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SPRAY NOZZLE WEAR EFFECTS ON DROPLET POPULATION

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KEYWORDS

accelerated wear, volume median diameter, application technology, flow rate.

ABSTRACT

The wear rate of spray nozzles affects several factors. This study aimed to investigate the influence of spray nozzle wear rate on droplet characteristics, such as droplet size, droplet homogeneity, droplets prone to drift, and flow rate variation. Eight hydraulic nozzles models (AIXR-110-02, JSF-110-02, TT-110-02, DG-110-02, XR-110-02, ADI-110-02, XR-110-02, and AI-110-02) were subject to an accelerated wear test, and their effects were measured at six experimental wear times (0, 10, 20, 30, 40, and 50 hours). The following variables were evaluated: volume median diameter, percentage of spray volume containing droplets smaller than 100 µm (prone to spray drift), flow rate (L min^{-1}), and relative span, which indicates droplet size homogeneity. The droplet population was measured using a laser particle size analyzer. The use of the spray nozzle tip influences the quality of the spray application due to the wear rate. This study revealed a linear increase in the flow rate and volume median diameter as functions of the wear rate increment. The droplet size increased over the wear time, which consequently modified the volume percentage of droplets smaller than 100 µm and significantly increased the relative span.

INTRODUCTION

Phytosanitary products play an important role in agriculture because of the growing need for high yields and the intensive production of food in a sustainable manner (Bueno & Cunha, 2020). The vast majority of agrochemicals used are sprayed via hydraulic spray nozzles. However, part of the product does not reach the target because of the incorrect choice of the spray nozzle or its wear, which affects the droplet pattern homogeneity and directly influences the target coverage, causing drift losses and environmental contamination (Bueno et al., 2017). Thus, the correct selection of spray nozzles or droplet-generating devices is fundamental to obtaining satisfactory and efficient results in hydraulic applications (Parafiniuk et al., 2018). The misuse of pesticides due to the application of worn-out nozzles translates into a higher operational cost, increased risks of environmental pollution, and, in some cases, causing direct damage to the plant (Milanowski et al., 2022).

Since the beginning of hydraulic sprayer use, it has been known that there is wear on the nozzles depending on the time and use conditions (Nagy et al., 2014). The wear on the spray nozzles affects the flow rate, among other characteristics. Therefore, only this variable has been analyzed by the majority of published articles, and few studies have been conducted to characterize the population of droplets generated as a function of the wear rate of the spray nozzles (Singh & Bhatt, 2018). There is a lack of studies on other variables involving technology spraying applications, such as how the wear of the spray nozzles affects the droplet size or spray homogeneity.

The rate of wear depends on factors such as spray pressure, abrasiveness of the sprayed liquid, and the material of the nozzle (Milanowski et al., 2022). Agricultural spray nozzles are manufactured using various materials, including brass, stainless steel, hardened stainless steel, nylon, plastic, and ceramic. An easy way to determine how badly worn a nozzle may be is to gauge its flow rate with a calibration container, stopwatch, and pressure gauge fitted on a nozzle body on the spray boom (Matthews et al., 2015). With this setup, we compare the flow rate through a

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nozzle with a new nozzle of equal size. If the flow rate through a nozzle exceeds that of the new spray nozzle by more than 10%, it should be replaced (ASABE, 2001).

Use of a nozzle can lead to wear. Other factors that affect nozzle wear include the shape and size of the orifice, usage time, and the type of formulation applied (Nagy et al., 2014). It is known that some formulations of pesticides can enhance the wear of nozzles, especially formulations that are not diluted with water in the tank mixture, such as wettable powder formulations (Singh & Bhatt, 2018). Because of the large number of variables involved, it is difficult to predict the durability of a nozzle operating under normal field conditions (Singh et al., 2019).

Knowing the droplet size variation and application rate according to nozzle wear is paramount for an efficient spray application (i.e., with lower environmental contamination, lower production cost, and better performance against weeds, pests, and diseases) because manufacturers provide information only about the new nozzle. Thus, this study aimed to investigate the effects of spray nozzle wear rates on droplet characteristics, such as droplet size, droplet homogeneity, droplets inclined to drift, and flow rate variation.

MATERIAL AND METHODS

The experiment was carried out at the Agricultural Spraying Laboratory of the Federal University of Mato Grosso do Sul, Brazil. Eight hydraulic nozzle tip models (Table 1) were subjected to an accelerated wear test, and the effects of the test were measured at six wear time points (0, 10, 20, 30, 40, and 50 h). The experimental design consisted of a completely randomized block with five blocks (spray nozzle tip units) and ten replications (sample readings). The experimental procedure was based on the standard ASAE S471 - Procedure for Measuring Sprayer Nozzle Wear Rate (ASABE, 2001). However, this procedure focuses only on the flow rate measurement, and assessing the effects of other variables due to nozzle wear is new. During the experimental period, the ambient temperature in the laboratory was maintained at 24°C, and the relative air humidity was 80%. The following variables were evaluated: volume median diameter (VMD), percentage of spray volume containing droplets smaller than 100 μm (prone to spray drift), flow rate (L s^{-1}), and relative span, which indicates droplet size homogeneity.

