EVALUATION OF THE RELATIONSHIP BETWEEN SPRAY LIQUID PRESSURE AND MACHINE SPEED USING THREE TYPES OF NOZZLES ON A BOOM SPRAYER

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ABSTRACT

This study investigates the efficiency of three types of flat fan nozzles (blue, red, and brown) when operating with a boom sprayer under low-volume spraying conditions in the Gorno Botevo village area of Central Bulgaria. The experiment evaluated the sprayer's operational speed and working pressure across eight working regimes, focusing on the impact of speed and nozzle type on application performance. Statistical analyses, including univariate ANOVA and correlation analysis, revealed significant differences in performance among the nozzles. The blue, red, and brown nozzles achieved optimal performance at 8.5 km/h, 12 km/h, and 16 km/h, respectively, while maintaining the recommended pressure range of 4–5 bar. Predictive nonlinear models were developed, explaining 42.2% to 75.4% of the variation in nozzle pressure as influenced by speed. These models provide practical guidance for optimizing sprayer operation, enhancing pesticide application efficiency, and minimizing resource waste. This study contributes to advancing precision agricultural practices by offering actionable insights into the interplay between speed, pressure, and nozzle performance under field conditions.

Keywords: sprayers, nozzles, working pressure, operational speed, predictive models.

مجلة العلوم الزراعية العراقية- 2025 :56 (3):1210-1221 تيهانوف وآخرون

تقييم العلاقة بين ضغط سائل الرش وسرعة الآلة باستخدام ثلاثة أنواع من الفوهات على مرشة ذراعية

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المستخلص

تبحث هذه الدراسة في كفاءة ثلاثة أنواع من الفوهات المسطحة ذات الرشاش المروحي)الأزرق، الأحمر، والبني (عند تشغيلها باستخدام مرشة ذراعية في ظل ظروف الرش ذات الحجم المنخفض في منطقة قرية غورنو بوتيفو بوسط بلغاريا .قيّم التجربة سرعة تشغيل المرشة وضغط العمل عبر ثمانية أنظمة تشغيل، مع التركيز على تأثير السرعة ونوع الفوهة على أداء التطبيق . كشفت التحليلات الإحصائية، بما في ذلك تحليل التباين الأحادي (ANOVA) وتحليل الارتباط، عن وجود فروق معنوية في الأداء بين الفوهات .حققت الفوهات الزرقاء والحمراء والبنية أداءً مثاليًا عند سرعات 8.5 كم/ساعة و 12كم/ساعة و 16 كم/ساعة على التوالي، مع الحفاظ على نطاق الضغط الموصى به من 4إلى 5بار .تم تطوير نماذج تنبؤية غير خطية، تفسر من 42.2% إلى 75.4%من التغير في ضغط الفوهة نتيجة للسرعة .تقدم هذه النماذج إرشادات عملية لتحسين تشغيل المرشات، مما يعزز كفاءة تطبيق المبيدات ويقلل من هدر الموارد .تساهم هذه الدراسة في تقدم ممارسات الزراعة الدقيقة من خلال تقديم رؤى عملية حول العلاقة بين السرعة والضغط وأداء الفوهات في ظل ظروف الحقل.

الكلمات المفتاحية :المرشات، الفوهات، ضغط العمل، سرعة التشغيل، النماذج التنبؤية.

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INTRODUCTION

Chemical plant protection against pests (weeds, diseases, and harmful insects) is achieved by applying pesticides using specialized equipment that has undergone significant innovative development in recent years (5, 10, 18, 20). Eliminating harmful insects and pests through spraying can minimize a large portion of production losses (9, 13). Global competitiveness in food pricing, combined with high costs, necessitates that farmers utilize plant protection machinery with higher productivity and efficiency. Additionally, adopting automated control systems enables precise measurement and application of resources. Agricultural machinery manufacturers offer farmers a wide range of modifications for plant protection equipment. In turn, farmers can adjust the equipment to create a system tailored to their needs and management style (2). Plant protection depends on the uniform distribution of pesticide droplets on the plant surface, the degree of coverage, and the biocidal action of the product. A key factor in this process is the droplet diameter and its behaviour under various machines and pesticide application technologies (3, 14, 17). Sprayers do not atomize the liquid into droplets of uniform size and speed; instead, they generate a spectrum of droplets with different sizes and operating velocities (11-12). Thus, selecting the right nozzles is a crucial step in performing plant protection activities (17). Proper nozzle selection can minimize deviations from the prescribed application rate. The nozzles need to distribute the droplets evenly, ensuring adequate plant coverage at the intended operating speed and solution pressure (1, 16).

The characteristics of agricultural spraying are among the most critical factors influencing the dispersion of the solution, its coverage and deposition on plants, and its biological efficacy. In this regard, several authors have studied the impact of nozzle type and size on working pressure and droplet characteristics during spraying (4, 7, 8, 15). Dimitrova et al. (4) determined the transverse distribution of the working liquid delivered along the boom's length under different operating variants of the nozzle. Hussain et al. (7) conducted a laboratory experiment to evaluate the effect of working pressures and nozzle mounting heights on droplet characteristics for three nozzle diameters of Nelson R3000 nozzles.

