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Predictive modelling for whitefly (*Bemisia tabaci*) control in cotton (*Gossypium* spp.): Evaluating sprayer efficiency using PLS regression and ANN techniques

SANTOSH KUMAR[1]*, APOORV PRAKASH[1], ANAND GAUTAM[1], VIJAY KUMAR[2] and MANDEEP PATHANIA[3]

Punjab Agricultural University, Ludhiana, Punjab 141 004, India

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ABSTRACT

Cotton (*Gossypium* spp. L.), a vital fibre cash crop in India, faces challenges from various insect-pests among which whiteflies pose a significant threat. A study was carried out in 2022 at Abhor district of Punjab to evaluate seven sprayers, including high clearance boom sprayer, air-assisted drop-up boom sprayer, auto-rotate gun, air-assisted electrostatic sprayer, engine-powered knapsack, manually operated knapsack, and UAV sprayers, based on droplet density, size, coverage, spray volume deposition, and bio-efficacy. From the experimental results, it was found that the electrostatic sprayer was most effective against whiteflies. An economic analysis considered costs, ANN and PLSR models predicted whitefly populations, with ANN showing superior accuracy, recommending engine-powered gun sprayers for optimal control. Field assessments favoured high clearance boom and drone sprayers, offering cost efficiencies. Eventually, the optimal choice of a sprayer should align with the specific needs and circumstances of the farm.

Keywords: ANN, Drone sprayer, High clearance sprayer, PLSR, UAVs

Cotton (*Gossypium* spp. L.) belonging to Malvaceae family is a major commercial crop cultivated worldwide for fibre and oilseed under diverse agro-climatic conditions (Meshram *et al.* 2022). India, China, the United States, Brazil and Pakistan together contribute more than 75% of global cotton production (OECD/FAO 2021). In Punjab, American cotton occupied 2.49 lakh ha during 2021–22, producing 0.639 million bales with an average lint yield of 4.36 q/ha (MoA&FW 2022). At the national level, cotton covers about 11.91 mha with an average productivity of 501.47 kg/ha (PAU 2023).

A wide range of sprayer technologies are available in South Asia, including knapsack sprayers, tractor-mounted boom sprayers, air-assisted sprayers, and self-propelled high-clearance sprayers (Pascuzzi and Cerruto 2015, Kumar *et al.* 2020a, b and c). Advanced technologies such as air-assisted electrostatic sprayers and unmanned aerial vehicles (UAVs) are increasingly being adopted due to improved coverage, reduced chemical use and higher field efficiency (Martin and Latheef 2017, Singh and Kumar 2022). However, each technology has inherent limitations related to field size, application uniformity, and dosage variability. Cotton productivity is highly susceptible to insect-pests, diseases, and changing climatic conditions. Among insect-pests, whitefly (*Bemisia tabaci*) and pink bollworm (*Pectinophora gossypiella*) are the most destructive, causing severe yield and quality losses in cotton crop (Wen *et al.* 2019). Effective management requires timely monitoring with chemical control recommended when populations of whitefly exceed six adults/leaf in the upper canopy (CPCRI 2022). Proper spray deposition on the underside of leaves is critical for effective control, and selective insecticides such as pyriproxyfen play a vital role in sustainable pest management (NCBI 2024). The whitefly was chosen over pests like pink bollworm because it has caused more severe and widespread damage in Punjab in recent years (Kumar *et al.* 2020a). Despite technological advancements and recent developments in data analytics and machine learning offering new opportunities to assess sprayer efficiency and predict pest infestation dynamics, it remains limited. Therefore, the present study employed partial least square regression and artificial neural network models for whitefly infestation to identify the most effective sprayer technology for uniform pesticide application, better pest control and sustainable cotton production.

[1]Punjab Agricultural University, Ludhiana, Punjab; [2]ICAR-Central Institute of Agricultural Engineering, Bhopal, Madhya Pradesh; [3]Regional Research Station (Punjab Agricultural University, Ludhiana, Punjab), Ballowal Saunkhri, Punjab. *Corresponding author email: caet.santosh@pau.edu

MATERIALS AND METHODS

Self-propelled and tractor-mounted sprayers: The detailed specifications of the high clearance boom sprayer, air-assisted drop-up boom sprayer, and auto-rotate gun sprayer are shown in Table 1. The spray machine consists of a hydraulic pump with a pressure gauge, a spray tank of 1,000 L, and a hydraulic-assisted boom controlling mechanism. The pump operates at 800 rpm to develop the desired spray pressure up to 35 kPa. The boom spraying mechanism consists of 14-hollow cone nozzles, facilitating its use in sprayer in cotton crop.