TABLE 1. Spray nozzle characterized by model and material.

Model	Brand	Type	Material	Code
AIXR-110-02	TeeJet	air induction extended range	polyacetal	PAI
JSF-110-02	Jacto	extended range	polyacetal	PSF
TT-110-02	TeeJet	wide angle pre-orifice	polyacetal	PTT
DG-110-02	TeeJet	reduced drift	polyacetal	PDG
XR-110-02 VK	TeeJet	extended range	ceramic	CXR
ADI-110-02	Jacto	pre-orifice	ceramic	CAD
XR-110-02 VS	TeeJet	extended range	stainless	SXR
AI-110-02 VS	TeeJet	air induction	stainless	SAI

The abrasive used in the accelerated wear test was aluminum silicate (kaolin clay) added to the spray solution at a concentration of 60 g L^{-1} of clean water (ASABE, 2001). The abrasiveness of the materials affects the final result; therefore, the primary reason for the substantial differences reported in nozzle wear rates is the considerable variation in abrasive materials and the concentrations of these materials used in the wear tests. Thus, for comparative reasons, it is crucial to strictly follow the standards established for this type of test (ASABE, 2001).

The nozzles were subjected to accelerated wear in a piece of stationary spray equipment with a closed hydraulic circuit, which allowed the maintenance of the hydraulic pressure at the nozzles. A stationary sprayer was built, which contained the basic sprayer hydraulic circuit and allowed the maintenance of the hydraulic pressure at the nozzle (Figure 1). The circuit had an auxiliary reservoir, where a suction pipe serpentine allowed the tank mixture to be maintained at ambient temperature during hours of accelerated wear (Figure 1). The tank mixture was replenished (water only) as it evaporated from the reservoir, depending on the period of usage. The bustle of the spray was kept constant by the hydraulic flow from the return circuit, and the working pressure was kept constant at 275 kPa (ASABE, 2001). The Jacto JP 75 piston pump was assembled on a hydraulic circuit, which contained five spray nozzle sample units.

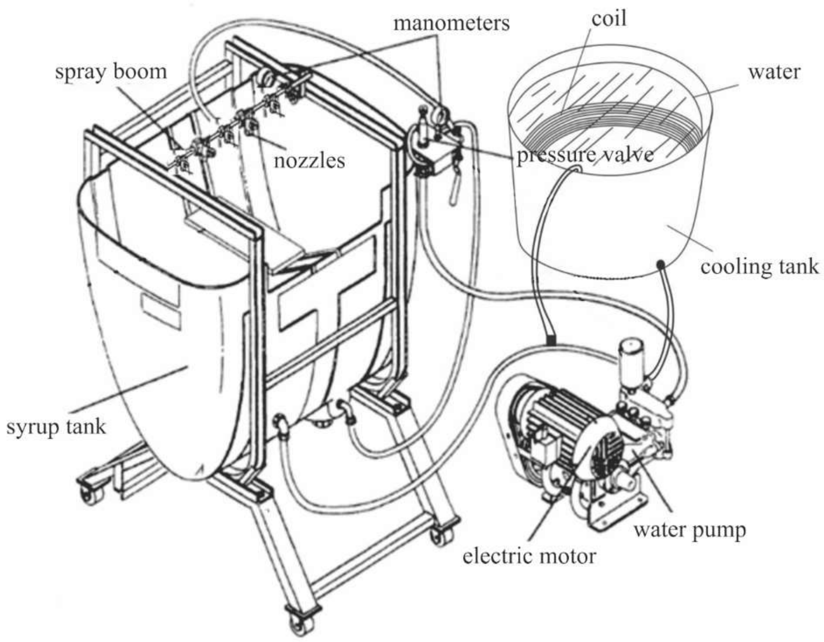

FIGURE 1. Stationary sprayer hydraulic circuit. Source: modified from Padovan (2004).

An Endress House pressure transducer (827 kPa model TPMP131) device was used to measure and monitor the working pressure of the hydraulic system, with over 0.5% accuracy, connected to the analog port of the Campbell Scientific CR1000 data logger. The pressure was monitored in real time during the tests using the PC200W software once this variable was critical to the experimental results, as the analog gauge was challenging to monitor correctly.

