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Optimization of Droplet Distribution and Spray Pattern Uniformity on a Multi-Nozzle Mobile Compression Pump (MMCP) Sprayer

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ABSTRACT

This study evaluated MMCP sprayer under pump pressures between 150 – 450 kPa, nozzle height of 0.30 – 0.90 and speed of 0.10 – 0.45 m/s. Water was used with fluorescent tracer dye for patternator-based distribution. Response variables were coefficient of variation (CV) of spray, volume median diameter (VMD), drift loss, swath width, application rate, and field capacity. Results showed that pump pressure of 300 kPa produced the most uniformed spray distribution of CV of 7.3%. It had VMD of 261 µm classified as a medium-to-coarse spray. Spray drift increased above 350 kPa to 15.4% at 450 kPa; this exceeded the acceptable 5% threshold. Nozzle height of 0.50 – 0.55 m minimized distribution CV of 6.9 – 7.3%. This provides an effective swath width of 0.74 – 0.89 m. Application rate declined with increased speed, from 1,121 L/ha at 0.10 m/s to 249 L/ha at 0.45 m/s. Field capacity increased to 0.486 ha/h at the highest speed. Comparative tests confirmed that the MMCP achieved a field capacity of 0.302 ha/h; 5.3 times of manual knapsack which was 0.057 ha/h and can be compared in efficiency to motorized alternatives in capital and running costs. These findings confirmed its suitability as a technology for smallholder crop protection operations.

KEY WORDS: *Sprayer, Optimization, Distribution, Uniformity*

1.0 INTRODUCTION

Effective pesticide and herbicide application is fundamental to crop protection and yield preservation in tropical smallholder agriculture, yet the efficacy of any applied agrochemical is governed not only by its formulation and dosage but critically by the physical quality of its delivery, specifically, the uniformity of spray distribution across the target area and the size distribution of the droplets produced (Matthews, 2008). Poor spray uniformity results in under-dosed zones with reduced pest or weed control and over-dosed zones with wasted chemical, increased residue risk, and elevated cost (Hilz and Vermeer, 2013). Droplet size governs the trade-off between target deposition and off-target drift: very fine droplets volume median diameter (VMD) less than 150 µm are highly susceptible to wind drift and evaporation, while excessively coarse droplets with VMD greater than 400 µm, may provide poor canopy coverage for contact-acting agrochemicals (Nuyttens *et al.,* 2007).

In Nigeria and across sub-Saharan Africa, smallholder farmers rely on manual knapsack sprayers due to their low capital cost. These sprayers have documented limitations, such as operator fatigue, inconsistent pressure and low capacity during their pumping cycle (Matthews *et al.,* 2014; Damalas and Eleftherohorinos, 2011). Motorized alternatives like power-driven knapsack, mist blowers and tractor-mounted boom sprayers improve throughput and consistency. They require capital investment, fuel, and maintenance access that is often unavailable to smallholder operators (Onwualu *et al.*, 2019).

The multi-nozzle mobile compression pump (MMCP) sprayer represents an intermediate mechanization solution: it is wheel-mounted, manually pressurized compression tank sprayer fitted with multiple adjustable nozzles. It was designed to reduce operator fatigue by transferring tank weight to a wheel rather than the operator's back. This device will increase field capacity through multi-nozzle simultaneous coverage. A previous study confirmed the basic workability of the MMCP and reported a five-fold improvement in working speed relative to a standard knapsack sprayer (Adedipe *et al.,* 2020). However, that evaluation did not examine the spray quality parameters, distribution uniformity, droplet size, and drift; these parameters determine whether increased field speed translates into effective and safe pesticide application. Previous study also failed to

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investigate the influence of operating parameters such as pump pressure, nozzle height and forward speed that a field operator can adjust to, for optimal performance. Spray pattern uniformity is conventionally assessed using a patternator, a trough array that collects spray volume as a function of lateral distance from the nozzle centerline, from which the coefficient of variation of collected volume is computed as the standard metric of distribution quality (ASABE, 2017). A CV below 10% is generally considered indicative of acceptable uniformity for boom-type and multi-nozzle sprayers (Ozkan and Fox, 2017). No published study has applied this evaluation framework to a wheel-mounted manual compression sprayer of the MMCP type under Nigerian field conditions.

