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Determination of Droplet Size Characteristics of Locally Manufactured Nozzles for Knapsack Sprayers

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HIGHLIGHTS

- Spray characteristics of local brass hollow-cone nozzles were evaluated.
- Flow rates showed high agreement with theoretical calculations.
- Nozzle design affected droplet size more than orifice diameter.
- Unverified nozzles may risk biological efficacy and drift potential.

Abstract

Droplet formation in spray nozzles primarily depends on nozzle design, while droplet size is of critical importance in crop protection due to the varying optimal ranges required for different target pests. In practice, locally manufactured brass nozzles are commonly used in orchard and knapsack sprayers, largely because of their low cost. However, most of these nozzles are produced without undergoing any research and development process, and their ability to generate droplet sizes suitable for effective pest management has not been scientifically verified. The present study aimed to evaluate the spray characteristics of brass hollow cone nozzles with different designs, which are widely sold in the domestic market but lack technical data in the literature beyond orifice size. Four nozzles were tested: two with an orifice diameter of 1.5 mm and two with 1.2 mm. Each nozzle was operated at pressures of 300, 400, and 500 kPa, with three replications and a spraying duration of 60 seconds. Droplet size distributions were measured using a laser diffraction analyzer, and volumetric parameters $DV_{0.1}$, $DV_{0.5}$, $DV_{0.9}$, together with span values, were recorded. The results showed that although flow rates closely matched theoretical expectations, droplet sizes varied significantly between nozzles of similar orifice diameters, indicating that internal design strongly influences spray performance. Notably, one nozzle consistently produced coarser droplets, while others generated finer sprays, and Relative Span values demonstrated clear differences in uniformity. These findings highlight that nozzle performance cannot be assessed based solely on nominal orifice size and emphasize the necessity of systematic evaluation to ensure effective pest control and minimize environmental risks.

Keywords: Hollow cone nozzle; Knapsack sprayer nozzle; Droplet size distribution; Spray quality; Pesticide application

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1. Introduction

Achieving high yield and quality products is becoming increasingly critical in light of the growing global population, shrinking agricultural land, and changing climatic conditions (Tilman et al., 2011). Modern agriculture aims to execute all processes with precision, among which effective and continuous management of harmful organisms (such as insects, pathogens, nematodes, and weeds) holds a central role (Oerke, 2006). These organisms can proliferate rapidly under favorable conditions (Savary et al., 2019). Particularly in regions with intensive production, failure to control pests leads to reductions in both yield and product quality; consequently, the amount of marketable produce declines, making economic losses inevitable (Popp et al., 2013). Moreover, when crop protection is insufficient, pests not only damage the current harvest but may also persist into the following production season, becoming a long-term problem (Zhang et al., 2018).

Although the Integrated Pest Management (IPM) approach seeks to reduce the use of chemical pesticides and promote environmentally sensitive control strategies, plant protection products (PPPs) continue to be widely applied in agricultural production (Privitera et al., 2023). However, the success of a pesticide application is not determined solely by the chemical properties of the product; factors such as the correct timing and technique of application, favorable environmental conditions, and the proper adjustment of equipment parameters also play a critical role (Longo et al., 2020). The droplet spectrum is one of the most important variables for ensuring biological efficacy and sufficient deposition on the target (de Cock et al., 2015). Increasing spray pressure results in smaller droplets, thereby significantly altering the droplet spectrum (Cerruto et al., 2021). Moreover, nozzle design has a pronounced effect on droplet characteristics. For instance, air-induction nozzles generate larger droplets compared to conventional flat-fan nozzles, thereby reducing drift (Miller et al., 2008). High-speed camera shadowgraphy allows precise measurement of droplet size and velocity distributions produced by different nozzles (Minov et al., 2016). In addition, digital image processing techniques have been successfully used to determine the size of free-falling droplets (Sudheer et al., 2000). Similarly, the automatic analysis of droplet deposition patterns on water-sensitive paper enables the evaluation of spray coverage quality (Cunha et al., 2019). With these advanced measurement techniques, spray quality can be objectively assessed, allowing for the optimization of equipment and application settings. Air-assisted spraying systems are also employed to enhance droplet penetration into plant canopies and reduce wind-induced drift (Zhai et al., 2014). In citrus orchards, studies on fixed spraying systems have demonstrated that nozzle type and arrangement significantly influence droplet deposition and pest control effectiveness (Chen et al., 2014). In conclusion, the highest efficiency and safety in pesticide applications can be achieved through integrated management strategies that holistically incorporate all these factors.