The test to evaluate nozzle flow was carried out by weighing the volume of water collected in grams with a Shimadzu BL-3200H analytical weighing scale, and assuming that the density of water was equal to one. The volume of water was collected for one minute, with a hydraulic circuit at a nominal pressure of 275 kPa. Pressure was monitored using a manometer installed near the nozzle. Three replicates were performed for each nozzle. The evaluations were performed using a Micron battery-powered stationary sprayer (Combat Model).

The droplet population characteristics were evaluated using a Spraytec model particle size analyzer (Malvern Spraytec) with a laser beam diameter of 10 mm, focal lens of 300 mm, and laser wavelength 632.8 nm. The particle analyzer has a laser diffraction sensor, which allows the measurement of spray particles and spray droplet size distributions in real time, following the standard ASAE S572.1 (ASABE, 2009). The equipment measured droplets from 0.1 to 2000.0 µm. The equipment software was configured to use water as the sprayer tank solution with a refractive index of 1.33. Initially, the alignment of the optical beam was verified to ensure its correct positioning in the detector system. The background system was monitored and calibrated before each reading. The variables measured were the volume median diameter (VMD), the percentage of spray volume containing droplets smaller than 100 µm (P100) (more prone to drift), and the relative span (RS). The nozzle tip was positioned at 0.5 m above the optical beam. RS indicates droplet size homogeneity according to [eq. (1)]. The narrower the distribution, the smaller the RS.

$$RS = \frac{Dv(90) - D\ (10)}{Dv(50)} \tag{1}$$

Where:

RS is the relative span;

Dv(10) is the particle size below which 10% of the spray lies;

Dv(50) is the VMD, and

Dv(90) is the particle size below which 90% of the spray lies.

The data were subjected to analysis of variance (ANOVA) using SigmaPlot v.11. Regression equations were adjusted for each nozzle as a function of wear time. The best equation was chosen based on the coefficient of determination and the significance of the regression coefficients using the t-test. A study of correlation and dispersion between the variables was performed using R. Subsequently, canonical variable analysis was performed to verify the similarity between treatments and which variables contributed to this similarity (Bhering & Teodoro, 2021). The analysis of canonical variables is a technique of multivariate statistics that allows study of the interaction between all the analyzed variables resulting from the applied treatments.

RESULTS AND DISCUSSION

Figure 2 presents the linear regression for all the measured variables. All the linear regressions were statistically significant, as indicated by the F-test. Regression adjustments using linear equations are interesting because of their simplicity in identifying trends. Over time, the nozzles wear out, impacting an increment in the flow rate in all hydraulic nozzle models (Figure 2A). Hence, it changes the dynamics of the drop formation of each nozzle, which alters their respective characteristics. The nozzle PAI presented a mean increase of 6.5% in its flow rate at ten hours of wear time, and a mean increase of

13.4% at 20 h of wear time exceeded the recommended replacement limit. The nozzle PGD presented a mean increase of approximately 2.5% in its flow rate at every ten hours of wear time up to 40 h of wear time, when it reached the recommended limit for replacement. The nozzle PSF presented a mean increase of 5.6% in its flow rate at ten hours of wear time and a mean increase of 13.3% at 20 h of wear time, exceeding the recommended limit for replacement. The average flow rate variation between the polyacetal nozzle tips was 20.4%, whereas the stainless steel nozzle tips showed an average variation of 14.0% and 14.6 %. The SAI (air induction) nozzle tip presented the lowest flow variation of the entire group of nozzle tip models, with a variation of 6.7%, pulling the average downwards.