This study was conducted to determine the actual operating speed of a tractor-sprayer unit required to maintain optimal working pressure for the application of pesticides using three types of nozzles during a plant protection activity in a field planted with wheat.

MATERIALS AND METHODS

Experimental field and studied object characteristics

The study was conducted in 2023 in the area of Gorno Botevo village, Central Bulgaria (42°25'03"N 25°49'08"E). The field has an area of 36.76 ha with a terrain slope of 2% (Fig. 1). The soil type is chernozem-smolnitsa. The object of the study was an Amazone UG 3200 trailed boom sprayer, aggregated with a Claas Arion 630 tractor (Fig. 2).

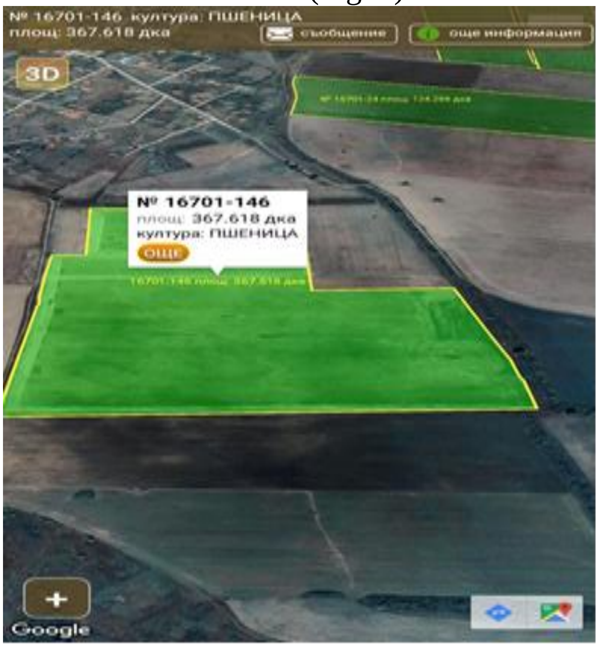

Figure 1. Experimental Plot (42°25'03"N 25°49'08"E)

Figure 2. Machine-Tractor Unit

The main technical specifications of the boom sprayer used for the study are presented in Table 1.

Table 1. Technical specifications of the Amazone UG 3200 Trailed Boom Sprayer

Main Technical Specifications	Value
Actual sprayer volume, *l*	**3200**
Flushing water tank, *l*	**400**
Working width, *m*	**28**
Transport height, *m*	**3.30**
Transport length, *m*	**5.90**
Transport width, *m*	**2.40**
Weight of the sprayer with the booms Super-S2, *kg*	**2917**
Sprayer pump flow rate, *l/min*	**370**
Maximum suction performance, *l/min*	**400**
Working pressure, *bar*	**< 10**
Spraying height, *m*	**0.5- 2.2**
Ground clearance, *m*	**0.7- 0.9**
Nominal operating speed range of the sprayer, km/h	**8–20**
Number of boom sections	**46**
Number of nozzles per section	**3**
Distance between nozzles, m	**0,5**

The nominal operating speed range of the sprayer used in this study (Amazone UG 3200) was 8–18 km/h, depending on the nozzle type and operational conditions. This range was selected to ensure optimal coverage and application efficiency while maintaining the target rate of 198 l/ha. During the plant protection operation of spraying, the selection of nozzles plays an important role, as it can significantly improve the quality of the sprayer's performance. Manufacturers design nozzles in different colors depending on the type of pesticide, the spraying period (pre-sowing or during vegetation), and their flow rate, corresponding to a numerical designation. Three types of flat fan nozzles with elliptical orifices designed to produce a uniform spray pattern were used for this study. The models of the tested flat fan nozzles were: Blue - TeeJet XR11003, Red - TeeJet XR11004, and Brown - TeeJet XR11005) manufactured by TeeJet. These nozzles have spray angles of 110°, flow rates of 0.8, 1.2, and 1.6 L/min, respectively, and are categorized as fine, medium, and coarse droplet size nozzles according to ISO 25358 standard.

The nozzle colors (blue, red, and brown) follow the standard ISO 10625 color-coding system, which categorizes nozzles based on flow rate at a given pressure. The selected nozzles correspond to different flow capacities and droplet sizes, as summarized below:

Blue nozzle (X)**:** Nominal flow rate of (0.8 L/min), suitable for lower application rates and finer droplets.

Red nozzle (Y)**:** Nominal flow rate of (1.2 L/min), offering medium application rates and droplet sizes.

Brown nozzle (Z)**:** Nominal flow rate of (1.6 L/min), designed for higher application rates and larger droplets.

Table 2 summarises the flow rate for each nozzle type at 4–5 bar and corresponding speeds. The sprayer dynamically adjusted flow to maintain the constant application rate of 198 l/ha using a speed-sensitive regulation system. This system continuously monitored the tractor's speed and adjusted the working pressure and flow rate accordingly. Smaller nozzles required higher pressure adjustments at increased speeds, while larger nozzles maintained flow rates with minimal pressure changes. Feedback from pressure and flow sensors ensured precise control throughout all operational variants.

