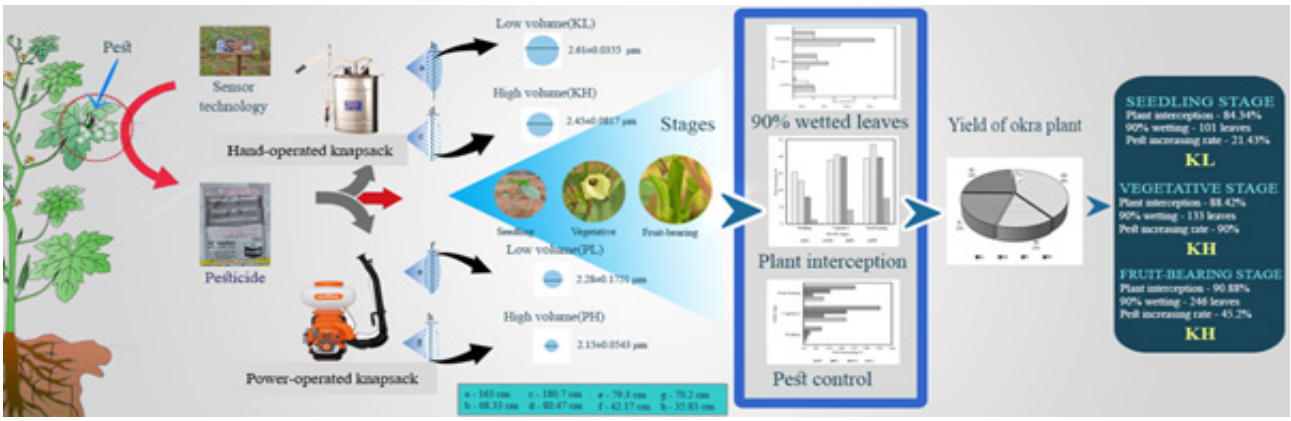
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RESEARCH ARTICLE

Optimizing Spray Volumes of Different Spraying Devices Under Controlled Conditions for *Abelmoschus esculentus* (Okra) Cultivation: A Scientific Exploration Towards Automation in Spraying

N. Mayuresh, S. Loveciya and N. Kannan

Graphical Abstract



Highlights

- Hand-operated high-volume sprayers achieved superior plant coverage and pest control
- Effective pest management depended on wetting efficiency; hand-operated sprayers excelled
- Okra pods under hand-operated high-volume treatment were longest, indicating better plant health
- Power-operated sprayers yielded less due to reduced efficacy in pest control

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RESEARCH ARTICLE

Optimizing Spray Volumes of Different Spraying Devices Under Controlled Conditions for *Abelmoschus esculentus* (Okra) Cultivation: A Scientific Exploration Towards Automation in Spraying

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Abstract

Spraying is one of the important techniques to control pest infestation in vegetable fields. Improper pesticide application leads to chemical wastage and ineffective pest control, causing environmental pollution and ultimately reducing crop yield. To overcome these issues and to suggest suitable spraying techniques for particular growth stages of *Abelmoschus esculentus* **(**okra), a comprehensive field experiment was planned. Four different spraying techniques using hand-operated knapsack sprayers and power-operated knapsack sprayers: hand-operated knapsack low-volume (KL), hand-operated knapsack high-volume (KH), power-operated knapsack low-volume (PL), and power-operated knapsack high-volume (PH), were used with the incorporation of sensor technology to identify the pest and suitable pesticides. Major differences in droplet sizes among the treatments KL, KH, PL, and PH were 2.6±0.03 µm, 2.4±0.08 µm, 2.3±0.17 µm, and 2.1±0.05 µm, respectively. The results showed that treatment KL outperformed the other treatments at the seedling stage, and treatment KH was the optimal choice for the vegetative and fruit-bearing stages of okra for plant infestation and 90% wetting. The highest pest infestation was observed during the vegetative stage. Yield performance was induced by treatment KH, with the longest average pod length at 23.2±0.37 cm. Overall, with the advantages of plant interception, environmental loss, plant height, and pest infestation level, the KH more effectively supported all stages of okra development. The findings of this study emphasized a suitable spraying technique for each growth stage of okra with minimum environmental loss by incorporating sensors. The use of technology in basic agricultural activities is highly expected; thus, these findings will be useful for agricultural experts, farmers, and researchers in promoting eco-friendly and sustainable agriculture by minimizing chemical usage through precision pest management.

Keywords: Automation; Okra; Optimization; Spray volume; Sprayer

INTRODUCTION

Humanity faces a significant problem in ensuring food security for a rapidly growing population, which grows at a rate of 1.05% per year by 2020 (Kousar et al., 2021). According to a recent study by the Food and Agriculture Organization of the United Nations, between 702 and 828 million people globally suffer from hunger, with approximately 2.31 billion people or one in three, experiencing severe food insecurity (FAO et al., 2022). Agriculture plays a vital role in the economic growth of developing nations, especially Sri Lanka. However, agricultural production is struggling to keep up with population growth, despite occupying over 5 billion hectares, which is 38% of the total land area (Moncayo, 2021). In Sri Lanka, this figure stands at 45.46% (FAO, 2023). Pests and diseases further worsened this problem, reducing crop yields by about 20 - 40% annually (Gemede et al., 2015), leading to significant losses and threatening food security (He et al., 2023).

Moreover, vegetables are particularly vulnerable to pest attacks, leading to a 25 - 30% reduction in yield, higher compared to fruits at 5 - 15% and orchards at 1 - 5% (Sharma et al., 2017). According to Dhandapani and Brann (2003), brinjal shoot and fruit borer (*Leucinodes orbonalis*) causes up to 70 - 75% losses in brinjal, while the cabbage diamondback moth (*Plutella xylostella*) and the

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cabbage butterfly lead to 52% and 40% in cabbage yields, respectively (Ali & Rizvi, 2007; Krishnamoorthy et al., 2004). Additionally, Choudhury et al. (2021) observed a 35% reduction in okra due to the okra shoot and fruit borer (*Earis vitelli*). Moreover, Kumaran & Joel Karunakaran (2007) noted losses of 7 - 48% from red spider mites. Furthermore, Dhandapani and Brann (2003) highlighted that tomato fruit borer (*Helicoverpa armigera*) caused losses of 50 - 80% in tomatoes.

At this juncture, okra, known for its versatility in culinary applications and nutritional value, faces severe pest infestations throughout its growth stages (Bhutto et al., 2017), due to whitefly (*Bemisia tabaci*), aphid (*Aphis gossypii*), and leafhopper (*Amrasca biguttula biguttula*), causing yield losses of 94%, 54%, and 40 - 88%, respectively (Singh et al., 2023). The literature related to standard spraying techniques to control different pests with minimum environmental impact is still at the developing stage. Therefore, there is a need to study the effective pest control mechanism using different spraying techniques. Approximately 13% of total pesticides play a vital role in safeguarding vegetables from pests and diseases (Chavan et al., 2022). However, excessive pesticide use can lead to biodiversity loss, environmental contamination, and human health issues. Only about 3% of applied pesticides reach their target. The rest is lost to the environment, where dispersion into water is relatively higher than into soil or air (Li et al., 2019). Additionally, pesticide applications are done by different methods: spraying, dusting, basal, foliar, band, and soil application. Among these, spraying is the most commonly used technique (Dhananjayan et al., 2020).

Sensor-based technology can effectively identify pests and recommend the appropriate pesticide, thereby reducing misuse and enhancing efficacy (Azfar et al., 2018).