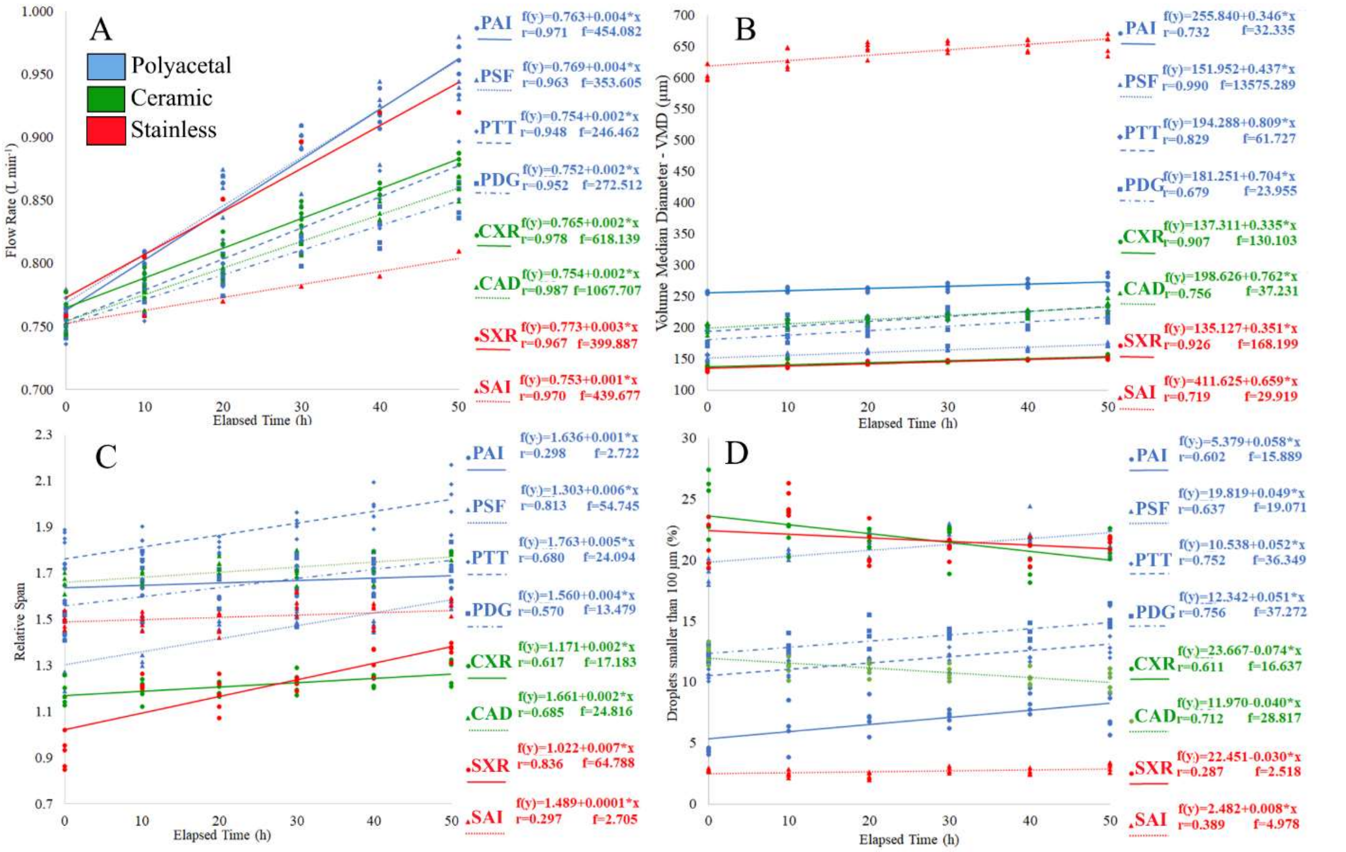

FIGURE 2. Variation of flow rate (A), volumetric median diameter (B), relative span (C), and percentage of spray volume containing droplets smaller than 100 μm (D) over the accelerated wear time on the test bench.

The nozzle wear conditions vary from farmer to farmer, and also depend on the number of applications per agricultural year. The nozzle that showed the lowest flow variation over the experimental period was the spray nozzle stainless steel with air induction) (6.7% at 50 h), most likely because of the larger dimension of the drop generation orifice (less influence of the hydraulic pressure passing through it), but also possibly as a function of the internal channels to the spray nozzle for the passage of the fluid, restricting the initial pressure at the top of the nozzle, which probably decreased the hydraulic energy concerning the inlet. A correct nozzle wear comparison must be performed between spray nozzles of the same technology (Singh & Bhatt, 2018). Comparing only the extended-range models, PSF (polyacetal), CXR (ceramic), and SXR (stainless steel), the flow variation obtained at 50 h of wear period was 25.4%, 15.2%, and 21.2%, respectively. Thus, the results were consistent with the literature (Lechler, 2011; Padovan, 2004; Baesso et al., 2014); the ceramic material was more durable with respect to the variation in the nozzle flow rate with the time of use.

The increased flow rate for the PTT and PGD nozzles, which are models with a pre-chamber, even when manufactured with the polyacetal material, had a lower accelerated wear rate than the models made with polyacetal PAI (air induction) or PSF (extended use). Most likely, the pre-orifice of these nozzles attenuates the hydraulic energy directly over the nozzle orifice, thereby decreasing the wear rate with respect to the time of use. It was found that the durability of the polyacetal material and stainless steel for spray nozzles using the same technology was similar. A 10% increase in the flow rate was achieved after approximately 30 h of the accelerated wear test. This is the acceptable limit for the increment over the flow rate to replace the nozzle.

The effects of nozzle wear on the variation of the VMD or other variables, such as the relative amplitude of the new nozzle, are still a little-studied subject. For each nozzle model, the equations for VMD were adjusted according to the wear time (Figure 2B). There was an increase in droplet size according to the period of accelerated wear. However, in the field, the original characteristics of the chosen VMD change according to the use of the nozzle, which can sometimes lead to low application quality when the target must be hit in the lower third of the plant (Camolese & Baio, 2016).