Table 2. Parameters for the tested nozzles

Nozzle Type	Pressure (bar)	Flow Rate (L/min)	Speed (km/h)	Application Rate (l/ha)
Blue	**4.0–5.0**	**(X)**	**8.5–11.0**	**198**
Red	**4.0–5.0**	**(Y)**	**11.0–14.0**	**198**
Brown	**4.0–5.0**	**(Z)**	**14.0–18.0**	**198**

Experimental design

The experimental plot was mapped and pre-set in the tractor navigation system. The sprayer’s work process and the section control are monitored from the tractor cab, where an ISOBUS terminal and AMACLICK controller are installed (Fig. 3). The field was divided into three plots, each containing eight sections, to accommodate the individual spraying options. According to agronomic requirements, a solution consumption rate of 198 l/ha was selected for the crop's needs (Fig. 4). The sprayer was filled with water and pesticide from one side of the field, at the end of the turning strip, using a tanker. However, the liquid was prepared using standard tap water and a commercially available pesticide following the manufacturer's instructions. The movement of the tractor-sprayer unit was shuttle with pear-shaped turns. The pressure was measured using a calibrated electronic pressure sensor with an accuracy of ±0.1 bar, ensuring precise regulation and recording of the sprayer's working pressure. Speed was monitored using a GPS-based system with an accuracy of ±0.1 km/h, providing reliable and consistent measurements across all operational variants.

Figure 3. Control terminal in the tractor cabin

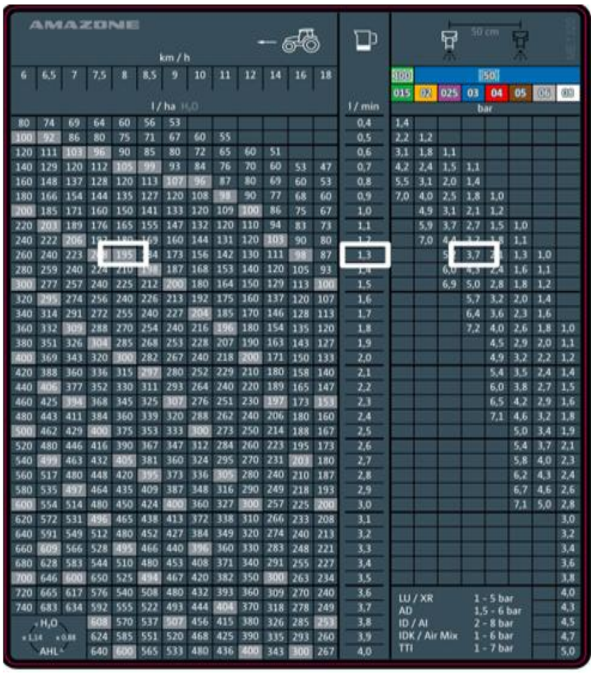

Figure 4. Sprayer adjustment nomogram

The optimal operating pressure required to maintain the sprayer ranges between 4 and 5 bar (Table 3). To determine the optimal working speed of the unit while using the three nozzle models, eight operating variants were tested at different working speeds – 8.5 ÷ 18 km/h (Table 3). The pressure range provided in Table 2 reflects the dynamic nature of the sprayer's operation. As the sprayer adjusted to maintain the target application rate of 198 l/ha under varying speeds (8.5–18 km/h) and nozzle types, slight fluctuations in pressure occurred due to the differences in nozzle orifice sizes and flow capacities. These variations were inherent to the system's regulation mechanism and are accurately represented as ranges rather than fixed values. The pressure ranges in Table 3 result from the system's efforts to dynamically maintain a constant application rate of 198 l/ha across varying speeds and nozzle types. This constant rate ensures uniform pesticide distribution, with pressure adjustments accounting for the specific flow characteristics of each nozzle type.

Table 3. Sprayer operating variants with the three types of nozzles (blue, red and brown)

Variant	Speed (*Vp*), km/h	Operating pressure (p), bar
Variant 1, (V1)	**8.5**	**4 ÷ 5**
Variant 2, (V2)	**9**	
Variant 3, (V3)	**10**	
Variant 4, (V4)	**11**	
Variant 5, (V5)	**12**	
Variant 6, (V6)	**14**	
Variant 7, (V7)	**16**	
Variant 8, (V8)	**18**	

Note: The pressure ranges reflect dynamic adjustments made by the sprayer's control system to maintain a constant application rate of 198 l/ha under varying operational conditions. The pressure ranges in Table 3 result from the system's efforts to dynamically maintain a constant application rate of 198 l/ha across varying speeds and nozzle types. This constant rate ensures uniform pesticide distribution, with pressure adjustments accounting for the specific flow characteristics of each nozzle type.