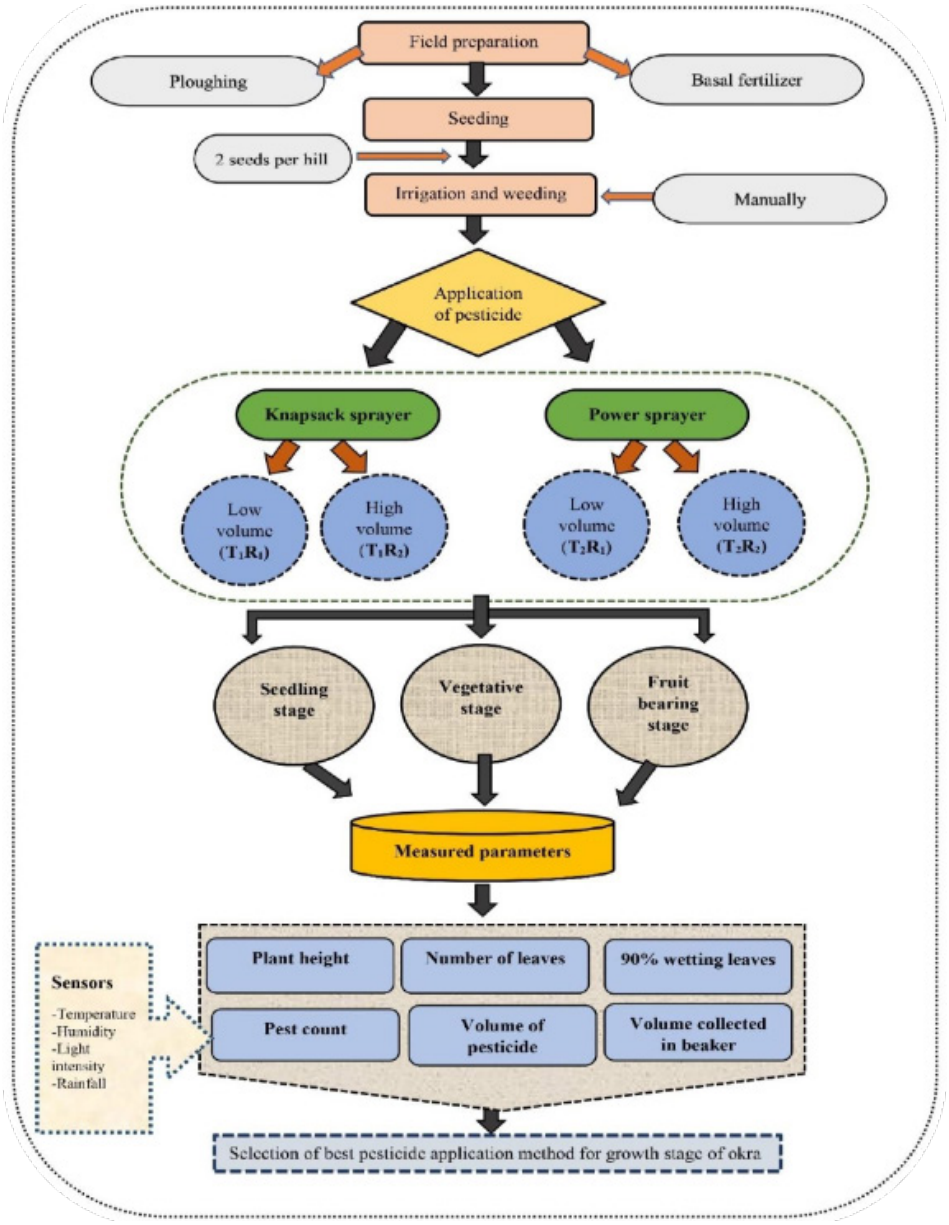


Figure 1: Research design and experimental procedure

The existing studies on spraying techniques with the incorporation of sensor-based technology are emerging recently. However, there is still limited experimental evidence linking sensor-based pest identification with the performance of commonly used spraying techniques under different spray volume conditions. This lack of comparative evaluation restricts the ability to recommend efficient spraying strategies that balance pest control efficacy with environmental safety. Therefore, this study was carried out to generate new knowledge on the application of sensor-based pest identification integrated with effective spraying techniques. Additionally, Low-Volume Spraying (LVS) and High-Volume Spraying (HVS) represent two distinct methods of pesticide application, differing in the amount of spray combination (water + agrochemical) delivered per unit area (Michael et al., 2022). The hand-operated knapsack is a standard device (Ahmad et al., 2021), while the power-operated knapsack sprayer and Unmanned Aerial Vehicle (UAV) offer more modern and automated alternatives (Ajayi et al., 2016).

Although there are existing studies available related to vegetable crops in Sri Lanka, data on okra are set to remain very weak. Therefore, it is essential to emphasize the use of pesticides using appropriate spraying techniques. This study was set to evaluate the performance of the hand-operated knapsack and power-operated knapsack sprayer under controlled conditions (LVS and HVS) for okra plants. Since there is limited literature related to this reported so far, this research seeks to optimize conditions for power-operated knapsack sprayer (LVS and HVS) and hand-operated knapsack sprayer (LVS and HVS) by investigating the interaction between pest control methods and environmental impacts. Moreover, advanced automated research has been conducted to facilitate the selection of sprayers for effective chemical application in controlling pests in okra fields.

METHODS

The procedures that were used for these experimental arrangements are shown in Figure 1. All these blocks, indicated in Figure 1, have been discussed systematically.

The study was carried out with a comprehensive set of instruments and materials intended to ensure precision and accuracy in collecting information and analysis. Hand-operated knapsack sprayer (Brand: Hayspray, made in Sri Lanka) and power-operated knapsack sprayer (Brand: DBL, made in Sri Lanka) were procured from the Department of Agricultural Engineering, Faculty of Agriculture, University of Jaffna, which were the principal spraying instruments, allowing insecticides to be applied at varied volumes and pressures. Farm machinery: A tine tiller and rotavator were used for initial land preparation. Traditional agricultural equipment: a mamoty was used to prepare the soil for planting. *Imidacloprid* ($C_9H_{10}ClN_5O_2$) and *Virtako* ($C_{18}H_{14}BrCl_2N_5O_2$ + $C_8H_{10}ClN_5O_3S$), which were bought from Green Agriculture and Consultant Services Pvt., Ltd, Kilinochchi, were the most often used insecticides due to their efficacy against a variety of pests in okra.

Precise measurements of plant growth parameters were obtained using a measuring tape. Plant height, stem length, and canopy spread were measured. Irrigation was done using water buckets and a rubber hose. Sensors: temperature and humidity (DHT11), pressure (BMP180), light intensity (LDR), and raindrops were used for real-time pest identification and were purchased from *Skytronic* Kohuwala, Sri Lanka. Accurate measurements of liquids were taken using beakers (250 mL) and pipettes (5 mL and 10 mL). Polythene sheets were used to collect agrochemicals, which were left over in the plant and reached the environment from each plant. Chemically impervious gloves, boots, and facial masks were used as safety devices during the experimental period.

Field preparation

The study was conducted from April to July 2024 during a single cultivation season in a 20 × 19 square meter field, planted with the okra variety "MI 5" in Ariviyal Nagar, Kilinochchi, Sri Lanka (latitude: 9º19' 06" N, longitude: 80º23' 52" E, altitude: 47.3 m). The okra was planted with a spacing of 90 cm within rows and 90 cm between rows. The plants were assigned to four treatments as shown in Figure 2. The low and high-volume application rates for both hand-operated and power-operated knapsack sprayers were achieved by adjusting the trigger valve, as shown in Figure 3. Each treatment was replicated six times in a completely randomized design. Each replicate consisted of 3 rows × 5 plants. Prior to sowing, basal fertilizer, comprising 50 kg ha^{-1} of Urea, 195 kg ha^{-1} of TSP and 25 kg ha^{-1} of MOP, was applied to the field *(DOA, SL)*. The sowing process was carried out with precision. Two seeds per hill were placed, maintaining the above-mentioned spacing between the hills to provide sufficient room for each plant to grow and develop without competition for resources

This arrangement resulted in a total of 360 plants, which was slightly lower than the maximum possible (400 plants) due to the strategic placement of several bunds. These bunds served a dual purpose: facilitating navigation across the field and providing a clear distinction between different treatment areas. This study aimed to compare two primary treatments: the hand-operated knapsack and the power-operated knapsack sprayer. Each treatment was applied to half of the total plants, resulting in 180 plants per treatment. This division ensured a balanced comparison between the two sprayer types. The number of plants needed for each plot was calculated using Eq. 1 given below:

$$\text{Number of plants} = \frac{\text{Plot area } (m^2)}{\text{Spacing } (m^2)} \quad (1)$$

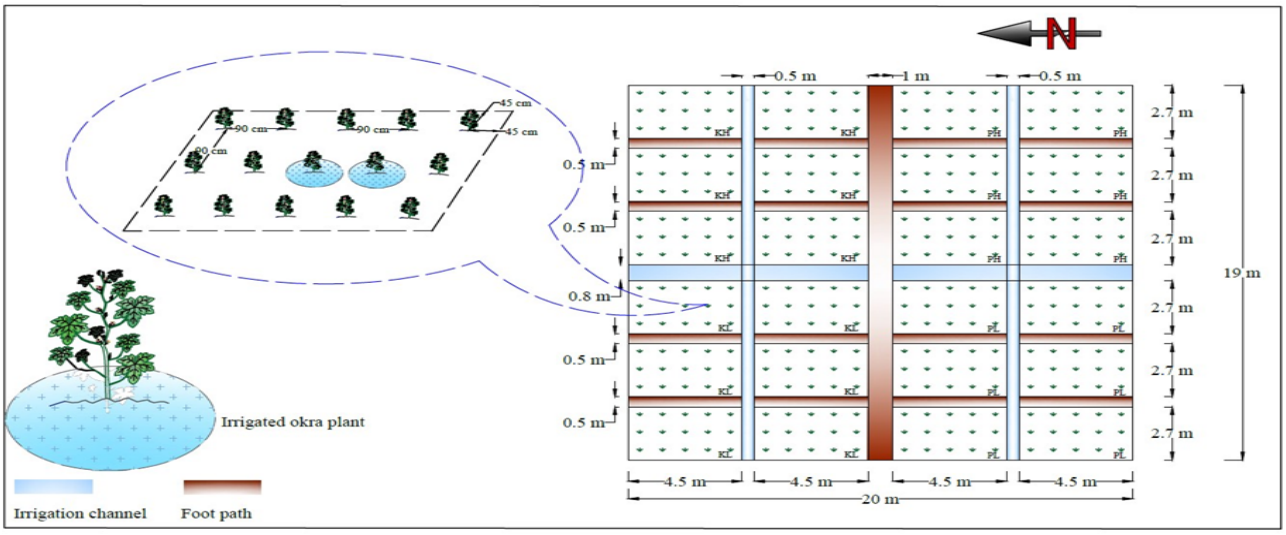


Figure 2: Experimental field layout (KL- Hand-operated knapsack low-volume, KH- hand-operated knapsack high-volume, PL- power-operated knapsack low-volume, and PH- power-operated knapsack high-volume)