All the nozzles increased the VMD with the accelerated usage time, and, as expected, the nozzles containing air induction technology showed the highest values of VMD (Figure 1B and Figure 3). Air induction nozzles are commonly used as a drift reduction strategy to apply crop protection products. There was an increase in the VMD and flow rate due to the time elapsed in conditions of accelerated wear rate, as well as an increase in this variable due to the increase in pressure applied in the test condition at the benchtop.

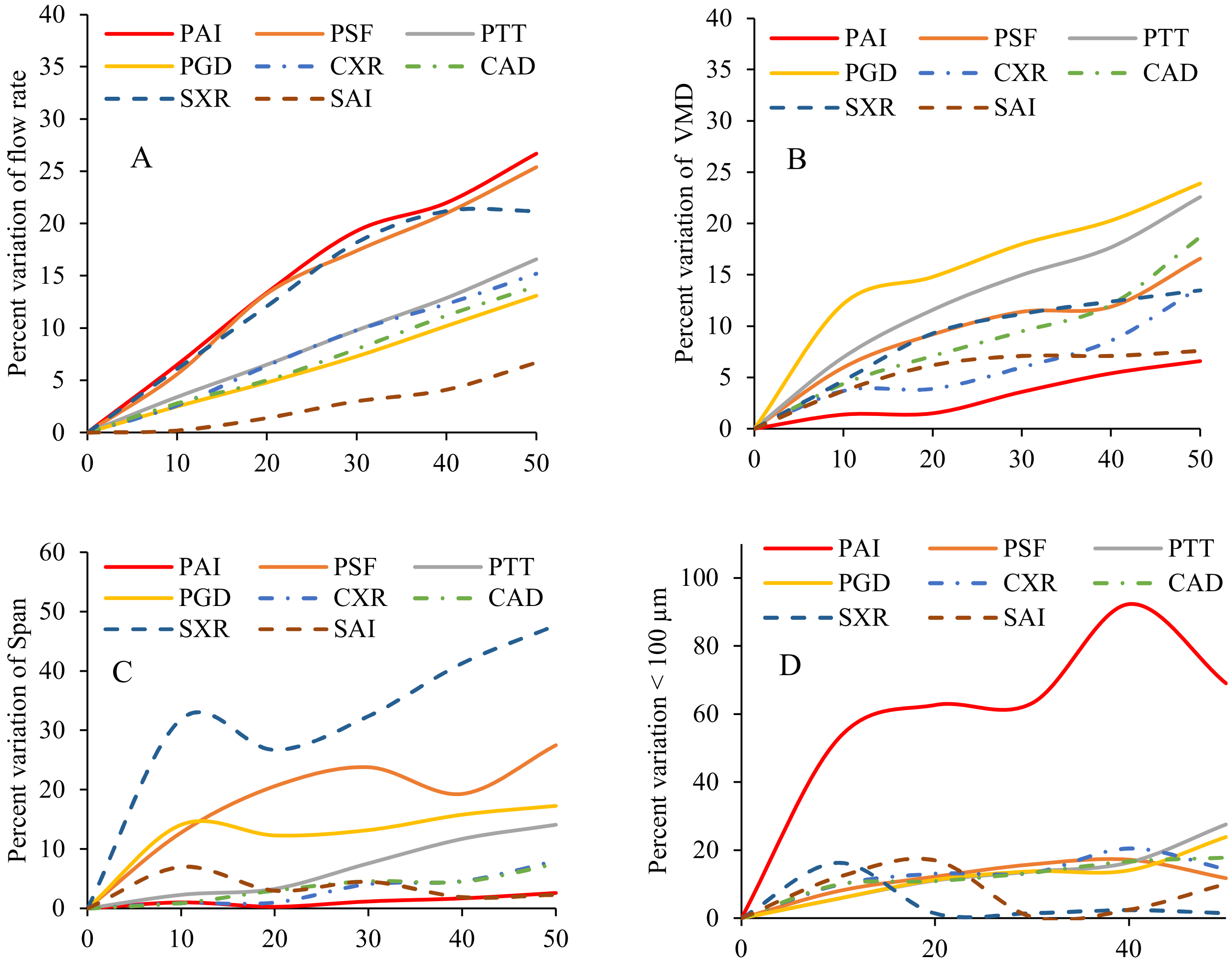

FIGURE 3. Percent variation (%) of flow rate (A), volumetric median diameter (VMD) (B), relative span (C), and percentage of spray volume containing droplets smaller than 100 µm (% < 100 µm) (D) according to accelerated wear rate time of the nozzles.