Before starting the spraying operation, the sprayer was inspected for leaks and blockages. To ensure better coverage of the crop, all nozzles were cleaned using a brush. After the sprayer was activated, the working pressure was adjusted to the target range of 4–5 bar to meet the experimental requirements and ensure proper operation of the nozzles. The operating speed of the tractor-sprayer unit was measured using the tractor's integrated GPS-based navigation system. This system allowed for real-time tracking of the tractor's speed as it moved through the experimental field. The GPS used in the study is accurate to within ±0.1 km/h, ensuring reliable and precise speed data throughout the experimental process. This level of accuracy was sufficient to monitor and adjust the sprayer's speed within the predefined operating speed ranges (8.5 to 18 km/h). The speed data was continuously recorded and monitored via the control terminal in the tractor cabin. This allowed for adjustments to be made during operation to maintain the desired speeds for each variant tested. In this study, the control system was set to maintain an application rate of 198 l/ha, ensuring consistency in pesticide distribution across the field. The regulation system adjusted pressure and flow dynamically to meet this target under varying speeds (8.5–18 km/h) and with different nozzle types (blue, red, and brown).

Data analysis

To investigate the differences in the operating variants of the sprayer based on working speed and the types of nozzles used, a univariate ANOVA analysis with a post hoc Scheffe test was applied. The strength of the relationship between the sprayer's working speed and the pressure of the respective nozzles was calculated using a correlation analysis at $p < 0.01$. The influence of the sprayer's working speed on the pressure of the respective nozzles was examined through regression analysis at $p < 0.05$. Non-linear predictive models were derived to establish the relationships between the studied parameters, expressed by the following equation:

$$Q = a + b_1 x + b_2 x^2 \qquad (1)$$

where: Q – the parameter representing the operating pressure for the eight working variants of the aggregate unit;

x – the factor representing the working speed of the tractor-sprayer unit;

a, b_1 and b_2 – the coefficients of the model.

The computational procedures were performed using IBM SPSS Statistics 26.0 software.

RESULTS AND DISCUSSION

The sprayer employs a sophisticated pressure regulation system to effectively maintain a target pressure range of 4–5 bar during varying operational speeds. The working pressure of the sprayer was measured at the point immediately after the pump, where the pressure is regulated before being distributed to the nozzles. Below is a schematic representation of the key components involved in Figure 5:

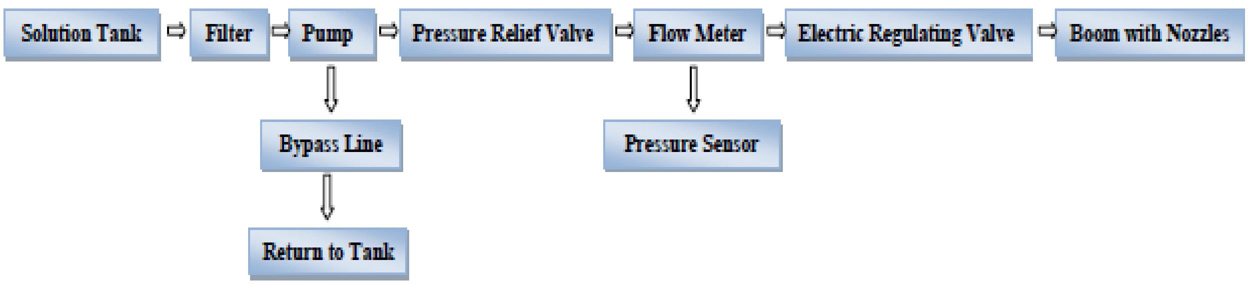

Figure 5. Schematic showing the key components of the pressure regulation system

Pump: Draws the spray solution from the tank and delivers it under pressure to the system.

Pressure Relief Valve: Ensures system safety by redirecting excess pressure back to the tank via the bypass line, preventing over-pressurization (6). Flow Meter: Measures the actual flow rate of the liquid being sprayed, providing real-time data to the rate controller (22). Electric Regulating Valve: Adjusts the flow rate to the boom based on signals from the rate controller, fine-tuning the pressure to maintain the desired application rate(6). Pressure Sensor: Monitors the system's pressure, supplying data to the rate controller to ensure the target pressure range is maintained. Speed Sensor/GPS: Tracks the ground speed of the sprayer, providing essential data to the rate controller for flow rate adjustments corresponding to speed variations (22). Rate Controller: The central processing unit that receives input from the flow meter, pressure sensor, and speed sensor. It calculates the necessary adjustments and signals the electric regulating valve to modify the flow rate, ensuring consistent application rates.

Pressure Regulation Process:

-Speed Monitoring: As the sprayer moves through the field, the speed sensor continuously updates the rate controller on the ground speed (22).

-Flow Measurement: The flow meter measures the actual liquid flow, and the rate controller compares this with the desired rate (22).

-Adjustment Mechanism: If adjustments are needed, the controller instructs the pump or regulating valve to modify flow(22).

-Pressure Maintenance: The pressure relief valve adjusts the flow between the nozzles and the bypass line back to the tank, ensuring the system operates within the target pressure range (6).

This integrated system allows the sprayer to adjust dynamically to varying operational speeds, maintaining the target pressure range of 4–5 bar and ensuring precise application rates. During the experiments a constant application rate of 198 l/ha was maintained. The pressure increase observed with blue nozzles at higher speeds reflects the system's effort to meet the target rate by adjusting flow through nozzles with smaller orifice diameters. These findings underscore the interaction between application rate consistency, nozzle characteristics, and operational parameters. The recommended pressure of 4–5 bar was maintained when the equipment operated at speeds of 8.5 to 12 km/h for blue and red nozzles and 12 to 18 km/h for brown nozzles.