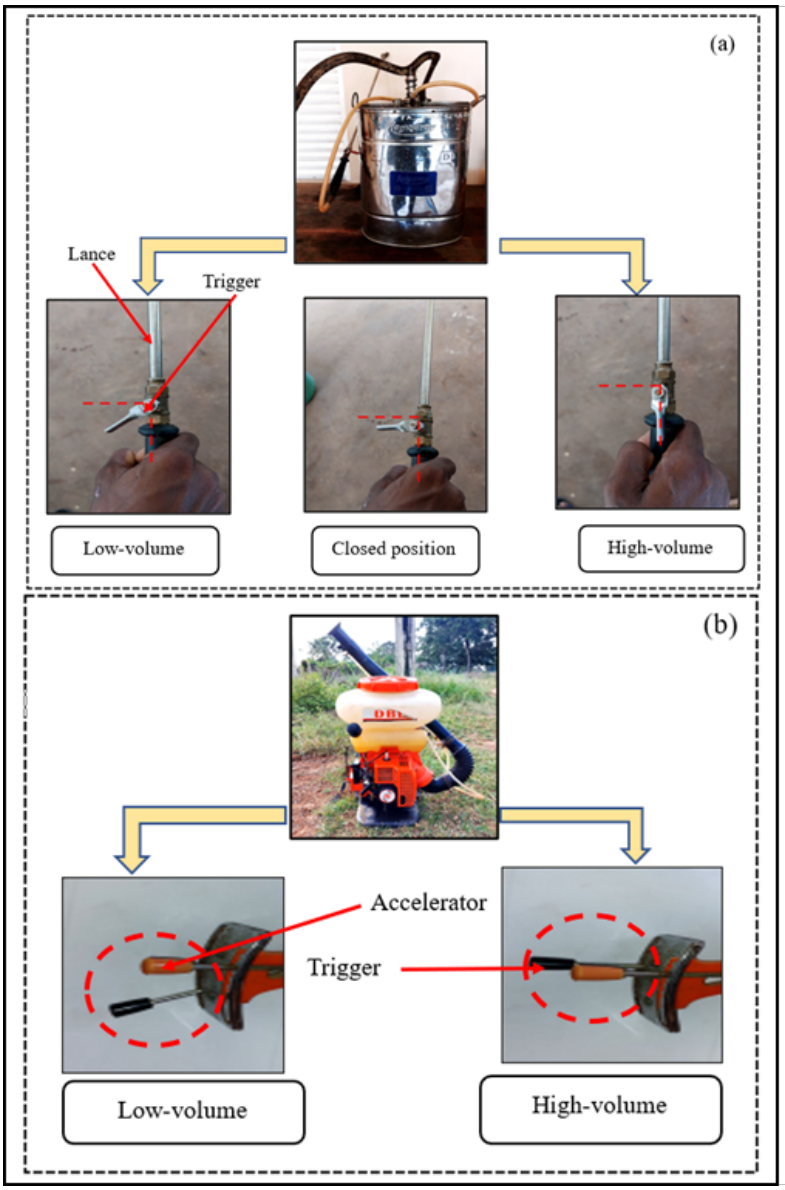


Figure 3: Low- and high-volume spraying methods: (a) Hand-operated knapsack sprayer; (b) Power-operated knapsack sprayer.

Agronomic practices

These practices were designed to optimize the growth conditions for the plant, ensuring a healthy crop and a bountiful harvest. During the seedling stage, when the young plants were most vulnerable, irrigation was primarily done using water buckets. Immediately after seedling emergence, thinning out was performed by removing excess seedlings and retaining one healthy plant per hill. In areas where seedlings failed to emerge, gap filling was carried out. As the plants matured and their water requirements increased, hose pipes were used for irrigation. The irrigation frequency was carefully adjusted according to the growth stages of the okra. Once the plants reached the vegetative stage, the irrigation interval was reduced to once daily. Following fruit emergence, watering was further reduced to once every two days, balancing the need for plants to prevent overwatering.

Furthermore, the weed-free condition was maintained throughout the growth period, promoting healthier plant growth and higher yields. Since young okra plants are sensitive to excess sunlight, teak tree leaves were used to provide shade. Urea and Muriate of Potash (MOP) were applied at 50 kg ha^{-1} and 25 kg ha^{-1} after 2 weeks of planting; 100 kg ha^{-1} and 50 kg ha^{-1} after 5 weeks of planting; and 100 kg ha^{-1} and 50 kg ha^{-1} after 8 weeks of planting, respectively.

Pesticide application

The walking speed during the operation was consistently maintained within the range between 0.7 ms^{-1} and 0.8 ms^{-1}. The application was carried out in the early morning from 5:45 a.m. to 6:45 a.m. during all three stages of the plant to take advantage of the low wind disruption and optimal conditions for spraying as advised by the Department of Agriculture (Department of Agriculture, 2002). Important environmental parameters: Temperature and humidity, light intensity, and pressure were accurately measured using sensor technology. This study included two types of sprayers as treatments: Hand-operated knapsack and power-operated knapsack sprayer, which were used for both low-volume and high-volume applications. These treatments were replicated across six plots, with each plot accommodating 90 okra plants, as depicted in Figure 2. This methodical procedure enabled a thorough evaluation of the efficiency of the sprayer in pesticide distribution under various environmental conditions.

Furthermore, the recommended dosage for the Active Ingredients (AI) was adhered to strictly, for *Imidacloprid* (30 g AI per hectare) and *Virtako* (80 g AI per hectare) (DOA, SL). In this study, the experimental area of 380 square meters (0.0380 hectares) was translated to 1.14 g of *Imidacloprid* and 3.04 g of *Virtako*. This careful approach has resulted in a final volume of 3.2 liters per plot. An electronic balance (Model: SF400) was used to measure the exact amount of chemicals precisely, ensuring a consistent application rate across all plots. Pesticide application by a hand-operated knapsack sprayer and a power-operated knapsack sprayer for the treatments: KL, KH, PL, and PH was given in Figure 4.

Measurements

The plant height was measured using a meter tape at three important stages of growth: Seedling, vegetative, and fruit-bearing. The number of leaves was manually counted at all three stages of the growth. The wetting percentage was observed manually by assessing the wetting of leaves with a target of achieving 90% wetting. Environmental loss was quantified by placing a polythene sheet around each plant, and the volume of pesticide that dripped off the leaves was measured. The environmental loss for each treatment was calculated by Eq. 2, given below:

$$E_{90} = \frac{E_{30}}{30} \times 90 \quad (2)$$

Where:

E_{90} - Environmental loss for 90 plants in each plot

E_{30} - Environmental loss for 30 random plants in each plot

Moreover, the amount of pesticide absorbed by each plot was calculated using Eq. 3 given below:

$$A = I_c - (E_{90} + T_b) \quad (3)$$

Where:

A - Plant absorption in each plot

I_c - Initial tank capacity

E_{90} - Environmental loss for 90 plants in each plot

T_b - Tank balance after the spraying operation

The pest count was measured using yellow sticky traps. Counts were taken before and after a three-day reading period, allowing for the calculation of the increasing rate of pests using Eq. 4 given below:

$$\text{Pest increasing } \% = \left(\frac{\text{Pest count}_{\text{Initial}} - \text{Pest count}_{\text{Final}}}{\text{Pest count}_{\text{Initial}}}\right) \times 100 \quad (4)$$

The walking speed, during spray, was calculated by dividing the total distance covered in one plot by the time taken, as shown in Eq. 5 below:

$$W_s = \frac{d}{t} \quad (5)$$

Where:

W_s - Walking speed of the operator

d - Total distance of the spraying operation

t - Total time taken for the spraying operation



Figure 4: Chemical spraying using (a) a hand-operated knapsack sprayer and (b) a power-operated knapsack sprayer.