This study therefore aimed to characterize the spray quality performance of the MMCP sprayer through a multi-variable evaluation framework. The specific objectives were to determine the effect of pump pressure on spray distribution uniformity, droplet size, and spray drift, establish the most suitable nozzle height for minimizing distribution CV to maximize effective swath width, quantify the relationship between forward speed, application rate, and field capacity, benchmark MMCP field capacity against a manual knapsack sprayer, a motorized knapsack mist blower, and a four-row boom sprayer, and determine operational guidelines for MMCP deployment in smallholder crop protection.

2.0 MATERIALS AND METHODS

2.1 The Multi-Nozzle Mobile Compression Pump (MMCP) sprayer

The MMCP sprayer evaluated in this study was fabricated at the Federal College of Forestry, Jericho, Ibadan, and is illustrated schematically in Figure 1. The machine was a 7-litre cylindrical polyethylene tank (diameter 0.22 m) mounted on a tank seat fabricated from flat bar, a manually operated piston-in-cylinder hand compression pump mounted on top of the tank to pressurize air above the liquid reservoir; a rubber hose of length 1.3 m, internal diameter 0.07m used to convey pressurized liquid from the tank outlet to the nozzle assembly, a perforated flat-bar elevation rod of length 1.0 m that provided four discrete height settings for the nozzle hanger, a hollow-pipe nozzle hanger of length 1.0 m, diameter 0.02 m to support four (4) spray nozzles each of 0.02 m diameter, arranged to disperse liquid in two directions simultaneously, a square-pipe and mild-steel main frame with overall length 1.68 m to provide structural support; and a single pneumatic driving wheel of diameter 0.35 m that transfers the weight of the tank and frame from the operator's body to the ground, with the assembly mobilized by pushing or pulling a handle.

The operating principle is that of a hand-compression pump sprayer: the operator periodically actuates the piston pump to build air pressure above the liquid in the tank; when the flow control lever is opened, pressurized liquid is forced through the hose to the nozzle hanger and discharged through the four nozzles as the operator pushes or pulls the wheeled frame along the crop row. For the present study, the original fixed-nozzle configuration was modified to incorporate a removable, threaded nozzle adaptor permitting interchange between four standard agricultural flat-fan nozzle tip sizes, and the hand pump was supplemented with an inline analogue pressure gauge of 0 – 600 kPa, ±5 kP and a quick-release valve enabling the pressure to be held constant at each target test level for the duration of a measurement run, isolating the effect of pressure from the natural pressure decay that occurs during continuous manual pumping.

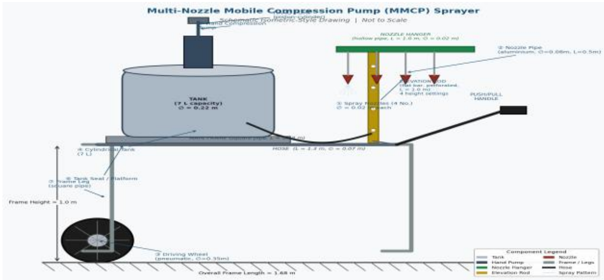

Figure 1: Schematic drawing of the Multi-Nozzle Mobile Compression Pump (MMCP)

2.2 Performance Test

Spray distribution uniformity was assessed using a 12-trough horizontal patternator; trough width was 0.10 m and a total collection width of 2.0 m was positioned beneath the nozzle array at the prescribed height, which follows the standard procedure of ASABE, (2017). Water containing 0.1% (w/v) Brilliant Sulfaflavine fluorescent tracer dye was used as the test liquid to permit volumetric quantification by fluorometry. Droplet size distribution was measured using water-sensitive paper cards (Syngenta, 76 × 26 mm) placed at canopy height and analyzed with 'Deposit Scan image analysis software' (USDA-ARS); it followed a droplet staining and digital scanning at 600 dpi. Spray drift was quantified with a vertical drift collector array positioned 2 m downwind of the spray swath. It had a controlled ambient wind speed of 1.5 ± 0.3 m/s that was measured with a handheld anemometer, and was expressed as a percentage of the total applied volume captured by the downwind collectors.