In agricultural spraying, nozzles are among the most critical components, ensuring the accurate delivery of pesticides to target surfaces. Depending on the type of pesticide used and the application purpose, nozzles generate droplets of different sizes, which directly influence the effectiveness of the treatment. In insecticide and fungicide applications, fine droplets within the range of 100–200 µm are generally preferred. Such small droplets distribute more uniformly across leaf surfaces and penetrate the microhabitats where pests reside, ensuring effective contact. Conversely, in herbicide applications, coarser droplets ranging between 250–400 µm are favored (Matthews, 2014), as herbicide treatments for broadleaf weeds typically involve larger target surfaces. Moreover, reducing drift risk is crucial to ensure deposition exclusively on the intended area. Droplet size determines both the amount of active ingredient reaching the target and the extent of environmental losses. Very small droplets (<100 µm) are easily carried away by wind, causing off-target deposition, while excessively large droplets may fail to adhere to surfaces and instead fall to the ground, diminishing efficacy. Therefore, the selection of an appropriate droplet size must align with the biology of the target pest and the formulation of the pesticide, with nozzle type chosen accordingly. The relationship between nozzle type, chemical properties, and droplet size has been the focus of numerous studies. Tuck et al. (1997) compared Phase Doppler Analyzer (PDA) and Particle Measuring System (PMS) devices for determining droplet size and velocity distribution in sprays generated by flat-fan nozzles. Their study revealed that PDA measured the volume median diameter (VMD) approximately 15% lower and the mean droplet velocity 2–3 m/s higher than PMS. Similarly, Nuyttens et al. (2007), in an experimental study involving 32 nozzle and pressure combinations using a Phase Doppler Particle Analyzer (PDPA), reported that air-induction nozzles operating at 3 bar produced VMDs in the range of 500–650 µm, whereas conventional flat-fan nozzles under the same conditions generated VMDs between 250–350 µm. Ferguson et al. (2015) tested 21 different drift-reducing nozzles in a wind tunnel at a constant wind speed of 8 m/s and found that VMD values varied by 30–40% (approximately 100 µm difference) depending on the liquid used, with significant inconsistencies even among nozzles of the same type. Likewise, Dorr et al. (2013) demonstrated that standard flat-fan nozzles produced droplets averaging 180 µm in diameter with velocities of 15 m/s at 3 bar, while air-induction nozzles under identical pressure generated droplets averaging 420 µm in diameter with velocities of 8 m/s, thereby significantly contributing to drift reduction potential.

The nozzle design is one of the most critical factors determining spray quality, requiring specific engineering expertise (know-how) and precise manufacturing processes. However, in some low-quality productions, fundamental functional components within the nozzle—such as constricted sections and turbulence chambers that enable droplet formation—are neglected. Instead, only the external geometry is imitated without understanding the design intent, and the nozzle is simply manufactured from wear-resistant materials such as brass. Nozzles produced through such non-standard manufacturing practices not only fail to provide the necessary control over droplet size but also exhibit significant deviations in spray performance, making it impossible for them to substitute original designs. In this study, droplet size measurements were conducted on non-standard nozzles either imitated from different orifice diameters or produced without substantial engineering design. The adequacy of the droplet sizes generated by these nozzles for relevant pest control applications was then evaluated.

2. Materials and Methods

2.1. *Description of the Nozzles Used in the Experiments*

Information regarding the manufacturers of the nozzles used in the experiments was not disclosed, and it was observed that they could be produced simultaneously by more than one company. Furthermore, data on flow rate and droplet sizes at nominal pressure are not available. The nozzles were numbered, and their orifice diameters along with visual representations are presented in Figure 1. All nozzles used in the experiments were brand new and had not been previously operated.