The stopwatch (Brand: RECALL) was used to measure the nozzle reaction time with the plant. The horizontal and vertical reaches of each sprayer were measured by spraying at the recommended height of 50 cm above the plant canopy using a meter tape (DOA, SL). The droplet size for low and high-volume sprays from the hand-operated knapsack and power-operated knapsack sprayers was measured by adjusting the height between the nozzle and the plant. The nozzle height was kept constant at 50 cm, 40 cm, 30 cm, 20 cm, and 10 cm from ground level. The size of the droplet, when it left the nozzle, was then calculated using a digital vernier caliper (Model: E-PITA15).

The leaf area was calculated by measuring the length and width of the leaf from randomly selected plants from each plot and subsequently multiplying these dimensions by a species-specific coefficient for okra plants (0.62) at all three stages, as shown in Eq. 6 below:

$$LA = L \times W \times C \quad (6)$$

Where:

LA - Leaf area of the plant

L - Length of the leaf

W - Width of the leaf

C - Coefficient factor for okra

The initial and final volumes in the tank of the sprayers were measured using a measuring cylinder. The fuel consumption by the power-operated knapsack sprayer was measured by comparing the initial and final fuel levels. Finally, the size and diameter of the okra pod were measured using a digital vernier caliper for precise readings.

Data analysis

Data analysis was done by using SAS (version 9.4) and Excel (version 2017) statistical software. The results were used to analyze the effects of different spraying techniques used in this study

RESULTS AND DISCUSSION

Comparison of specifications between hand-operated and power-pperated knapsack sprayers

Table 1 outlines the fundamental features of the hand-operated knapsack sprayer and power-operated knapsack sprayer, used in this experiment, highlighting the important elements that influence their operational efficiency and suitability for various agricultural applications. These sprayers mainly differ in their power source, pressure, flow rate, and resulting spray distance, all of which are important to their functionality. Specifications of hand-operated and power-operated knapsack sprayers are given in Table 1 below.

Effect of pesticide application by different treatments at various growth stages of okra

Figure 5 (a) represents the plant interception percentages of four treatments: KL, KH, PL, and PH, at three different growth stages: Seedling, vegetative, and fruit-bearing. For treatment KL, the intercepted percentages across stages were 84.34%, 87.08%, and 87.51%, aligning closely with the range (78.8% to 83%) reported by Megahed et al. 2021. These results indicate that the treatment KL had a minimal effect on plant interception, which was consistent across all stages. Thus, from the outcome of this study and previously available literature, both suggest that hand-operated knapsack sprayers with lower volume caused an insignificant influence on the interception percentage across developmental stages.

Based on Figure 5 (b), a slight reduction in environment losses from 2.81% to 0.76% was observed from the seedling stage to the fruit-bearing stage. These values fall within the 3% margin reported by Franke et al. (2010) and was attributed to the increase in the canopy and leaf area as the plant grew (Street et al., 2007). In comparison, treatment KH showed an increase in plant interception percentage from 82.19% (seedling) to 90.88% (fruit-bearing), with consistently higher interception percentage than KL at the vegetative and fruit-bearing stages, driven by the greater spray volume and smaller (2.45 µm) droplet size (Butts et al., 2024). A similar pattern has been obtained by Michael et al. (2022), who observed higher interception for KH compared to KL. However, the changes in environmental loss remained steady, with deviations of only 2% across different growth stages, while KH showed slightly higher environmental loss but remained effective for pest control.

In contrast, treatment PL showed a sharp increase in the volume of pesticides captured from 78.4% at the seedling stage to 87.95% at the vegetative stage, showing better capturing efficiency during early plant growth stages (Namiki, 2022). However, environmental loss for PL increased from the vegetative to fruit-bearing stages, a phenomenon linked to the high pressure (72 psi) of the power-operated knapsack sprayer, which produced small droplets (2.28 µm) compared to 2.61 µm for KL and 2.45 µm for KH. This smaller droplet size increased pesticide release and environmental loss (Camara et al., 2008; Marangoni Junior & da Costa Ferreira, 2019). The smaller droplets led to increased plant interception, and the higher environmental loss for PL makes it less desirable compared to hand-operated knapsack sprayers.

Similarly, treatment PH showed a consistent increase in interception from72.94% (seedling) to 78.05% (fruit-bearing), but the environmental loss dropped from 10.65% at the seedling stage to 2.85% at the vegetative stage as depicted in Figure 5 (a). As described in detail previously by Wang et al., (2022) PH achieved a spray coverage starting at 70.12%, which is aligned closely with observations of this study.

Based on the evidence shown above, treatment KL outperformed at the seedling stage, achieving 84.34%interception and lower environmental loss (2.81%) compared to the other treatments. It is consistent with findings by Chen et al. (2013) and Holownicki et al. (2000). In the vegetative stage of okra, treatment KH showed a higher plant interception percentage (88.42%) and efficient pest control. Moving to the fruit-bearing stage, treatment KH showed the highest plant interception rate across all stages and lower environmental loss (0.38%) compared to other stages, as shown in Figures 5 (a) and (b). On the other hand, treatments PL and PH showed inefficiency as of lower plant interception rates (87.76% and 78.05%) and higher environmental loss (1.74% and 1.45%), confirming

Table 1: Comparison of hand-operated knapsack and power-operated knapsack sprayer specifications

Specification	Hand-operated knapsack	Power-operated knapsack
Power source	Manual	Engine
Capacity	16 liters	16 liters
Pressure	3 - 4 bar	5 - 25 bar
Flow rate	0.5 - 2 L min^{-1}	5 - 10 L min^{-1}
Spray distance	Vertical: 0.6 - 0.8 meters Horizontal: 1.6 - 1.8 meters	Vertical: 0.35 - 0.43 meters Horizontal: 0.7 - 0.8 meters
Weight	5 - 10 kg	9 - 12 kg
Mobility	Portable and carried in the back	Portable and carried in the back
Usage	Small to medium areas	Large areas
Cost	Relatively low	Higher than a hand-operated knapsack
Maintenance	Simple and less frequent	More complex
Noise level	Quiet	Noisy
Suitability	Small-medium farms	Large farms and orchards
Nozzle type	Wide variety	Limited
Operator fatigue	Higher due to manual pumping	Lower due to powered operation
Tank material	Stainless steel	Metal or heavy-duty plastic

that hand-operated knapsack sprayers (KL and KH) are more efficient than power-operated sprayers (PL and PH) (Hiremath et al., 2024).

Effect of pesticide application on different growth stages at 90% wetting percentage

The fraction of leaves that achieved 90% or greater wetting among 90 plants was analyzed manually for each treatment, along with different stages as shown in Figure 6. During the seedling stage, the treatment KL achieved a high degree (101 leaves) of wetting (Vashisth et al., 2020). However, in the vegetative stage, a 15% reduction in wetted leaves was observed, presumably due to increased canopy density, which limited spray penetration (Yang et al., 2014). Despite this reduction, the total leaf surface area increased (209.08±9.22 cm^2), resulting in a higher overall plant interception rate of 87.08%. Moreover, during the fruit-bearing stage, wetted leaves increased by 88% from the vegetative stage and 60% from the seedling stage. This increased wetting percentage was due to significant vertical growth, improving canopy penetration and creating more accessible leaf surfaces, resulting in an interception rate of 87.51% (Berland et al., 2017).

The analysis of the treatment KH across the okra developmental stages showed distinct foliar patterns. In the seedling stage, KH wetted more (99 leaves) with a plant interception rate of 82.19% due to the less dense canopy (Vashisth et al., 2020). In the vegetative stage, wetted leaves increased by 34% from the seedling stage. This improvement was attributed to the higher spray pressure (58 psi) and smaller droplet size (2.45 µm) of treatment KH, which increased coverage (Camara et al., 2008), simultaneously, the plant interception rate increased to 88.42%. On the other hand, KL showed a 15% reduction in wetted leaves during this stage due to lower spray pressure (29 psi) and larger droplet size (2.61 µm). In the fruit-bearing stage, wetted leaves increased by 85% from the vegetative stage and by 150% from the seedling stage (Berland et al., 2017). This significant increase was accompanied by a plant interception rate of 90.88%.

The treatment PL showed roughly a 25% increase in wetted leaves from the seedling to the vegetative stage, with a considerable increase in plant interception rate from 78.41% to 87.95% (Vashisth et al., 2020). However, from the vegetative to the fruit-bearing stage, the wetted leaves decreased by 7.5%, correlating with a slight drop in interception rate from 87.95% to 87.76%. This minor decrease can be explained by the characteristics of the PL, where the high air pressure (145 psi) caused the plants to bend and reduce capturing efficiency (Kouhen et al., 2023). Additionally, the particle size in PL was relatively larger (2.28 µm) compared to PH (2.15 µm). This phenomenon was further seen by Camara et al. (2008), who concluded that particle size reduced with the increasing pressure, which was analyzed using a laser particle analyzer.