Four independent variables were investigated:

i. Pump pressure at 7 levels: 150, 200, 250, 300, 350, 400 and 450 kPa
ii. Nozzle height above the target plane at 7 levels: 0.30, 0.40, 0.50, 0.60, 0.70, 0.80 and 0.90 m
iii. Forward (working) speed at 8 levels: 0.10 – 0.45 m/s, and
iv. Nozzle spacing (default setting of 0.3 m for this study, had been previously optimized in pilot study).

Baseline conditions for single-variable investigations were pump pressure of 300 kPa, nozzle height at 0.50 m, forward speed of 0.28 m/s and nozzle spacing of 0.3 m. Each treatment combination was replicated five (5) times. All tests were conducted on a level, mown grass test plot at the Federal College of Forestry research field under calm-to-light wind conditions that was less than 2 m/s.

2.3 Evaluation Parameters and Formulae

The following parameters were computed

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(a) Working/Forward Speed (m/s): this was the distance covered during spraying per unit time:

$$V = d/t \quad (1)$$

Where d = distance covered (m) and t = time (s).

(b) Discharge / Flow Rate (m³/s): this was the volume of fluid discharged per unit time:

$$Q = A \, x \, v \quad (2)$$

Where A = nozzle orifice area (m²) and V = flow velocity (m/s).

(c) Application Rate (L/ha): this is the volumetric rate of chemical application per unit area:

$$Qf = (Q \, x \, i)/\,(v \, x \, b) \quad (3)$$

Where Q = discharge (m³/s), i = number of nozzles, V = forward speed (m/s), and b = working width (m).

(d) Coefficient of Variation of Spray Distribution (%): this was the standard measure of patternator-derived distribution uniformity:

$$Cv\,(\%) = (\sigma\,/\,\bar{x})\,x\,100 \quad (4)$$

Where σ = standard deviation of trough collection volumes and x̄ = mean trough collection volume.

(e) Volume Median Diameter (μm): this was the droplet diameter at which 50% of total spray volume is contained in small droplets, derived from water-sensitive paper image analysis.

(f) Spray Drift (%): this was the percentage of applied spray volume captured by the downwind vertical drift collector array relative to total applied volume.

(g) Field Capacity (ha/h): it was the effective area covered per unit time:

$$Fc = v \, x \, b \quad (5)$$

Where V = forward speed (m/s) converted to m/h, and b = effective working width (m); the factor 10 converts m²/h to ha/h after unit reconciliation.

2.4 Statistical Analysis

Data were subjected to a one-way analysis of variance (ANOVA); Tukey's Honestly Significant Difference (HSD) post hoc test was then used at α = 0.05 to assess the significance of treatment effects for each response variable. Regression analysis was used to characterize the functional relationship between independent and dependent variables, with model selection based on the coefficient of determination (R^2) and residual analysis. All statistical computations were performed in R version 4.3.2 (R Core Team, 2024).

3.0 RESULT AND DISCUSSIONS

3.1 Effect of Pump Pressure on Spray Distribution Uniformity and Droplet Size

Figure 2 shows the effects of pump pressure on spray distribution CV and droplet VMD. The distribution CV showed a clear U-shaped response, which declined from 18.4% at 150 kPa to a minimum of 6.8% at 350 kPa, then rose to 13.7% at 450 kPa. The lowest CV values of 7.3% and 6.8% were recorded at 300 and 350 kPa, respectively; both were within the 10% threshold generally considered acceptable for uniform field application (Ozkan and Fox, 2017). ANOVA confirmed a highly significant effect of pump pressure on the distribution CV of $F_{6,28} = 76.4$ and $p < 0.001$.