The nozzles without air induction presented a higher RS variation with usage time than the nozzles with air induction (Figure 2C). This result may have occurred because the mixture of air and liquid inside the nozzle with the air induction chamber causes each droplet to have a more significant amount of air inside, corroborating the smaller variations in its diameter. The tips manufactured with ceramic material also showed less variation in RS over time of use when compared to the polyacetal nozzle, because the ceramic nozzle material allowed greater durability of the original characteristics over the spray flow rate, as the manufacturers say (Albuz, 2019), with less corrosion of the tip orifice, as evidenced by the lower flow rate variation. The SXR nozzle tip (stainless-steel extended range) showed the most significant variation in the RS variable as a function of the accelerated wear time, with a variation of 47.7%. The PAI (polyacetal air induction extended range) tip showed a smaller variation, with 3.6%. The nozzle SAI presented the lowest values for the RS variation in all the wear time measurements.

The incremental behavior demonstrated was also linear for the volume percentage of droplets smaller than 100 µm as a function of wear time (Figure 2D). The tip models CXR (ceramic - extended range), CAD (ceramic pre-orifice), and SXR (stainless - extended range) showed a reduction in the P100 with accelerated wear time. All other nozzle tip models showed an increase in this variable. The greatest variation was obtained using the polyacetal air induction extended range (PAI) tip, with a 92.3% increase in the percentage of drops smaller than 100 µm.

Accelerated wear tests using highly abrasive materials have been used by researchers; however, there is a concern that the results may not accurately represent the relative wear rates of various nozzle materials used to spray common pesticides (Parafiniuk et al., 2018). On the other hand, the results of field trials with this approach would be very imprecise, since each farmer uses different formulations and mixtures in the spray tank mixture, and each farmer and harvest varies the number of hours of sprayer use. Thus, experiments conducted under laboratory conditions are important when comparing the results of different trials.

When evaluating only nozzle models with the same technology (extended range), the spray nozzle manufactured with polyacetal showed a more significant variation in VMD (Figure 4). Nozzles made of ceramic and stainless steel exhibited similar VMD variations. The nozzle tip made of stainless steel (SXR) showed a significant disparity in the results measured for the variables RS and P100. Controlling the flow rate of a hydraulic nozzle is crucial. This is because, over time, the flow rate tends to increase owing to nozzle wear.

FIGURE 4. Pearson's correlation between the variables evaluated for the condition of the nozzle tip material, using the same spray pattern technology (extended range): ceramic (red color); polyacetal (green color); and stainless material (blue color).

According to a test of the durability of spray nozzles of different materials using the accelerated wear technique, it was observed that ceramic nozzles withstand approximately 400 h, thermoplastics 400 h, stainless steel 400 h, nylon 200 h, and brass 100 h (Novak & Cavaletto, 1988). However, these tests were conducted only to determine the variation in the nozzle flow rate. According to the spray nozzle manufacturer, the wear resistance of the nozzle material increases in the following order: brass < stainless steel < plastic < ceramic (Lechler, 2011).

The association between different nozzle manufacturing materials and different droplet generation technologies showed different results for the variables analyzed (Figure 5). The results indicate that the most significant variations in the measured values were the flow rate when compared between various materials and technologies of droplet formation (last column with the larger dimension of the box plot figure). It has been reported that spray tank mixture formulations can affect the homogeneity of the droplet spectrum formed, and consequently, the VMD. Emulsions were more effective at decreasing the P100 and RS while increasing the Dv(10) and Dv(50) (VMD) values than the dispersion-type formulations, represented by dispersible granules and suspension concentrate formulations (Carvalho et al., 2017). However, this comparison is useful to obtain an idea of the whole when facing the challenge of choosing the best technology associated with the best manufacturing material.

