0.0262), BD (+0.0348), and especially the quadratic effect of L/D ratio (C^2 = +0.1001) increase droplet size distribution. The large positive coefficient of C^2 suggests that droplet size distribution decreases initially with increasing L/D ratio but rises sharply at higher values, corroborating the curvature observed in Figure 4.3(c). The model exhibited exceptional predictive capability with an R^2 of 1.0000, adjusted R^2 of 0.9999, and predicted R^2 of 0.9430, indicating that virtually all variation in droplet size distribution was explained by the model. Additionally, the very low coefficient of variation (0.0255%) and high Adequate Precision value (395.01) confirm excellent experimental precision and model reliability. These results suggest that droplet size distribution is governed by complex interactions among nozzle geometry and operating conditions, with optimum uniformity achievable through careful adjustment of orifice diameter, spray pressure, spray height, and L/D ratio. These findings are consistent with the recent reviews of Makhnenko *et al*. (2021), Privitera *et al*. (2023), and Chegini *et al*. (2025), which emphasized that nozzle geometry, operating pressure, and spray system configuration are the primary factors controlling droplet size distribution, spray uniformity, atomization quality, and overall spray performance in agricultural applications. The Coefficient of Variation (CV) values of 0.0255, less than 10, suggest that the model is reproducible, implying that the developed model can reliably reproduce the response under similar operating conditions and is suitable for comparative analysis and optimization within the studied design space.

Model Development

The model presented in Equation 2 indicates that increasing the orifice diameter, spray pressure, and swirl chamber L/D ratio tends to reduce droplet size distribution. Similarly, the interaction effects between orifice diameter and spray pressure, as well as between orifice diameter and L/D ratio, contribute to a further decrease in droplet size. In contrast, an increase in spray height leads to a rise in droplet size distribution, and this effect is reinforced by the interaction between spray pressure and orifice diameter, as well as the interaction between the swirl chamber L/D ratio and orifice diameter.

$$DSD = +1.54 - 0.0271\,A + 0.0045\,B - 0.0035\,C + 0.0262\,D - 0.0188\,AB + 0.0348\,BD - 0.0219\,CD - 0.0425\,A^2 - 0.0473\,B^2 + 0.1001\,C^2 - 0.0071\,D^2 \quad (2)$$

Where: DSD = Droplet Size Distribution (dimensionless); A: Orifice diameter, mm; B: Spray pressure, kPa; C: L/D ratio; D: Spray Height, cm

CONCLUSION

Nozzle geometry and operating conditions significantly influenced droplet size distribution in swirl nozzles. Orifice diameter was identified as the most influential parameter affecting spray atomization and droplet uniformity, while spray pressure, swirl chamber L/D ratio, and spray height also contributed significantly to variations in droplet distribution. The study further showed that interactions among these parameters strongly affected spray characteristics, confirming the nonlinear nature of atomization processes in swirl nozzles. Response surface methodology and second-order polynomial regression effectively predicted droplet size distribution under varying operating conditions. ANOVA results confirmed the statistical significance of the developed model, while the predictive equations adequately captured the dominant trends in spray behaviour. The study established that optimized nozzle geometry and operating conditions can improve spray uniformity, atomization efficiency, and overall performance of swirl nozzles in agricultural and industrial spraying applications.

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