Nozzle No	Orifice Type
1	Hollow Cone 1.5 mm
2	Hollow Cone 1.5 mm
3	Hollow Cone 1.2 mm
4	Hollow Cone 1.2 mm

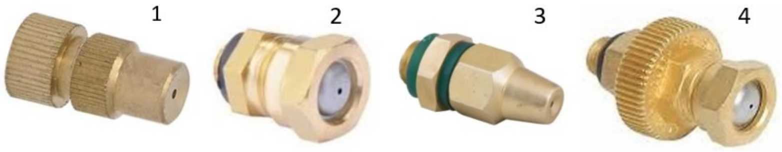

Figure 1. Orifice Types and Visual Representations of the Nozzles Used in the Experiments

2.2. *Properties of the Tap Water Used in the Experiments*

Surface tension measurements were conducted using a KRÜSS (Germany) Drop Shape Analyzer, and the dynamic surface tension of tap water on a polyethylene surface (PCE RVI2) was determined. The viscosity values of the spray liquids were measured using a digital rotational viscometer. Based on three replicates, the surface tension of tap water was measured as 74.79 ± 0.1 mN/m, while its viscosity was 1.00 ± 0.11 mPa·s.

2.3. *Measurement of Nozzle Flow Rates*

Prior to the experiments, the flow rates of the nozzles were measured. For accurate flow rate measurements, a simple experimental setup was constructed (Figure 2). In this system, compressed air was supplied by a compressor (1), and its pressure was regulated by a pressure regulator (2). The air adjusted to the desired pressure entered a premix tank (3), where tap water was stored at the bottom and compressed air at the top. From the outlet of the premix tank, only tap water was discharged, and before reaching the nozzle, its pressure was conditioned once more using a secondary pressure regulator (4). A solenoid valve with a time relay (5) allowed water to pass through the nozzle for 60 seconds, after which the valve automatically closed. The nozzles (6), connected individually to the solenoid outlet, were equipped with stoppers to prevent dripping, enabling flow rate measurements (L/min) with a graduated container (7). In the experiments, each of the four nozzles was tested individually at pressures of 300, 400, and 500 kPa with three replications. Additionally, the measured nozzle flow rates were compared with theoretical flow rates, which were calculated using the following formula (Çengel and Cimbala, 2017):

$$Q_t = C_d A \sqrt{\frac{2\Delta P}{\rho}} \tag{1}$$

In the formula, P represents the liquid pressure supplied to the nozzle (Pa), Q_t denotes the theoretical flow rate (L/min), ρ is the liquid density (kg/m³), A is the orifice area (m²), and C_d is the discharge coefficient. In this equation, the C_d value was assumed to be 0.65 for hollow cone nozzles (Matthews, 2014). For each pressure level, the theoretical flow rate was calculated and compared with the measured flow rate, and the deviation (%) was determined as follows:

$$\frac{Q_m - Q_t}{Q_t} = D\ (\%) \tag{2}$$

In this equation, Q_m represents the measured flow rate (L/min), Q_t denotes the theoretical flow rate (L/min), and D indicates the deviation value (%).

Figure 2. Schematic Representation of the System Used for Accurate Measurement of Nozzle Flow Rates

2.4. *Measurement of Droplet Sizes*

For droplet size measurements, a 200 L tank-mounted orchard sprayer was used to provide the required nozzle pressure. However, the pump of this sprayer was operated electrically. During the experiments, tap water at 20°C was used. The desired pressure was adjusted using the pressure regulator, and prior to each droplet size measurement, the pressure indicated on the manometer attached to the regulator was verified and continuously monitored throughout the measurement. Droplet size distributions were obtained using a Malvern STP5399 laser diffraction particle size analyzer (Malvern, UK). During droplet size measurement, the laser beam emitted from the device passed through the sprayed droplets and was diffracted; this diffraction was then analyzed by the receiver to determine droplet sizes. Measurements were conducted only along the central axis of the spray pattern, rather than across the entire spray cone, due to the analyzer's capability to measure droplets solely along a single line. In the experiments, each nozzle was tested at 300, 400, and 500 kPa with three replications, during a spraying period of 60 seconds. For each application, the volumetric distribution characteristics $DV_{0.1}$ (diameter below which 10% of the volume of droplets is found, µm), $DV_{0.5}$