An auto-rotated gun sprayer has a two-gun nozzle boom mounted, DC motor, and hydraulic piston type pump and spray tank of 600 L. The spacing between the two guns is kept 9 m apart on the boom. Each gun rotates 120° to cover about 20 m of the wide span of the sprayer at a liquid pressure of 29.40–34.30 kPa. These guns can be operated independently if required. The boom height can be adjusted between 0.50–1.50 m from the ground surface to the sprayer at all the growth stages of the cotton crop.

The air-assisted drop-up sprayer consists of a sprayer tank, hydraulic pressure pump, one blower, foldable and height adjustable boom with air-assisted and drop-up type nozzles. A High-Density Polyvinyl Chloride (HDPVC)-made water tank has 600 L capacity of spray. The hydraulic pump required 3.70 kW to run through tractor. The air blower fan has a diameter of 0.60 m and runs at 3,500 rpm. The blower has two air stream discharge pipes with a diameter of 0.11 m connected with an assisted nozzle boom through a flexible PVC pipe diameter of 0.11 m. A foldable and height-adjustable boom is mounted on the rear side of the spray frame. The total length of the boom is 9.50 m, with five sections to fold on each side, left and right, with one fixed middle section. The height of the boom was adjusted from 0.30–2.50 m from the ground. The boom consists of two arrangements of nozzles air assisted and drop-up hollow

Table 1 Technical specification of air assisted drop-up boom, auto-rotate gun and high clearance boom sprayer used in experiment

Particulars	High-clearance boom sprayer	Auto-rotate gun sprayer	Air-assisted drop-up boom sprayer
Spray tank capacity, L	1000 (500 + 500)	600	600
Agitator	Hydraulically	Hydraulically	Hydraulically
Pump			
Type	Hydraulic piston pump	Hydraulic piston pump	Hydraulic piston pump
Discharge pressure range, bar	15–35	15–35	15–35
Recommended revolution range, RPM	600–800	700–900	600–800
Required, hp	3–7	5	3–7
Discharge volume range, L/min	60–80	50	60–80
Operating pressure, bar	18–20	30–35	18–20
Width of boom, m	9.50	9.50	9.30
Range of boom height adjustment, m	0.30–2.50	0.50–1.50	0.50–1.50
Type of nozzles attachments			
Drop-up type nozzle			
No. of drop-up type nozzles	-	-	15
Type of nozzle	-	-	Hallow cone
Make and model	-	-	TeeJet& TXA8002VK
Sprayer nozzle angle, degree	-	-	80
Spacing between two adjacent nozzles, m	-	-	0.67
Length of drop-up nozzle adjustment from boom	-	-	75
Max. nozzle discharge rate, L/min	-	-	2
Type of nozzle attachment	Boom type	Gun type	Air Assisted boom-type
Boom pipe diameter, mm	-	-	110
No. of nozzle on boom	14	2	17
Type of nozzle	Hallow cone	Hallow cone	Hallow cone
Make and model	TeeJet & TXA8002VK	TeeJet	TeeJet & TXA8002 VK
Spacing of nozzles on boom, mm	0.67	9.50	0.59
Max. nozzle discharge rate, L/min	02	20	02
Sprayer nozzle angle, degree	80	Adjustable	80
Dia. of blower fan, m	-	-	0.60
Blower, rpm	-	-	3,500

cone to match the row to row spacing of cotton.

Backpack-type sprayers: A mobile backpack air-assisted electrostatic sprayer mounted on a bicycle wheel is powered by a 3.70 kW petrol engine with an on-board compressor and spray gun used for spraying cotton crops. Two 9 V rechargeable DC batteries have been provided to charge the spray particles in the nozzle. The charge to mass ratio of electrostatic sprayer varies from 0.8–1.0 mC/kg at voltage range of 4–5 kV which lies in the range of 0.0–1.4 mC/kg as reported by Lin *et al.* (2023).

The engine powered knapsack gun sprayer has a 2-stroke petrol engine of 0.74 kW that drives the hydraulic pump to develop the desired pressure for atomising the liquid into smaller droplets with a hollow spray nozzle. A manual hand lever-operated knapsack sprayer was selected for the treatment. The detailed specifications of an air-assisted electrostatic sprayer, engine-powered knapsack gun sprayer and knapsack sprayer are shown in Table 2.

Drone sprayer: An unmanned hexa-copter aerial vehicle (UAV) has 10 kg payload capacity powered by two Li-Po batteries. The UAV sprayer has a maximum flight time of 15 min with two 24 V and 16,000 mAh batteries. The UAV also enables loitering and autonomous application in specific areas using pre-established coordinates via GPS navigation system. The UAV sprayer system consisted of four hollow cone spray pattern nozzles fitted beneath the propeller with a spray angle of 80°. The swath width of UAV spraying is 2.66 mm with four nozzles. Additionally, a small independently supplied electric pump with a voltage of 12 V DC motor is used to develop a maximum operating pressure of 300 kPa for atomisation of liquid. The spray control system allows the pump to be turned on or off remotely and the speed to be varied from a remote control station.