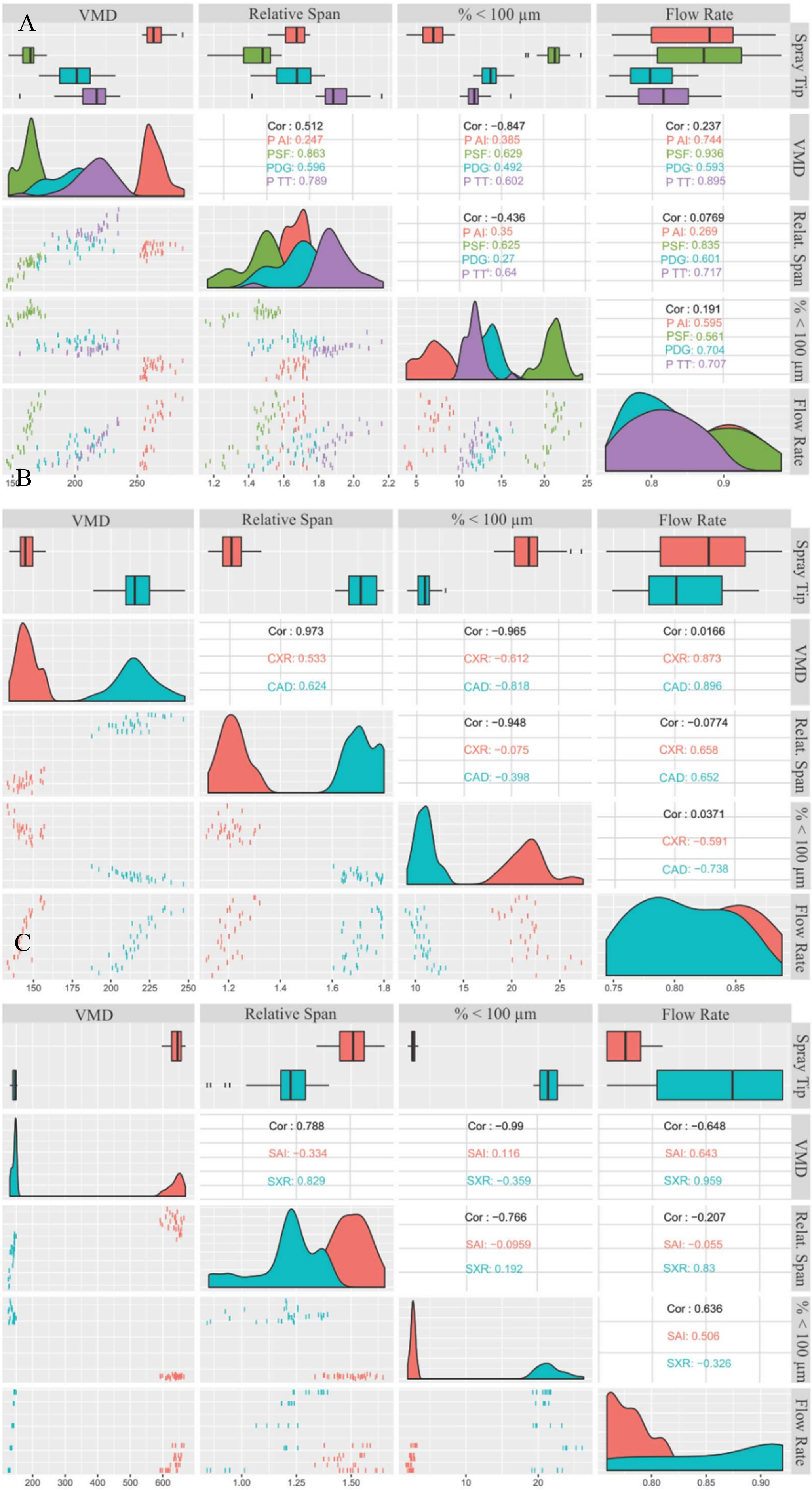

FIGURE 5. Pearson's correlation between the variables evaluated for the condition of the nozzle tip technology, using the same material: polyacetal (A); ceramic (B); and stainless (C).

Multivariate analysis associates the different intrinsic variabilities, grouping them, and illustrating the disparities. Canonical variables analysis (Figure 6) was carried out to verify the similarity between treatments and detect the variables that contributed to this similarity. The first canonical compounds captured 99.8% of the total variance among treatments, illustrating a large safety margin when analyzing the responses presented by the model (Bhering & Teodoro, 2021). This analysis corroborates the previous findings. The variable percentage of the volume with droplets smaller than 100 µm exhibited the least variation when the tips were made of ceramic and stainless steel. The greater contribution of the effects of accelerated wear can be attributed to an increase in the nozzle flow rate. Therefore, the flow of the nozzle over a greater variation in the effects of accelerated wear than the variation of the other measured variables is independent of the material.