On the other hand, treatment PH showed a 95% increase in wetted leaves from the seedling to the vegetative stage, with a rise in interception rate from 72.94% to 75.28% because of the lower efficiency at the seedling stage, resulting in low initial wetting (Singh et al., 2019; Vashisth et al., 2020). The number of wetted leaves from the vegetative to the fruit-bearing stage decreased by 5% in PH and 7.5% in PL due to the larger particle size (2.28 µm) compared to that of PH. Hence, the interception rate increased from 75.28% to 78.05% for treatment PH. This improvement can be attributed to the smaller droplet size (2.15 µm) in PH, which allows for better penetration and coverage within the denser canopy, resulting in high interception rates despite a slight decrease in wetted leaves.

Furthermore, these results indicate that during the seedling stage, the treatment KL had the highest plant interception rates compared to all other treatments, as shown in Figure 5 (a). Concurrently, the superior performance

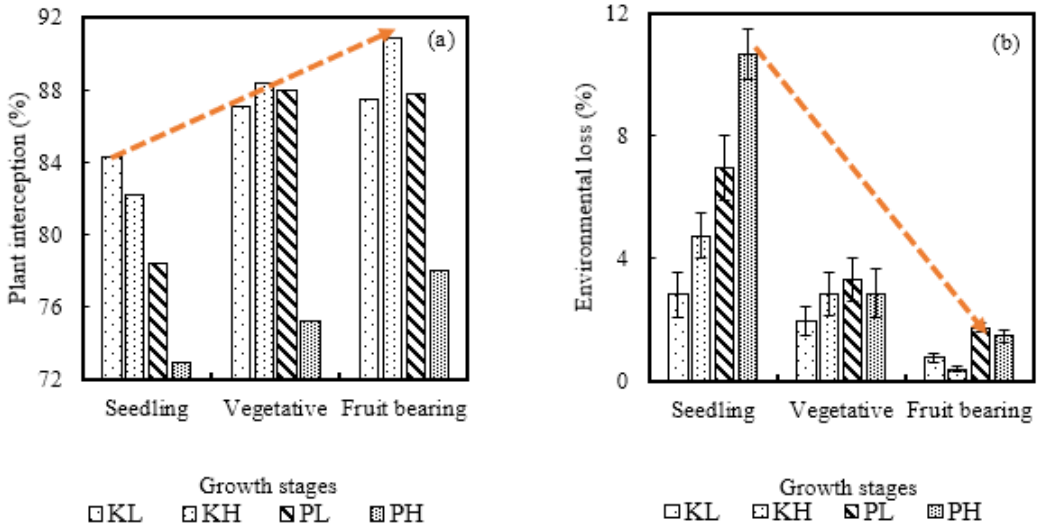


Figure 5: (a) Plant interception rate across different growth stages; (b) Percentage of environmental loss across growth stages. PH = Power-operated Hand sprayer, PL = Power-operated Low-volume sprayer, KH = Knapsack High-volume, KL = Knapsack Low-volume.

of KL, compared to KH, PL, and PH treatments during the seedling stage, is further confirmed by 90% wetting rates. This consistent trend is evidenced by Figure 5 (a), highlighting KL as the most effective treatment, followed by KH, PL, and PH in a descending order. Furthermore, treatment KH demonstrates a notable advantage during the vegetative and fruit-bearing stages, exhibiting the highest plant interception rates among all treatments as depicted in Figure 5 (a), with the superior 90% wetting performance during the vegetative and fruit-bearing stages as shown in Figure 6. A crucial factor in determining the ideal spraying technique for okra at every stage of growth is the measurement of 90% wetted leaves, which ensures maximal plant interception. This strategy promotes sustainable crop protection methods, lowers environmental losses, and improves the effectiveness of pesticide application.

Effect of pest infestation percentage at different growth stages of Okra

Figure 7 illustrates pest control evaluated by placing yellow sticky traps before and after three days of pesticide application. The graph indicates that overall pest attack peaked during the vegetative stage, a common scenario due to the production of more leaves and a denser canopy, which provides a larger and more favorable habitat for pests (Mesmin et al., 2019). This was followed by the fruit-bearing stage, with much lower pest attacks observed during the seedling stage. It is further seen by Sarjan et al. (2021), who reported peak pest attacks on potatoes at the vegetative stage. The treatment KL initially resulted in a 21.43% increase in pest population during the seedling stage.

However, as plants progressed to the vegetative stage, a substantial increase in pest population (176.19%) was observed. This was partly due to 15% reduction in wetted leaves at the vegetative stage. Furthermore, the plant interception rate increased from 84.34% to 87.08%. This increase can be attributed to the expanded leaf area and the increased number of leaves at the vegetative stage, which limited the wetting pattern but trapped more amount pesticide (Yang et al., 2014). In the fruit-bearing stage, increased interception (87.51%) and 88% increase in wetted leaves led to a 50% reduction in pest population. This showed that the increased plant interception and the improved capture of pesticides effectively controlled the pest population (Braekman et al., 2009).

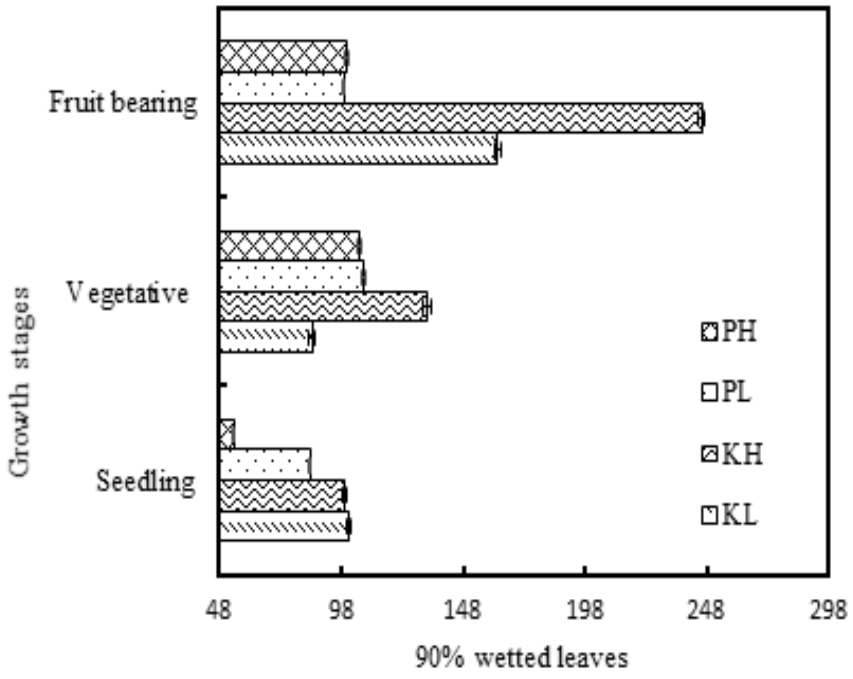


Figure 6: Wetting percentage across different growth stages of okra. PH = Power-operated Hand sprayer, PL = Power-operated Low-volume sprayer, KH = Knapsack High-volume, KL = Knapsack Low-volume.

Treatment KH initially achieved 24.32% pest control in the seedling stage. However, it showed a significant increase of 90% in the vegetative stage. Although the plant interception rate improved to 88.42%, the increased pest population was due to the dense canopy and larger leaf area, which limited the even spray coverage and penetration (Liao et al., 2020). In the fruit-bearing stage, the effectiveness of KH improved with the reduction of pest population by 50% from the previous stage. This improvement was the combined effect of a substantial increase in plant interception rate to 90.88% and an increase in wetted leaves, which was 150% more than in the seedling stage and 85% more than in the vegetative stage (Braekman et al., 2009).

Throughout the stages of okra development, treatment PL showed varying levels of effectiveness. It started with a pest control efficacy of 35.44% in the seedling stage, with a plant interception rate of 78.41%, and 85 leaves achieved 90% wetting. As the crop progressed to the vegetative stage, the interception rate improved by 12%, corresponding to a 26% increase in wet leaves. Hence, there was increased pest activity from 35.44% to 178.57%. This rise in pest activity suggests that treatment PL with effective coverage was balanced by the capacity to manage pests without excessively promoting much proliferation than other treatments: KL and PH (Mesmin et al., 2019).

A clear pattern emerged across the stages of the okra with treatment PH. At the seedling stage, the plant interception rate was 72.94% with 54 leaves achieving 90% wetting. The pest population at this stage was 80.33%. As the crop grew into the vegetative stage, the interception rate increased by 3.3%, and the number of leaves wetted significantly increased by 95%. Despite these improvements, the pest population experienced a dramatic rise of 312% (Mesmin et al., 2019). By the fruit-bearing stage, the interception rate further increased by 4% from the previous stage, while the number of wet leaves decreased slightly by 5% from the previous stage. The pest infestation level, however, lowered by 32% from the vegetative stage, indicating some control over pest dynamics (Kouhen et al., 2023).