Univariate ANOVA Analysis

ANOVA analysis was applied to determine the optimal parameters of the study. Figures 6, 7, and 8 show the significant differences among the sprayer's various operating regimes, depending on the working speed of the three types of nozzles. Figure 6 shows that when using blue nozzles, no significant differences in operating pressure (4.30 to 4.90 bar) were observed across the sprayer's first four operating variants (V1 to V4). The equipment maintained the recommended nozzle operating pressure during operation at speeds of 8.5 to 11 km/h. The other four variants (V5 to V8) showed significant differences, both from the first four variants and among themselves. When spraying at speeds exceeding 11 km/h, the operating pressure increased significantly, ranging from 5.47 to 8.72 bar. This pressure rises in the system is attributed to the small diameter of the blue nozzle orifices. The system's control unit attempts to maintain the preset application rate of the working solution, resulting in uneven flow through the nozzles and reduced spraying quality on the plant leaves.

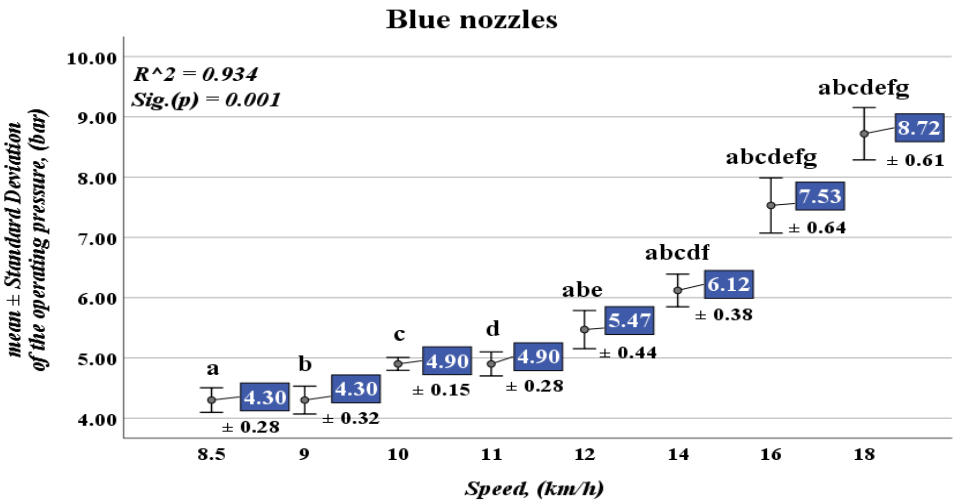

Figure 6. Multiple comparisons of the operating pressure, (bar) at the different working variants of the aggregate unit equipped with blue nozzles

The results obtained using the red nozzles are shown in Figure 7. No significant differences in nozzle pressure (4.00 to 4.88 bar) were observed across the sprayer's first five operational variants (V1 to V5). The recommended pressure was maintained when the equipment operated at 8.5 to 12 km/h. Figure 6 also demonstrates that the operational variants V6, V7, and V8 significantly differed, both from the first five variants and from each other. When operating the equipment with the red nozzles, a similar effect is observed as with the blue nozzles. At an actual working speed of the equipment exceeding 12 km/h, the working pressure increases significantly (from 5.41 to 8.87 bar). This increase is again attributed to the small diameter of the nozzle openings.

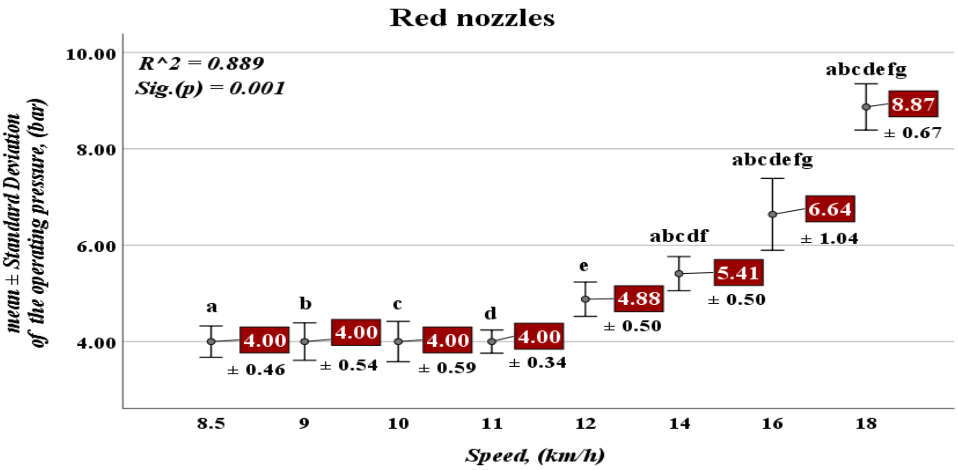

Figure 7. Multiple comparisons of the operating pressure, (bar) at the different working variants of the aggregate unit equipped with red nozzles

When spraying with the brown nozzles, opposite results are observed compared to the blue and red nozzles (Fig. 8). No significant differences in pressure (4.90 to 4.20 bar) are found in working variants V5–V8. The recommended pressure is maintained when the sprayer operates at 12 to 18 km/h. The first four working variants (V1–V4) show significant differences, both among themselves and compared to the other variants. At lower speeds of 8.5–12 km/h, the working pressure of the sprayer ranges from 5.43 to 8.93 bar. In this case, the equipment aims to maintain the set application rate, which increases working pressure. Variant 1 for the brown nozzles corresponds to the highest pressure value (5.43 bar) because their larger orifice size allows a higher flow rate at lower speeds. The system adjusts the pressure upwards to maintain the constant application rate of 198 l/ha at the slower speed of Variant 1. This contrasts with the red and blue nozzles, where smaller orifice sizes result in lower flow requirements and pressure adjustments under the same conditions.