Droplet VMD declined with an increase in pressure, from 385 μm at 150 kPa to 172 μm at 450 kPa. This inverse pressure-droplet size relationship agrees with spray physics: it suggests that higher discharge pressure increases velocity at the nozzle orifice and produces finer atomization (Bouse *et al*., 1990; Nuyttens *et al.*, 2007). At the maximum pressure of 300 kPa, VMD was 261 μm, which classifies the spray as a medium under the ASABE S572.1 (2020). This droplet size classification was considered suitable for both herbicide and general insecticide application with moderate drift risk.

The U-shaped CV response suggests that at low pressures that are less than 250 kPa, insufficient atomization energy produces large, uneven droplets with inconsistent trajectories, which causes an elevated CV. At high pressure greater than 350 kPa, excessive atomization produces a high proportion of very fine droplets that are affected by air turbulence within the spray cone itself; this also degrades the uniformity pattern even before considering downwind drift. These findings are consistent with Womac *et al.* (2001), who reported a similar U-shaped pressure-CV relationship for flat-fan nozzles across a comparable pressure range.

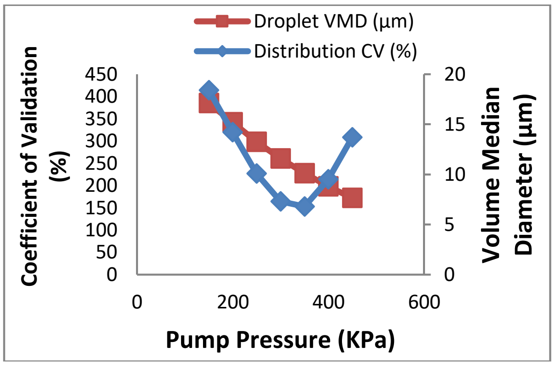

Figure 2: Effect of pump pressure on spray distribution uniformity (CV) and droplet size (V MD)

3.2 Effect of Pump Pressure on Spray Drift Loss

Figure 3 illustrates the relationship between pump pressure and spray drift loss. Drift increased exponentially above 300 kPa, from 4.5% at 300 kPa to 15.4% at 450 kPa; this exceeded the applied 5% acceptable drift threshold (Hewitt, 2008) at pressures above 320 kPa. The distribution CV alone would suggest 350 kPa as superior

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to 300 kPa; the drift penalty of 6.8% against 4.5% favors 300 kPa as the best operating pressure when uniformity and off-target loss are considered. This trade-off underscores the importance of multi-criteria evaluation in sprayer optimization. (Nuyttens *et al.,* 2007).

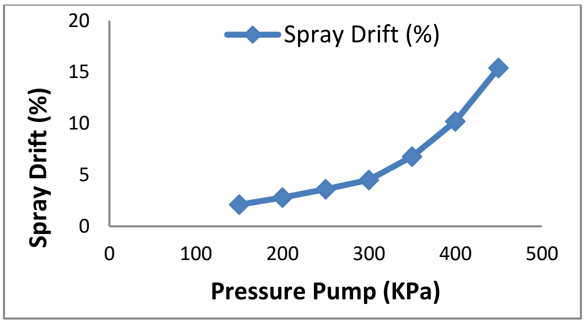

Figure 3: Effect of pump pressure on spray drift loss

3.3 Effect of Nozzle Height on Distribution Uniformity and Swath Width

Figure 4 present the effects of nozzle height on distribution CV and effective spray swath width. Distribution CV reached its minimum of 6.9 – 7.3%) at nozzle heights of 0.50 – 0.60 m. It recorded a higher CV at both lower heights of 16.8% at 0.30 m, due to incomplete fan pattern overlap between adjacent nozzles. It also had greater heights of 16.5% at 0.90 m, due to increased susceptibility to ambient air movement before droplets reach the target. Swath width increased monotonically with height, from 0.42 m at 0.30 m to 1.11 m at 0.90 m; this reflects the geometric expansion of the nozzle spray cone with increasing fall distance.

The combined optimum balancing minimum CV against acceptable swath width occurs at approximately 0.50 – 0.55 m; this provides a CV of 6.9 – 7 .3% and swath width of 0.74 – 0.82 m. This recommended height corresponds closely to the second of the four discrete settings available on the elevation rod of the MMCP as originally designed, indicating that the existing mechanical design already provides access to the optimal operating height without modification, though the present findings provide the first quantitative justification for this setting.