In summary, the effectiveness of various treatments differed at the stages of okra. The treatment KL showed the lowest rate of pest increase in the seedling stage. This was connected with a greater rate of plant interception and a higher 90% wetting rate. This implies that KL was successful in providing early pest coverage and control. During the vegetative stage, the higher plant interception rate, greater 90% wetting, and the lower pest growth rate of treatment KH made it the most appropriate treatment. Ultimately, the treatment KH indicated to be the most successful in the fruit-bearing stage once more. This was mainly because of the highest rate of plant interception, superior wetting rate, and greater pest infestation level compared to other treatments.

This study identifies the pest increase rates across the growth stages of okra, pinpointing the most vulnerable stage. The results guide the selection of effective treatments, providing valuable insights for farmers to optimize pest management and enhance crop yields.

Yield of the okra plant for different treatments

The yield of okra across different treatments is shown in Figure 8, with KH yielding the highest at 374.48 kg ha^{-1} (40%), followed by KL at 219.48 kg ha^{-1} (24%), PL at 190.67 kg ha^{-1} (21%), and PH at 140.60 kg ha^{-1} (15%). The treatment KH demonstrated superior performance due to high plant interception rates, particularly in the vegetative (88.42%) and fruit-bearing stages (90.88%). Moreover, minimal environmental loss (0.38% at fruit-bearing) and effective pest control result in the most favorable combination of parameters for yield. Conversely, PH had the lowest yield due to the lowest interception rates and the highest environmental loss (10.65% at the seedling stage), coupled with high pest growth rates and inadequate wetting patterns. The key factors influencing yield included plant interception, environmental loss, pest population dynamics, and leaf wetting coverage. These results align with the overall study objective to provide recommendations for optimizing spray treatments, maximizing yield, and minimizing environmental impact through the effective use of low and high-volume spraying systems.

Impact of droplet size on spray precision

The data showed that throughout the development of okra, KL and KH treatments had higher interception rates. In particular, at the seedling stage, KL had an interception rate of 83.34% while KH measured 82.19%, compared to 78.41% for PL and 72.94% for PH. This trend persisted through the vegetative and fruit-bearing stages, with KH reaching as high as 90.88% interception in the fruit-bearing stage, while KL reached 87.51%. These increased interception rates for KL and KH were attributable to their larger particle sizes: KL (2.6 µm) and KH (2.4 µm) as shown in Figure 9. These larger droplets were less susceptible to drift and increased adherence to plant surfaces, crucial for efficient spray application (Gibbs et al., 2021).

In terms of 90% wetting, KL and KH treatments showed greater efficiency. In terms of leaf wetting during the seedling stage, KL achieved wetting of 101 leaves and KH achieved 99 leaves, significantly outperforming PL (85 leaves) and PH (54 leaves). In keeping with this pattern, KH was able to remarkably wet 246 leaves, while it was only 162 leaves for KL in the fruit-bearing stage, which indicated thorough and consistent leaf coverage. During this application, the droplet sizes of KL and KH were 2.6 µm and 2.4 µm, respectively. Such coverage is essential for effective pest management and overall plant health. By comparison, the smaller droplets from PL (2.3 µm) and PH (2.1 µm), were more prone to evaporate and drift, which resulted in less leaf coverage and less efficient wetting (Yu et al., 2009). The third indication of the efficacy of droplet size in KL and KH was the rise in pest rates. In the seedling stage, KL had a pest increase rate of 21.43%, and KH had 24.32%, which were substantially lower than PL (35.44%) and PH (80.33%). This effectiveness continued in the vegetative stage, where KH had a pest increase rate of 90%, compared to 176.19% for KL, 178.57% for PL, and a remarkable increase of 312% for PH.

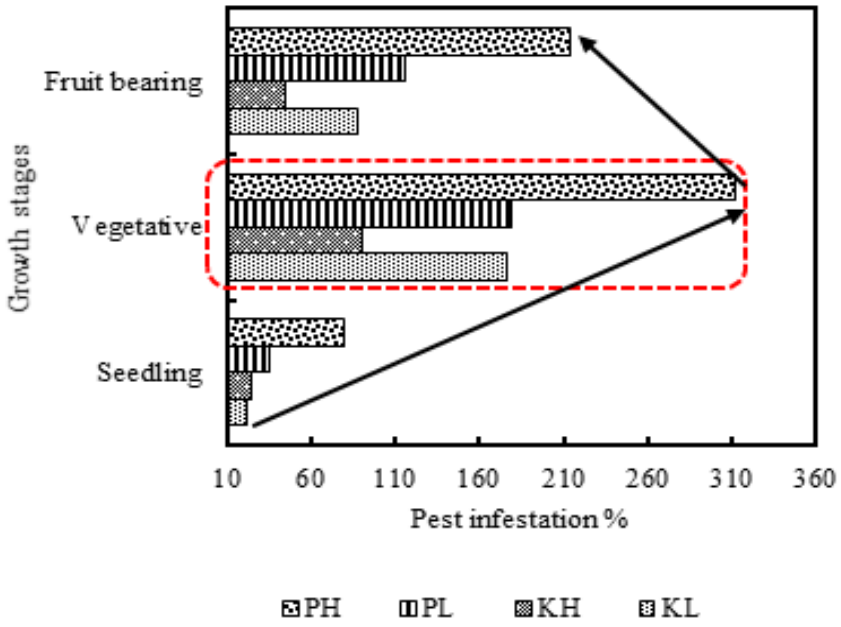


Figure 7: Pest infestation percentage in different growth stages of okra. PH = Power-operated Hand sprayer, PL = Power-operated Low-volume sprayer, KH = Knapsack High-volume, KL = Knapsack Low-volume.

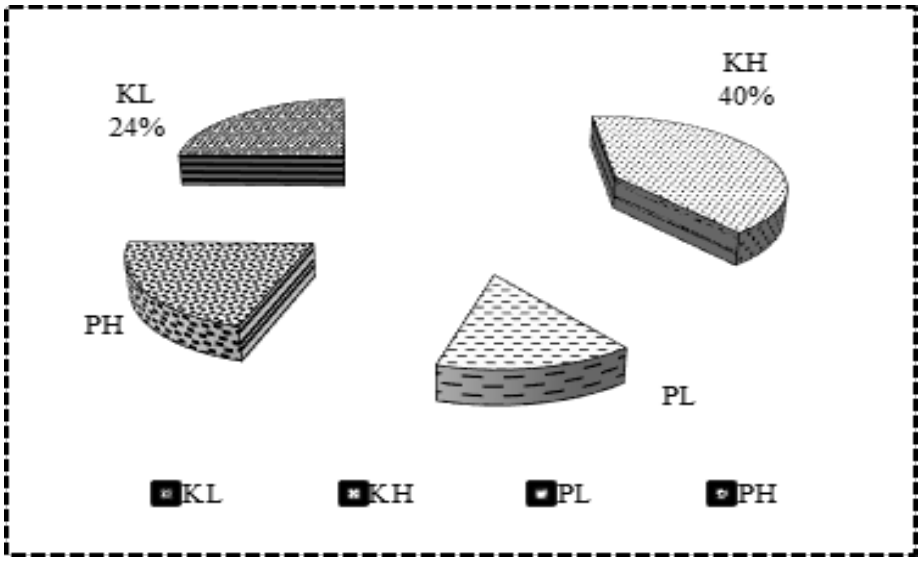


Figure 8: Yield of okra for different treatments. PH = Power-operated Hand sprayer, PL = Power-operated Low-volume sprayer, KH = Knapsack High-volume, KL = Knapsack Low-volume.

The lower pest infestation level for KL and KH showed their superior pest management. Especially in the fruit-bearing stage, KH had the lowest rate at 45.21%. This phenomenon was due to the formation of a more uniform and protective layer on plant surfaces due to the larger droplets from KL and KH, whereas the smaller droplets from PL (2.3 µm) and PH (2.1 µm) caused less effective pest control due to increased drift (Smith et al., 2000).

Data on yields supported the effectiveness of droplet size in the treatments KL and KH. Among the treatments, KH achieved the highest yield at 374.48 kg ha^{-1}, followed by KL (219.48 kg ha^{-1}), PL (190.67 kg ha^{-1}), and PH (140.60 kg ha^{-1}). This phenomenon was due to their larger droplet sizes of KL (2.6 µm) and KH (2.4 µm) to have better interception, more effective wetting, and more pest control. The combination of these factors contributed to their higher yields because of more even coverage and reduced drift, provided by these larger droplets, thereby plant health and productivity increased (Gibbs et al., 2021; Smith et al., 2000; Yu et al., 2009). On the other hand, yield was negatively impacted by greater drift and uneven application, caused by the smaller droplets used in the treatments of PL (2.3 µm) and PH (2.1 µm) (Chen et al., 2020).