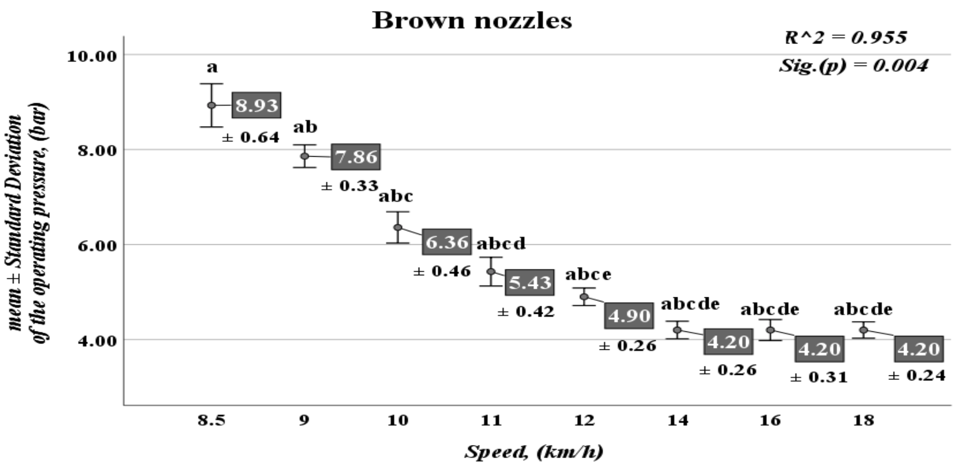

Figure 8. Comparison of operating pressure (bar) across various working variants of the aggregate unit using brown nozzles

Bivariate correlation

Tables 4, 5 and 6 present the results of the correlation analysis, which demonstrates the strength and direction of the relationships between the operating speeds of the "tractor-sprayer" unit and the working pressure when spraying with blue, red, and brown nozzles. When spraying with the blue nozzles, only for variant V1, the relationship between speed and working pressure is moderate (r = 0.457) and statistically significant (Sig. = 0.018) (Table 4). From this, it can be concluded that the optimal speed at which the recommended pressure of 4÷5 bar is maintained when using the blue nozzles is 8.5 km/h.

Table 4. Correlation between speed and operating pressure of blue nozzles at the different working variants of the aggregate

		Variant 1	
n=10		**Speed, V1**	**Operating pressure, V1**
Speed, V1	**r**	**1**	**0.457***
	Sig. (2-tailed)		**0.018**
		Variant 2	
n=10		**Speed, V2**	**Operating pressure, V2**
Speed, V2	**r**	**1**	**0.270**
	Sig. (2-tailed)		**0.451**
		Variant 3	
n=10		**Speed, V3**	**Operating pressure, V3**
Speed, V3	**r**	**1**	**-0.340**
	Sig. (2-tailed)		**0.336**
		Variant 4	
n=10		**Speed, V4**	**Operating pressure, V4**
Speed, V4	**r**	**1**	**-0.066**
	Sig. (2-tailed)		**0.856**

Note: *Correlation is significant at 0.05 level (2-tailed), n - is the number of the observations

When spraying with the red nozzles the optimal working variant is V5 (Table 5), where a strong (r = 0.745), statistically significant (Sig. = 0.018) correlation was observed between the speed and the working pressure of the nozzles. The optimal speed at which the recommended pressure of 4–5 bar is maintained is 12 km/h.

Table 5. Correlation between speed and operating pressure of red nozzles at the different working variants of the aggregate

		Variant 1	
n=10		**Speed, V1**	**Operating pressure, V1**
Speed, V1	**r**	**1**	**- 0.174**
	Sig. (2-tailed)		**0.631**
		Variant 2	
n=10		**Speed, V2**	**Operating pressure, V2**
Speed, V2	**r**	**1**	**0.005**
	Sig. (2-tailed)		**0.989**
		Variant 3	
n=10		**Speed, V3**	**Operating pressure, V3**
Speed, V3	**r**	**1**	**0.394**
	Sig. (2-tailed)		**0.260**
		Variant 4	
n=10		**Speed, V4**	**Operating pressure, V4**
Speed, V4	**r**	**1**	**0.168**
	Sig. (2-tailed)		**0.642**
		Variant 5	
n=10		**Speed, V5**	**Operating pressure, V5**
Speed, V5	**r**	**1**	**0.745***
	Sig. (2-tailed)		**0.013**

Note: *Correlation is significant at 0.05 level (2-tailed), n - is the number of the observations

From the examined working variants when spraying with the brown nozzles, the highest correlation coefficient (0.783) was obtained for variant V7 (Table 6). In this case, the relationship between the speed and working pressure of the nozzles is statistically significant (Sig. = 0.007). The optimal speed at which the recommended working pressure of 4–5 bar is maintained is 16 km/h.