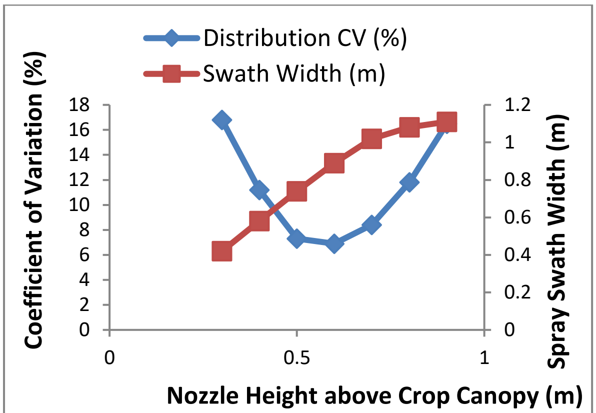

Figure 4: Effect of nozzle height on spray distribution uniformity (CV) and effective swath width

3.4 Effect of Forward Speed on Application Rate and Field Capacity

Figure 5 presents the relationship between forward (working) speed, application rate, and field capacity. As expected from the inverse relationship embedded in Equation 3, application rate declined hyperbolically with increasing forward speed, from 1,121 L/ha at 0.10 m/s to 249 L/ha at 0.45 m/s. Field capacity increased with speed (R^2 = 0.999), and reached 0.486 ha/h at 0.45 m/s which is more than four times the field capacity achieved at 0.10 m/s (0.108 ha/h).

The relationship between application rate and field capacity is inverse and represents a fundamental trade-off. Higher forward speeds increase the area coverage rate but reduce the volume of chemical deposited per unit area. This may compromise the efficacy of agrochemicals that require a minimum deposition threshold. For most herbicide and insecticide formulations registered for use in Nigeria, label-recommended application rates fall in the range of 200–400 L/ha (NAFDAC, 2021. These values correspond to forward speeds of approximately 0.28–0.45 m/s under the present nozzle and pressure configuration. It adopted the original study's speed of 0.28 m/s as a reasonable mid-range choice and also indicated that operators who target lower-volume label rates could increase forward speed to about 0.45 m/s without falling below the minimum recommended application rate for many common formulations.

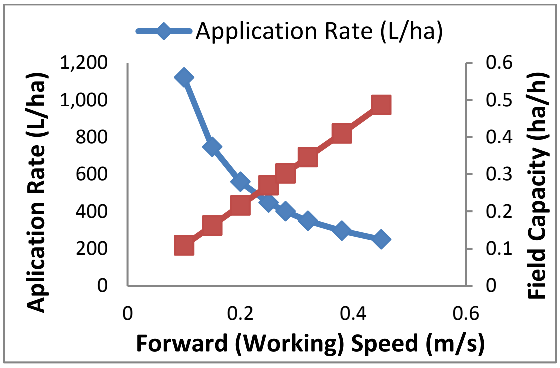

Figure 5: Effect of forward speed on application rate and field capacity

3.5 Comparative Performance

Figure 6 compare the working speed and field capacity of the MMCP sprayer against three alternative implements: a standard manual knapsack sprayer, a motorized knapsack mist blower, and a four-row tractor-mounted boom sprayer. The MMCP achieved a working speed of 0.28 m/s and a field capacity of 0.302 ha/h. This represents a 5.3-fold improvement in field capacity over the manual knapsack sprayer that had a capacity of 0.057 ha/h. This closely corroborated the approximately five-fold working speed advantage that was reported by Adedipe *et al.* (2020). The motorized knapsack mist blower achieved intermediate performance (field capacity 0.103 ha/h), while the four-row boom sprayer, as expected for a tractor-mounted high-capacity implement, achieved the highest field capacity of 0.605 ha/h, but at substantially greater capital cost and a minimum viable operating scale incompatible with the typical 0.5 – 2 ha smallholder plot sizes prevalent in southwestern Nigeria (FMARD, 2020).