The previous discussions and literature support these results. Bretthauer et al. (2008) have reported a higher yield in soybeans at higher droplet size. The superior performance of KL and KH treatments over PL and PH was supported by the different ways droplet size variations affected the plant interception, wetting, pest control rate, and yield. Larger droplet sizes enhanced leaf coverage by reducing drift, thereby improving resistance to pest infestation. This ensures the energy of the plant is directed toward growth and production rather than combating pests. Consequently, these results offer farmers effective pest control strategies that contribute to increased crop yield.

Vertical reach of hand-operated and power-operated knapsack sprayers in Okra cultivation

The horizontal and vertical reaches of different treatments using hand-operated knapsack and power-operated knapsack sprayers are illustrated in Figure 10, explaining key insights into their effectiveness in okra cultivation. Treatment KL, with a vertical reach of 68.33 cm and horizontal reach of 163 cm, proved ideal for the seedling stage, ensuring good plant interception (84.34%) and sufficient pest control (21.43%). Similarly, treatment KH demonstrated superior performance during the vegetative and fruit-bearing stage with a vertical reach of 80.47 cm and horizontal reach of 180.7 cm, resulting in higher plant interception (88.42% and 90.88%) and effective pest management (90% and 45.2%).

In contrast, treatments PL and PH exhibited significantly lower reach, limiting their effectiveness during later plant growth stages. The consistent weather conditions maintained during the experiment ensured valid comparisons between treatments. Weather conditions and time of application of pesticides throughout the experiment are tabulated in Table 2. The reported values represent time-averaged sensor readings for particular treatment period, with spray volume (low or high) being the only variable across treatments. Observations were taken consistently in the early morning to ensure reliable data. Overall, the hand-operated knapsack sprayers (KL and KH) provided greater reach and reduced environmental loss, making them more suitable for different stages of okra development, with the contribution to improved pest control and yield. These findings offer valuable recommendations for farmers on optimal sprayer selection to maximize crop performance.

Comparative analysis of treatment effects on growth parameters of okra

The effectiveness of different treatments: KL, KH, PL, and PH across various growth stages of okra: seedling, vegetative, and fruit-bearing, was statistically measured based on the important parameters: Plant interception, environmental loss, plant height, and pest infestation level using SAS (version 9.4) statistical software, as shown in Tables 3 and 4. The significant differences among these treatments were highlighted by statistical analysis, which showed insight into their specific efficiency.

Plant absorption differed significantly among treatments at the seedling stage ($F = 238.78$, $df = 3$, and $P < 0.0001$) as shown in Table 3. The treatment KL (30) showed greater absorption compared to PL (27.87), KH (29.99), and PH (24.45). This suggests that the hand-operated knapsack, low-volume (KL), more effectively supports early development (Chen et al., 2013; Holownicki et al., 2000). Significant differences in the environmental loss were observed among treatments ($F = 12.03$, $df = 3$ and $P < 0.0001$), where KL (1) showed minimal loss, whereas KH (1.68) indicated next. Higher losses in treatments: PL (3.79) and PH (3.78), suggest a less effective plant interception and greater impact on the environment (Wang et al., 2022). Significant differences in plant height were noted in this stage ($F = 12.61$, $df = 3$, and $P < 0.0001$). Taller plants were produced by the treatments: KL (12.58) and KH (12.44) than by the treatments: PL (11.84) and PH (9.87). The sprouting advantage was attributed to improved spray distribution, which facilitated more efficient absorption of agrochemicals. The pest infestation level was lowest for KL (23.54) and highest for PH (73.5), though it was only marginally significant ($F = 2.53$, $df = 3$ and $P = 0.086$). This indicates that the treatment KL provided better pest management.Plant absorption fluctuated greatly throughout the vegetative stage ($F = 298.61$, $df = 3$, and $P < 0.0001$). Absorption was higher for the treatments: KH (31.42) than for the treatments: PL (31.26), KL (30.96), and PH (26.73), as shown in Table 4. Reiterating the superior efficacy of KL and KH, environmental loss at this stage also differed considerably ($F= 3.31$, $df = 3$ and $P = 0.022$), with PL (0.97) demonstrating the most loss and KL (0.6133) the lowest. There were notable variations in plant height during the vegetative stage ($F = 4.3$, $df = 3$, and $P = 0.0064$). The plant average height was higher for treatment KH (31.16) than for the rest of the treatments. The pest infestation level was highest for PH (367.5), PL (234.58), and KL (183.34), despite being marginally significant ($F = 2.47$, $df = 3$, and $P = 0.0918$).This suggests that treatment KH (124.72) has higher pest control efficacy.

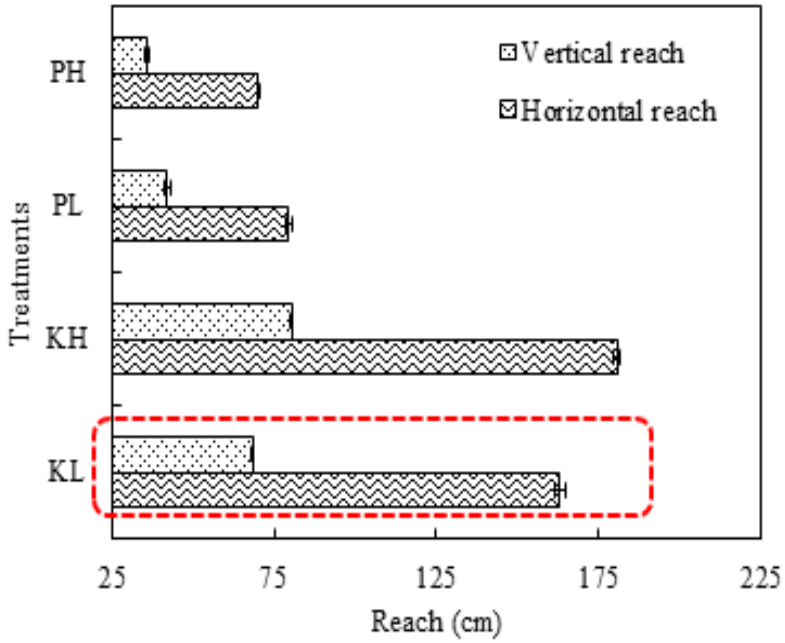


Figure 10: Horizontal and vertical reach of different treatments in okra cultivation. PH = Power-operated Hand sprayer, PL = Power-operated Low-volume sprayer, KH = Knapsack High-volume, KL = Knapsack Low-volume.

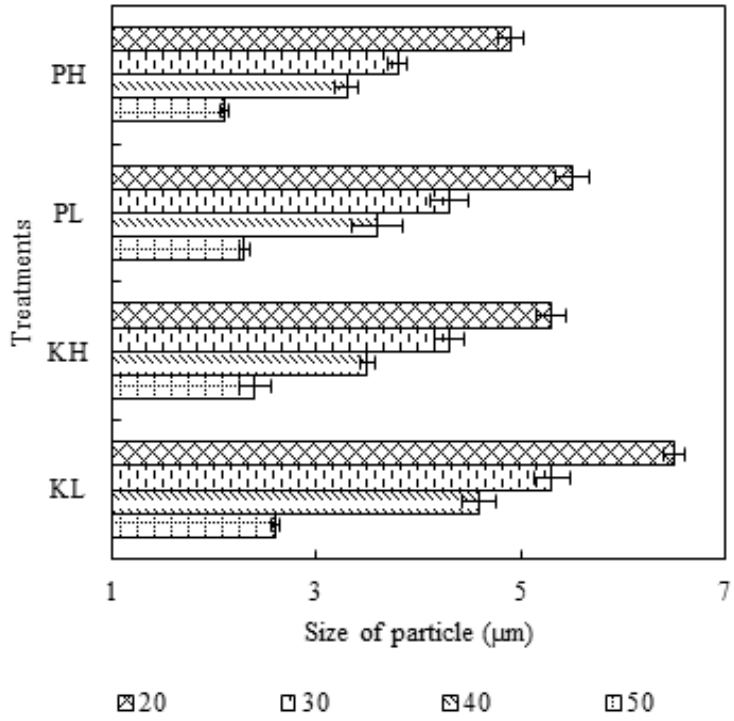


Figure 9: Droplet sizes under different treatment conditions. PH = Power-operated Hand sprayer, PL = Power-operated Low-volume sprayer, KH = Knapsack High-volume, KL = Knapsack Low-volume.

Table 2: Weather conditions and time of application of pesticides throughout the experiment

	Growth stages of okra											
Parameters	**BBCH 15**				**BBCH 33**				**BBCH 61**			
	KL	**KH**	**PL**	**PH**	**KL**	**KH**	**PL**	**PH**	**KL**	**KH**	**PL**	**PH**
Temperature (ºC)	28	28	29	29	29	29	29	29	28	29	29	29
Humidity (%)	98	92	88	84	98	94	84	83	98	96	95	86
Wind velocity (kmh^{-1})	5	5	8	8	6	7	8	8	6	6	7	7
Wind direction (a.u.)	South	South	South	South	Southwest	Southwest	Southwest	Southwest	South	South	South	South

[1]BBCH 15 - Seedling stage; BBCH 33 - Vegetative stage; BBCH 61 - Fruit-bearing stage. PH = Power-operated Hand sprayer, PL = Power-operated Low-volume sprayer, KH = Knapsack High-volume, KL = Knapsack Low-volume.