Table 6. Correlation between speed and operating pressure of brown nozzles at the different working variants of the aggregate

		Variant 5	
n=10		**Speed, V5**	**Operating pressure, V5**
Speed, V5	**r**	**1**	**-0.094**
	Sig. (2-tailed)		**0.797**
		Variant 6	
n=10		**Speed, V6**	**Operating pressure, V6**
Speed, V6	**r**	**1**	**0.126**
	Sig. (2-tailed)		**0.729**
		Variant 7	
n=10		**Speed, V7**	**Operating pressure, V7**
Speed, V7	**r**	**1**	**0.783***
	Sig. (2-tailed)		**0.007**
		Variant 8	
n=10		**Speed, V8**	**Operating pressure, V8**
Speed, V8	**r**	**1**	**-0.490**
	Sig. (2-tailed)		**0.151**

Note: *Correlation is significant at 0.05 level (2-tailed), n - is the number of the observations

The variation in the correlation coefficients is due to several factors:

Technical Characteristics of the Nozzles:

- The blue nozzle has smaller orifices compared to the red and brown nozzles, which makes it more sensitive to changes in operational speed. This sensitivity results in greater variability in pressure as speed changes, leading to a moderate correlation coefficient (r = 0.457).
- The red and brown nozzles, with larger orifices, allow for more consistent pressure maintenance across a wider range of speeds. This stability explains the stronger correlation coefficients (r = 0.745 for red and r = 0.783 for brown).

Operational Factors:

- At lower speeds (e.g., 8.5–12 km/h), the blue nozzle operates closer to its performance limits, making small variations in speed disproportionately impact pressure. In contrast, the red and brown nozzles perform within a more stable operational range at these speeds, resulting in stronger correlations.

Methodology and Data Distribution:

- The observed correlation coefficients also reflect the specific speed intervals tested for each nozzle type. The speed intervals chosen for blue nozzles may have introduced more variability in the pressure-speed relationship compared to the intervals for red and brown nozzles.
- Differences in droplet size and spray pattern among the nozzles further influence the pressure response, contributing to the variation in correlation strength.

Models summary and parameter estimates

Based on the results from the variation and correlation analyses, predictive, nonlinear models were calculated for the optimal working variants of the tractor-sprayer unit with three types of nozzles (Fig. 9). These are V1 (speed = 8.5 km/h, pressure = 4.30 bar) for working with blue nozzles, V5 (speed = 12 km/h, pressure = 4.00 bar) for working with red nozzles, and V7 (speed = 16 km/h, pressure = 4.20 bar) for spraying with brown nozzles, respectively. The predictive models were designed to capture the relationship between operating speed and pressure across a range of speeds, not just at the optimal value (e.g., 8.5 km/h for blue nozzles). Including data points at speeds like 7 km/h and 9.5 km/h enables us to evaluate the behavior of the sprayer unit under realistic variations in operating conditions, reflecting possible deviations encountered in field operations. This approach provides a more comprehensive understanding of the system's response, enhancing the robustness of the model for practical applications.