(volume median diameter, μm), and $DV_{0.9}$ (diameter below which 90% of the volume of droplets is found, μm) were recorded. Based on the results, the values of $DV_{0.1}$, $DV_{0.5}$, and $DV_{0.9}$ were used to calculate the relative span (RS) value (Wang et al., 2022):

$$RS = \frac{\mathrm{DV}_{0.9} - \mathrm{DV}_{0.1}}{\mathrm{DV}_{0.5}} \tag{2}$$

$DV_{0.5}$ (μm) measurements were analyzed using IBM SPSS Statistics (IBM Corp., Armonk, NY, USA). Each pressure level (3, 4, and 5 bar) was treated as an independent sub-experiment; within this framework, nozzle type (4 levels) was considered as the single factor, and $DV_{0.5}$ as the dependent variable, with n = 3 replicates per cell, using one-way analysis of variance (ANOVA). Prior to analysis, assumptions of normality (assessed via Q–Q plots and, considering the sample size, supported by Shapiro–Wilk test) and homogeneity of variances (Levene's test) were examined; ANOVA results were interpreted when no significant deviations were observed. When ANOVA indicated significance (α = 0.05), Fisher's Least Significant Difference (LSD) post hoc test was employed for pairwise comparisons, and the lettering in the figures (compact letter display) was based on LSD results: groups sharing the same letter were not statistically different, whereas groups with different letters exhibited significant differences at $p < 0.05$. Descriptive statistics were reported as mean ± standard deviation (SD), and the error bars in the graphs represent ±SD.

3. Results

3.1. Flow Rates of the Nozzles under Different Pressures

The theoretical and measured flow rates of four different nozzles at operating pressures of 300, 400, and 500 kPa, along with their percentage deviations, are presented in Table 1. Nozzles 1 and 2 have relatively larger orifice diameters (1.5 mm), and therefore exhibit higher theoretical flow rates. Nozzles 3 and 4 possess smaller orifice diameters (~1.2 mm), resulting in lower theoretical flow rates. Since the nozzles were new at the time of testing, no substantial differences were observed between the theoretical and measured values. Consequently, no meaningful standard deviation could be calculated for the triplicate measurements. In addition, for Nozzles 2, 3, and 4, the measured flow rates were found to be sometimes higher and sometimes lower than the theoretical values, depending on the pressure level.

Table 1. Comparison of Theoretical Flowrate (Q_t), Measured Flowrate (Q_m), and Deviation under Different Pressures

Nozzle	Pressure (kPa)	Q_m (L/min)	Q_t (L/min)	Deviation (%)
1	300	1.7	1.775	4.41%
	400	1.9	1.975	3.95%
	500	2.2	2.25	2.27%
2	300	1.7	1.725	1.47%
	400	1.9	1.875	-1.32%
	500	2.2	2.235	1.59%
3	300	1.1	1.09	-0.91%
	400	1.2	1.22	1.67%
	500	1.4	1.375	-1.79%
4	300	1.1	1.08	-1.82%
	400	1.2	1.17	-2.50%
	500	1.4	1.37	-2.14%

3.2. Comparison of Droplet Sizes of the Nozzles under Different Pressures

In the droplet size measurements, statistical analyses were conducted to determine whether the four different nozzles produced droplets of similar or different sizes under varying pressures. The results indicated that each nozzle generated droplets of distinct sizes at different pressures (Table 2).

Table 2. Statistical Evaluation of $DV_{0.5}$ Values of Four Different Nozzles at Various Pressures

Pressure (kPa)	F-value	p-value
300	41152.675	<0.01*
400	21010.643	<0.01*
500	1331.995	<0.01*

*p < 0.05 indicates a statistically significant difference.

Increasing spray pressure from 3 to 5 bar resulted in a consistent decrease in $DV_{0.5}$ across all nozzle types. For example, Nozzle 4 produced the largest droplets at 3 bar ($DV_{0.5} \approx 225.5$ µm), which decreased to approximately 154.8 µm at 5 bar. Similarly, Nozzle 1's $DV_{0.5}$ declined from ~178.7 µm at 3 bar to ~151.9 µm at 5 bar, illustrating the general trend that higher operating pressures generate finer droplets. At each pressure level, significant differences ($p < 0.05$) were observed among nozzle types, as indicated by distinct significance letters. At 3 bar, Nozzle 4 produced the largest $DV_{0.5}$ (~225.5 µm), while Nozzle 1 generated the smallest (~178.7 µm). At 5 bar, Nozzle 4 again yielded the largest droplets (~154.8 µm), whereas Nozzle 2 produced the smallest (~143.9 µm). These patterns indicate that nozzle design strongly influences droplet size at a given pressure. The rank order of nozzle performance was generally consistent: Nozzle 4 consistently produced the largest droplets, while the smallest $DV_{0.5}$ values varied among Nozzles 1, 2, and 3 depending on pressure. The absence of overlapping error bars and the separation of significance groupings confirm the distinct droplet size distributions for each nozzle–pressure combination.