Table 3: Statistical analysis of factors affecting plant growth in okra under different treatments across growth stages. Variance, degrees of freedom (df), sum of squares (SS), mean squares (MS), F-values, and P-values are shown

Stages	**Variance**	**df**	**ss**	**ms**	**F**	**P**
Seedling	Plant absorption	3	614.75	204.92	238.78	<.0001
	Environmental loss	3	186.77	62.26	72.03	<.0001
	Plant height	3	140.89	46.96	12.61	<.0001
	Pest infestation rate	3	8265.37	2755.12	2.53	0.086
Vegetative	Plant absorption	3	456.61	152.20	298.61	<.0001
	Environmental loss	3	2.02	0.67	3.31	0.0226
	Plant height	3	157.96	52.65	4.3	0.0064
	Pest infestation rate	3	192984.61	64328.20	2.47	0.0918
Fruit-bearing	Plant absorption	3	330.60	110.20	3787.21	<.0001
	Environmental loss	3	4.45	1.48	70.68	<.0001
	Plant height	3	251.83	83.94	7.39	0.0001
	Pest infestation rate	3	15519.86	5173.29	3.16	0.0472

In this stage, KH showed higher environmental loss compared to KL. However, while considering other factors, KH outperforms KL.

At the fruit-bearing stage, plant absorption continued to differ significantly between treatments ($F = 378.21$, $df = 3$, and $P < 0.0001$). In comparison to PL (31.14), KL (30.866), and PH (27.65), treatment KH (32.04) showed greater interception. At this point, the environmental loss was also significant ($F = 70.68$, $df = 3$ and $P < 0.0001$), with the maximal loss in PL (0.62) and minimal loss in KH (0.13) (Lefrancq et al., 2014; Viret et al., 2003). Significant variation existed in plant height at the fruit-bearing stage ($F = 7.39$, $df = 3$, and $P = 0.0001$), with KH (36.16) having the greatest height, followed by PL (35.33), PH (35.36), and KL (32.36). The pest infestation level was significant ($F = 3.16$, $df = 3$ and $P = 0.0472$), with KH (47.79) exhibiting a lower pest infestation level compared to other treatments, as shown in Table 4.

Overall, the treatment KH consistently showed superior performance across all stages of okra development in terms of plant absorption, environmental loss, plant height, and pest infestation level. The ultimate objective of this study was to determine the most effective treatment among the four spraying techniques for each stage of okra development individually. This statistical analysis provides a more reliable method of evaluating the efficacy of each treatment than depending just on observational data. These results provide insights that are both approachable and supported by scientific rigor, enabling a more comprehensive examination of the underlying mechanisms and patterns observed. This study provides a strong basis for future researchers and innovators, while also meeting the practical demands of farmers. Future developments in agricultural methods and technology can be guided by the knowledge gained by this study.

RECOMMENDATIONS FOR FUTURE PERSPECTIVES

Based on the analysis, several drawbacks have been identified: the inability to precisely identify the exact impact of pests on crops. Current methods lack the accuracy needed to target specific areas of infestation, leading to the broad application of pesticides across all plants. This approach not only increased pesticide usage but also resulted in the exposure of healthier plants to chemicals, contributing to bio-magnification and other adverse effects on human health. Furthermore, both hand-operated knapsack sprayers and power-operated knapsack sprayers require manual operation, leading to operator fatigue and inconsistent application. Additionally, the large droplet sizes produced by these sprayers cause significant environmental loss, and much of the pesticide is lost by evaporation and drift rather than being absorbed by the plants. However, by implementing ultra-low volume (ULV) application methods, it is possible to reduce environmental loss due to the smaller droplet sizes, which cause a larger surface area and higher coverage compared to low-volume and high-volume applications used in traditional and modern sprayers.

There is a critical issue regarding the ineffective adaptation of different growth stages and specific application requirements by farmers. Instead of using suitable sprayers for each growth stage, farmers tend to use the same type of sprayer, leading to increased environmental loss, resource wastage, pollution and economic loss. In order to address these challenges, it is crucial to implement strategies that involve automatic monitoring of weather and pest parameters.

Currently, the use of such advanced monitoring systems in Sri Lanka is at an early stage with limited adoption and integration into standard agricultural practices. However, future technological advancements offer practical solutions to these issues. There is a great deal of promise for improving agricultural methods in Sri Lanka through the use of Unmanned Aerial Vehicles (UAVs).

High-resolution photography from UAVs can be used to monitor crop health and identify pests and diseases. Additionally, they make it possible to apply pesticides precisely with lower waste and increase the efficacy, especially in difficult-to-reach places. However, the use of UAVs in agriculture faces challenges like: restrictions on flight operation, technical limitations like: battery life, payload capacity and the impact of weather conditions on performance. The obstacles for implementing UAVs can be overcome by considering practical solutions like: cooperative ownership among farmers and governmental subsidies. In comparison to hand-operated knapsack sprayer and power-operated knapsack sprayers, ULV application through UAVs has the potential to substantially reduce pesticide usage, minimize operator fatigue and improve overall efficiency in pest control.

Despite the advances in traditional and modern spraying techniques explored in this study, a notable gap remains in the application of Unmanned Aerial Vehicles (UAVs) combined with image processing techniques. This gap highlights the potential for further refinement and sophistication in precision spraying. The integration of real-time image analysis with UAVs is possible to enhance the accuracy and efficiency of agrochemical applications, addressing current challenges in uniformity and coverage. Closing this gap could lead to more targeted and sustainable pest management practices, significantly improving crop protection outcomes.

CONCLUSION

This study mainly focused on the effectiveness of four different spraying techniques: KL, KH, PL, and PH, on different growth stages of okra with integrated sensor-based technology. The effectiveness of the spray technique was influenced by droplet size, horizontal and vertical reaches. The spraying technique had a significant impact on plant interception and environmental loss. Among these treatments, KH was most effective, especially during vegetative and fruit-bearing stages. It produced the longest pods (23.2±0.37 cm) and achieved the highest yield (374.48 kg ha^{-1}). The superiority of KH was further confirmed by statistical analysis. In contrast, significance was observed

Table 4: Comparison of different treatment effects on growth parameters of okra

Stages	Variance	KL	KH	PL	PH
Seedling	Plant absorption	30[a]	29.99[a]	27.8783[b]	24.4583[c]
	Environmental loss	1[c]	1.68[b]	3.7917[a]	3.785[a]
	Plant height	12.5833[a]	12.44[a]	11.8433[a]	9.87[b]
	Pest increasing %	23.5433[b]	44.2267[a]	34.6033[b]	73.5083[a]
Vegetative	Plant absorption	30.9667[b]	31.4233[a]	31.2667[a]	26.73[c]
	Environmental loss	0.6133[b]	0.8133[b]	0.97[a]	0.8667[b]
	Plant height	27.9333[b]	31.1667[a]	29.4667[b]	29.7333[a]
	Pest increasing %	183.34[b]	124.72[b]	234.58[a]	367.50[a]
Fruit-bearing	Plant absorption	30.8667[c]	32.04[a]	31.1433[b]	27.65[d]
	Environmental loss	0.2733[c]	0.1333[d]	0.6200[a]	0.5167[b]
	Plant height	32.3667[b]	36.1667[a]	35.3333[b]	35.3667[b]
	Pest increasing %	82.6150[a]	47.7900[b]	117.75[a]	69.0650[b]

PH = Power-operated Hand sprayer, PL = Power-operated Low-volume sprayer, KH = Knapsack High-volume, KL = Knapsack Low-volume.

in KL during the seedling stage only. Notably, compared to KL and KH, nominal performance was observed for PL and PH. The new piece of information, created by this experiment, is the integration of sensor-based technology for pest identification with KH as the best combination of spraying for vegetable crops, yielding high plant interception and minimum environmental loss. Reliable information can be obtained through sensor technology to detect pests and appropriate pesticides. Therefore, the study provides a strong foundation for the upcoming world towards sustainable agriculture.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflicts of interest

FUNDING INFORMATION

No funding was received for this work

AUTHOR CONTRIBUTION

Conceptualization: **K.N.;** Methodology: **M.N., L.S., K.N.;** Data collection: **M.N.;** Data analysis: **L.S.;** Formal analysis: **M.N., L.S.;** Writing the original draft: **M.N.;** Management of resources, Validation: **K.N.;** Review and editing: **L.S., K.N.**

DATA AVAILABILITY STATEMENT

All data generated or analyzed during this study will be made available to the public upon request.

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