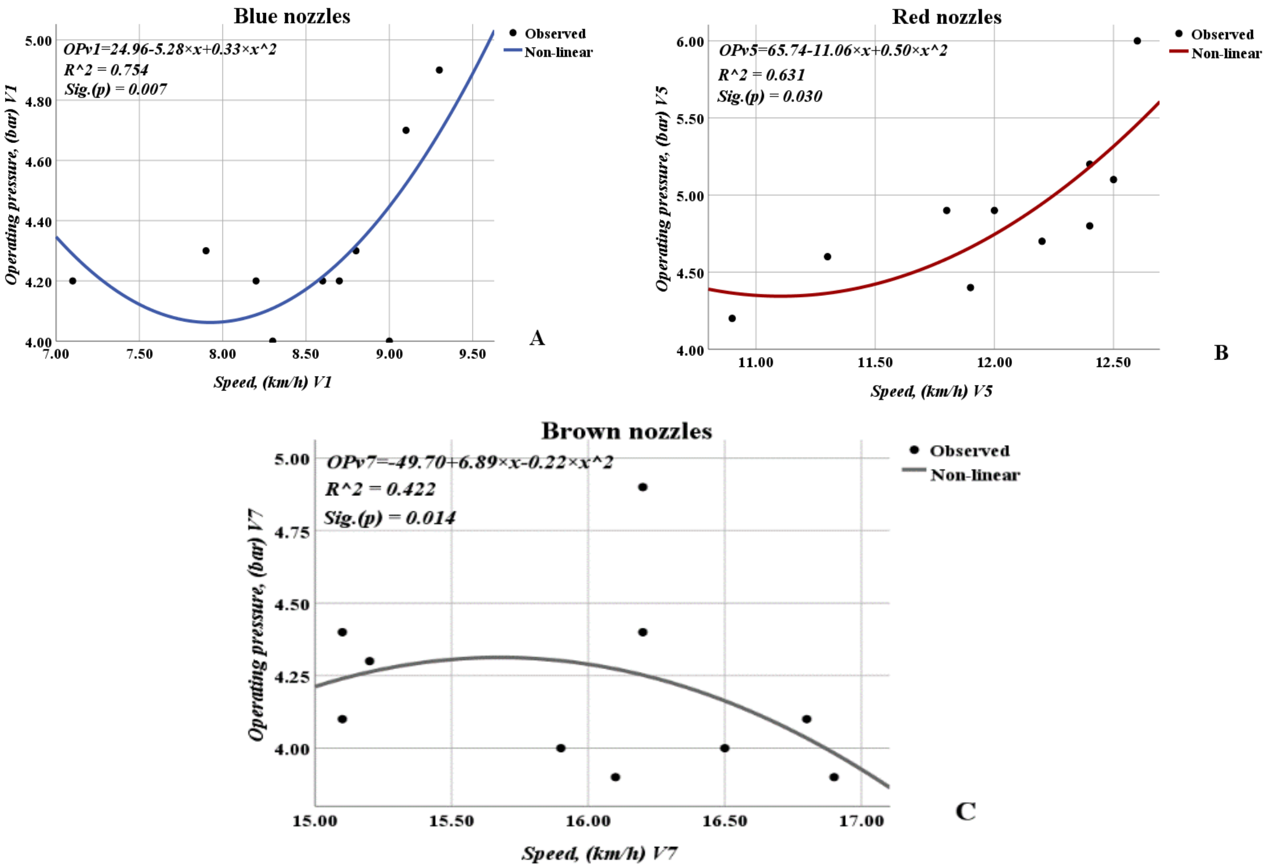

Figure 9. Nonlinear predictive models for the optimal operating variants of the unit working with the respective nozzles, (A) - V1 for blue nozzles, (B) - V5 for red nozzles and (C) - V7 for brown nozzles

The obtained models are statistically significant at $p < 0.05$. Their coefficients of determination are $R^2 = 0.754$, 0.631 and 0.422 respectively, i.e. 42.2% to 75.4% of the variations in the nozzle pressure are due to the influence of the working speed. These models are intended as a decision-support tool for operators to forecast the pressure at various speeds and adjust operating conditions accordingly to maintain the recommended range of 4–5 bar. While the models are most accurate near the optimal speeds (e.g., 8.5 km/h for blue nozzles), they also provide valuable estimates for slight deviations, enabling operators to anticipate potential pressure fluctuations and take corrective measures. Womac et al. (2001) investigated the effects of sprayer speed and venturi nozzles on application uniformity (21). Their findings highlight the significant influence of speed on droplet distribution. Similarly, the present study demonstrated that operating speed significantly affects nozzle pressure, with specific optimal speeds determined for blue (8.5 km/h), red (12 km/h), and brown (16 km/h) nozzles. Unlike Womac et al. (2001), which focuses on venturi nozzles, this research evaluated flat fan nozzles, offering detailed recommendations for each type based on pressure and speed. The results of this experiment align with Womac's general conclusions about the importance of speed while extending the analysis to predictive modeling specific to the nozzle type. Van de Zande et al. (2005) studied the effect of sprayer speed on spray drift, emphasizing environmental considerations (19). While this research focuses primarily on application efficiency and pressure maintenance, it also was observed that exceeding optimal speeds (e.g., >12 km/h for red nozzles) compromises droplet uniformity, which may contribute to drift. Van de Zande's work provides a broader environmental context, while the present study offers granular insights into optimal operating variants to enhance application effectiveness under field conditions. In contrast, this research provide predictive, nonlinear models linking speed and pressure for different nozzle types. These models can guide practitioners in achieving precise application rates and maintaining recommended pressures under specific conditions. They complement the findings of Womac et al. and Van de Zande by contributing to practical optimization strategies for field operations.

CONCLUSIONS

This study contributes to understanding the relationship between sprayer speed and working pressure for three distinct types of nozzles (blue, red, and brown). While nozzle types are widely studied, this research provides unique insights by:

- Developing predictive, nonlinear models for optimal operation under varying field conditions, which can be used as a decision-support tool for practitioners.

The tractor-sprayer unit was studied under eight operating variants, depending on the operating speed and the type of nozzles used.

The results offer actionable recommendations for practitioners, specifying the optimal speeds for maintaining the recommended pressure range of 4–5 bar:

- Blue nozzles: 8.5 km/h
- Red nozzles: 12 km/h
- Brown nozzles: 16 km/h

These findings can help farmers improve spraying efficiency, reduce waste, and enhance pesticide effectiveness, contributing to more sustainable agricultural practices.

While studies on nozzle performance and speed exist, the present research is distinct in its integration of predictive modeling, detailed comparative analysis of three nozzle types, and application-specific recommendations. This approach advances the current understanding of sprayer optimization.

Additionally, the inclusion of real-world field data under varying operational regimes enhances the finding's applicability and reliability.

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CONFLICT OF INTEREST

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