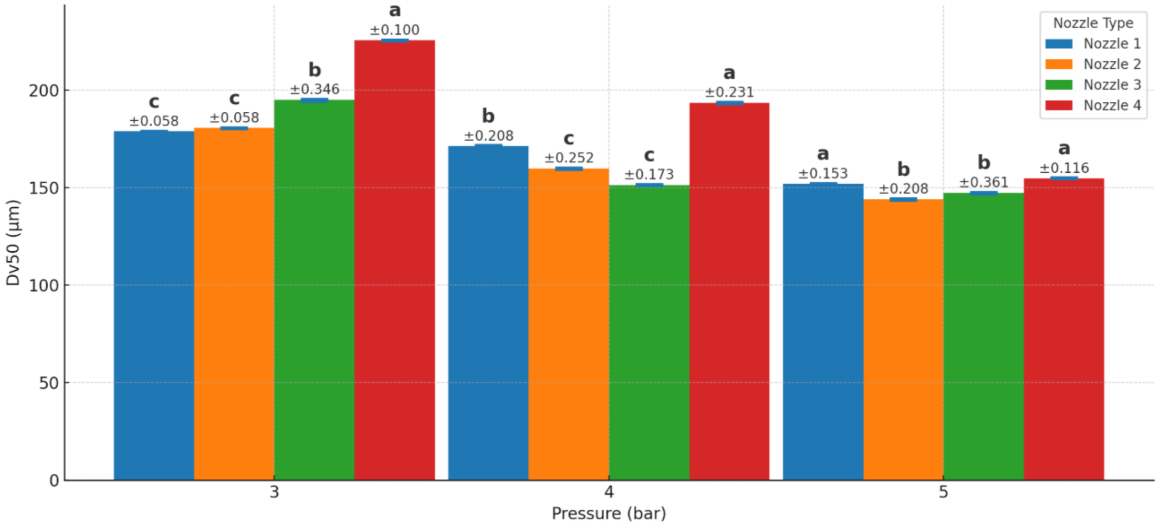

Figure 3. Comparison of Droplet Sizes Produced by Different Nozzle Types under Varying Pressures

3.3. *Droplet Spectrum*

The data in Table 3 present the droplet sizes and distribution characteristics of four different nozzles at various pressures. Overall, it was observed that droplet sizes decreased as pressure increased across all nozzles. For instance, the $DV_{0.5}$ value of Nozzle 1 was 178.7 µm at 3 bar, whereas it decreased to 151.9 µm at 5 bar. Similarly, in the other nozzles, higher operating pressures resulted in smaller droplets. This outcome is a natural consequence of increased liquid exit velocity at higher pressures, leading to finer droplet formation. Despite having a smaller orifice diameter, Nozzle 4 was found to produce coarser droplets. Likewise, Nozzle 3 generated larger droplets compared to the 1.5 mm orifice nozzles. On the other hand, the Relative Span value of Nozzle 4 was lower than that of the others.

Table 3. Droplet Size Parameters ($DV_{0.1}$, $DV_{0.5}$ and $DV_{0.9}$) and Relative Span Values of Nozzles under Different Pressures

Nozzle No	Pressure (kPa)	$DV_{0.1}$	$DV_{0.5}$	$DV_{0.9}$	Relative Span
1	3	85.5	178.7	347.3	1.465
	4	81.6	171.3	324.2	1.415
	5	68.52	151.9	285.2	1.426
2	3	84.5	180.5	333.6	1.382
	4	73.76	159.8	300.1	1.417
	5	70.18	143.9	268.8	1.38
3	3	103.1	194.8	348.7	1.261
	4	73.64	151.3	274.7	1.328
	5	66.11	147.2	262.8	1.336
4	3	123.6	225.5	389.2	1.177
	4	111.7	193.4	319.9	1.077
	5	79.5	154.8	270.6	1.234