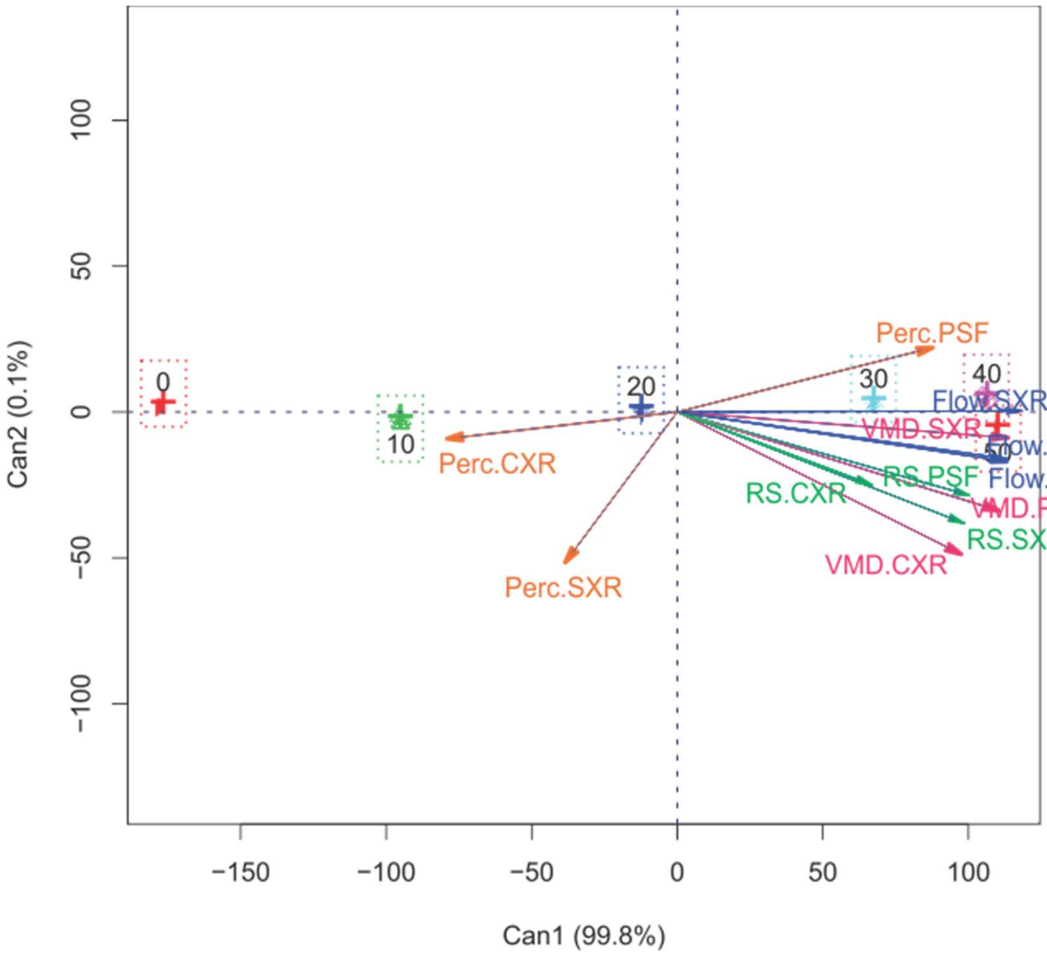

FIGURE 6. Canonical variables related to the treatments (0, 10, 20, 30, 40 and 50 hours of accelerated wear rate) and the nozzle tips with extended range technology and materials (Flow=flow rate; VMD =volumetric median diameter; RS=relative span; Perc=percentage of spray volume containing droplets smaller than 100 µm.

In an experiment evaluating the useful life of hollow-cone nozzles as a function of the manufacturing materials, Singh & Bhatt (2018) observed that the ceramic material maintained its durability until reaching a 15% variation in the flow rate 15 times compared to the plastic material and four times with stainless steel. However, it is essential to note that the working pressure applied in this experiment was 680 kPa, whereas the standard suggests 275 kPa (ASABE, 2001). Pesticides should be used in future wear tests to determine whether emulsifiable concentrates, wettable powders, or other formulations contribute to distinctive wear patterns (Krause et al., 2003).

Due to the lack of knowledge of the importance of the hydraulic nozzle of the sprayer, farmers have the habit of underestimating its importance, changing it less frequently than necessary after the wear caused by excessive use (Boller & Raetano, 2011). In Brazil, it is still possible to find situations in which farmers use nozzles with different colors (different flow rates), illustrating that there is still misinformation in some field conditions (Gandolfo & Antuniassi, 2003). Although all components of a sprayer are essential in the application, spray nozzles or drop-generating devices are the most critical components of a sprayer, providing an application with a satisfactory and efficient result. In Brazil, the use of worn tips is a chronic problem. In a periodic inspection program for sprayers conducted by Gandolfo et al. (2013) in the state of Paraná, Brazil, the authors observed that 47.3% of the equipment had tips with excessive wear.

New nozzle models and the interdisciplinary collaboration of experts in structural materials, mechanics, and probabilistic methods to control and minimize wear rates in the design of nozzles for food production and agricultural engineering applications must be further discussed (Singh et al., 2019).

CONCLUSIONS

The experiment confirmed the influence of nozzle wear on the spray characteristics of the different nozzle models. Consequently, the wear of the hydraulic nozzles increases the flow rate, VMD, relative span, and production of very fine droplets, which are more prone to drift.

This study revealed a linear increase in the flow rate and volume median diameter as functions of the wear rate increment. The droplet size increased over the wear time, which modified the percentage of the spray volume containing droplets smaller than 100 µm and significantly increased the relative span. The effects of accelerated wear were most evident for spray nozzles manufactured from polyacetal and extended-use models.

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