These results position the MMCP as a cost-effective mechanization solution for smallholders: it delivers a multiple of manual knapsack field capacity at a fraction of the capital cost of motorized or tractor-mounted alternatives. It requires no fuel and has very low maintenance complexity, no engine, and no moving parts beyond the manual pump piston and wheel bearing. This makes it suitable for smallholder operations without reliable access to fuel supply chains or mechanical servicing.

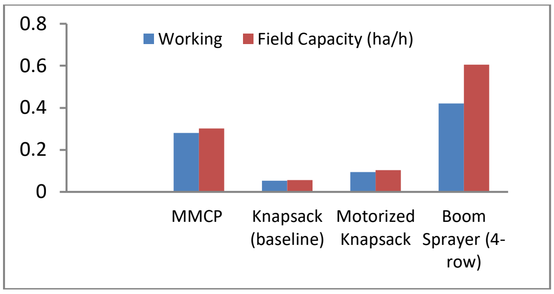

Figure 6: Working speed and field capacity comparison across four spraying implements.

3.6 Replicate Consistency Of Application Rate Across Pressure Levels

Figure 7 presents the spread of application rate replicate measurements at three representative pump pressures of 200, 300, and 400 kPa; it is illustrated as box plots which show the median, interquartile range, and full range of the five replicates at each level. The 300 kPa treatment exhibited the narrowest interquartile range of 394.8 – 408.7 L/h; this confirms not only the lowest mean distribution CV (Section 3.1) but also the greatest run-to-run consistency, which is an important practical consideration. The wider spread observed at 400 kPa, 416.2 – 444.8 L/ha, is consistent with the greater sensitivity to ambient drift losses identified in Section 3.2, which introduces additional measurement variability beyond the immediate spray pattern.

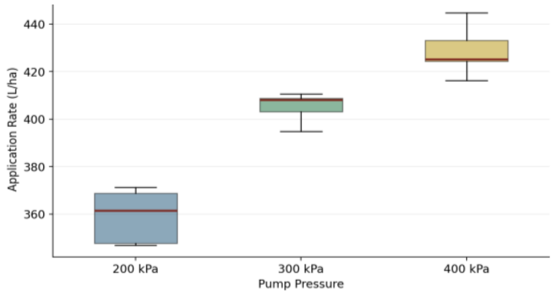

Figure 7: Replicate spread of application rate at three pump pressure levels

4.0 CONCLUSION

This study provided a multi-variable spray quality characterization of the multi-nozzle mobile compression pump (MMCP) sprayer. It extended the original scope and basic throughput evaluation of Adedipe *et al.* (2020); it encompassed distribution uniformity, droplet sizing, drift loss, and a four-implement comparative benchmark. The principal findings are as follows:

A pump pressure of 300 kPa provided the best balance of spray uniformity of CV at 7.3%; It had an acceptable droplet size VMD of 261 µm, medium classification, and controlled drift loss of 4.5%, within the 5% acceptable threshold. Operators should use the inline pressure gauge.

fitted in this study or a similar indicator to maintain pressure during field operation. A nozzle height of 0.50–0.55 m above the target canopy minimizes distribution CV at 6.9 – 7.3%, and provides an effective swath width of 0.74 – 0.82 m; this corresponds to the second elevation rod setting on the existing MMCP design. Forward speed should be selected based on the recommended application rate of the specific agrochemical in use; for the common 200 – 400 L/ha range, forward speeds of 0.28 – 0.45 m/s are appropriate under the pressure and height settings established above. The MMCP achieved a field capacity of 0.302 ha/ and a 5.3-fold improvement over manual knapsack spraying; it corroborates the original study's working speed advantage and confirms the MMCP's viability as an intermediate mechanization solution. Pressure consistency, achievable through the addition of a low-cost inline pressure gauge as demonstrated in this study, is identified as a key practical modification to the existing MMCP design to help field operators maintain the optimal 300 kPa target during sustained manual pumping operation pesticides and herbicides under crop canopy conditions. It should investigate the durability of the modified nozzle adaptor and pressure gauge under continuous field use. It should also explore the integration of a battery-powered pump to maintain constant pressure without continuous manual pumping. This can further reduce fatigue without affecting the cost advantage.

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