4. Discussion

The measured flow rates are consistent with values reported in the literature (Balcı and Yağcıoğlu, 1999). Sayıncı et al. (2013) also reported, in their experiments with hollow cone nozzles, that differences in flow rates among nozzles with the same orifice diameter generally remained within ±10%, and that nozzle plates or swirl plates should be replaced if this limit is exceeded. In the present study, the measured flow rates of all nozzles were found to be very close to their theoretical (expected) values, with no deviation exceeding 5%. As noted by Sivri and Çanakcı (2024), such deviations can be considered within acceptable limits for non-worn nozzles.

In the statistical analysis, the expectation was that nozzles with the same orifice diameter would produce droplets of similar size; however, this was not the case. When the droplet sizes were examined, it was determined that Nozzle 4 produced droplets in the coarse category, whereas the other nozzles generated droplets classified as fine (ANSI/ASAE S572.39). Considering the orifice diameters, it was theoretically expected that Nozzles 1 and 2 would produce larger droplets; however, at 300 and 400 kPa in particular, Nozzle 4 generated larger droplets compared with all other nozzles. This indicates that droplet formation is influenced not only by the orifice plate diameter but also by the internal design characteristics of the nozzles, which led to statistically significant differences. Indeed, even among nozzles with the same orifice plate diameter, differences in droplet size were observed (e.g., Nozzles 1 and 2 produced different droplet sizes at 400 and 500 kPa), while nozzles with different orifice plate diameters sometimes yielded statistically similar results (e.g., Nozzles 2 and 3 produced comparable droplet sizes at 400 and 500 kPa). These findings reveal that the droplet size distributions generated by the nozzles were not stable. Furthermore, the outcomes with agricultural pesticides and plant protection products (PPPs) that have different viscosities and surface tensions remain uncertain. The literature emphasizes that nozzle–pesticide interactions are of critical importance, and that not every nozzle is compatible with every pesticide formulation, with droplet size distributions being influenced by the characteristics of the formulation used (İtmeç et al., 2022). In this context, evaluations based solely on $DV_{0.5}$ values may not fully reflect the actual performance of nozzles, and both droplet size distribution characteristics and uniformity should also be taken into consideration.

Relative Span (RS) value is an indicator of the droplet spectrum, where higher RS values represent a broader range of droplet sizes produced by the nozzle (Wang et al., 2022). Through these data, the droplet spectra of unused nozzles were determined, thereby revealing the extent to which their designs were effective. As the RS value approaches 1, the droplets generated by the nozzle become more uniform in size, reflecting a more efficient nozzle design (Derksen et al., 2007). When the RS values of the nozzles at different operating pressures are examined, it is evident that Nozzle 1 exhibits relatively high RS values, indicating a wide droplet spectrum. In contrast, Nozzle 4 demonstrates considerably lower RS values, suggesting a narrower and more homogeneous droplet distribution; however, despite having a 1.2 mm orifice diameter, it produces larger droplets compared with the other nozzles.

5. Conclusions

In this study, the performance of hollow cone nozzles was assessed in terms of flow rate, droplet size distribution, and spray quality under different pressures. Flow rates matched theoretical expectations, yet droplet size did not always align with orifice diameter, indicating the strong influence of internal design. Notably, Nozzle 4 consistently produced coarse droplets, while others generated finer sprays, and RS analysis showed marked differences in uniformity. These results demonstrate that nozzle selection should consider not only orifice size but also design features, droplet size distribution, and RS values. Importantly, the study highlights that nozzle designs developed without adequate R&D can yield non-uniform patterns, excessive drift, and poor coverage, reducing pesticide efficacy and limiting the effectiveness of pest control when the required droplet size is not achieved, while increasing environmental risks. Comprehensive R&D—integrating simulation, material testing, and field validation—is therefore essential. Since nozzle performance also varies with pesticide formulations of different viscosities and surface tensions, further research is needed. Overall, systematic evaluation of nozzle characteristics is critical to improve efficiency, reduce drift, and support sustainable plant protection.

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