Experimental plan: The experiment was conducted in the Abohar district of Punjab at a farmer field during 2022.

Table 2 Technical specification of knapsack sprayers used in the experiment

Parameters	Electrostatic sprayer	Engine power knapsack gun sprayer	Knapsack sprayer
Type of nozzle	Solid cone	Hallow cone	Hallow cone
Tank capacity (L)	15.00	16.00	16.00
Flow rate of the nozzle (L/min)	0.10–0.12	2.00–2.50	0.80–1.00
Spray range (m)	2.50–3.00	3.00–4,000	1.00–2.00
Operating pressure (kPa)	280–350	300	300
Spray tank capacity (L)	15.00	16.00	16.00
Engine, petrol engine (kw)	3.70	0.76	-
Hose length (m)	3.00	1.50	1.50
Wheel tread (m)	0.65	-	-
Empty weight (kg)	110.00	6.00	4.50

Seven types of sprayers were selected for the experiment, viz. high clearance boom sprayer (T_1), auto-rotate gun sprayer (T_2), air assisted drop-up sprayer (T_3), electrostatic sprayer (T_4), engine powered knapsack gun sprayer (T_5), knapsack sprayer (T_6) and UAV sprayer (T_7). The experiment utilised the recommended dose of insecticide pyriproxifen at 100 g a.i./ha for controlling adult whiteflies in various farmer's fields in the Abohar region of south-western Punjab. The farmer's field were selected where the whitefly population exceeded the economic threshold level, ranging from 18–70 adults/3 leaves. For the field experiment conducted on 1 ha of cotton crop, the plot sizes were 0.2 ha for the tractor-operated sprayer and 0.10 ha each for the manually operated knapsack sprayer and the UAV sprayer. The total nozzle discharge was measured by collecting the liquid from each nozzle in L/min. Before conducting experiments, each sprayer machine was tested for its spray volume application rate. The application rate (L/ha) is obtained by dividing the total nozzle discharge multiplied by 10,000 by the product of forward speed, nozzle spacing, number of nozzles, and efficiency. The spray application rate was calculated by time taken to cover test plot area and total discharge of all nozzles on sprayer boom. The spray application rate for T_1, T_2, T_3, T_4, T_5, T_6, and T_7 were 600, 600, 600, 15, 300, 300, and 20 L/ha, respectively, for the tractor operated and knapsack sprayer as per the privilege practices of farmers. However, for drone sprayer, the application rate was accessed after initial field trials. During spraying, the operating speed ranged from 2.5–3.0 km/h for self-propelled sprayers, 3.0–3.5 km/h for tractor-mounted, 1.8–2.0 km/h for backpack sprayers and 10.8 km/h for UAV sprayer.

Oil- and water-sensitive paper methods were used to evaluate the spray performance parameters (Kumar *et al.* 2020b). Oil- and water-sensitive papers (76 × 26 mm) were attached to the abaxial and adaxial sides of the leaves at three different heights (top, middle, and bottom) and three numbers of cotton plants to replicate the data in each treatment plot. For measurement of sprayer parameter, the volume median diameter (VMD), droplet density/cm^2, % area coverage, and spray volume deposition (µL/cm^2) were measured. The computer software DropScan® was used to analyse the water and oil sensitive cards, converting each image spot area to the actual droplet diameter using the equation below:

$$D_d = 1.06\ As^{0.455}$$

Where D_d, Actual droplet diameter (µm); As, Spot area (cm^2).

The whitefly incidence was assessed on 20 randomly selected plants in each test field before spraying (BS) and 3, 7, and 10 days after spraying (DAS). The number of whitefly adults on three leaves of each plant was counted, and the average count/3 leaves was recorded in a data sheet to interpret the results. To access the field capacity of the sprayer, time required for the field operation, working width and speed were also measured.

Partial Least Squares Regression (PLSR) and Artificial Neural Networks (ANN): In this study, we compared PLSR and ANN models for predicting whitefly reduction rate in cotton crop after the sprayer. The predictor variables included sprayer type (T_1–T_7) and days after spraying (3, 5, 7, 10 DAS). The response variable was whitefly population/3 leaves. A feed-forward multilayer perceptron (MLP) neural network was developed consisting of one input layer with seven neurons, one hidden layer with 10 neurons, and one output neuron representing predicted whitefly population. The ReLU activation function was applied in the hidden layer and linear activation in the output layer. The model was trained using the back propagation algorithm with 70% data used for training and 30% for validation. Evaluation metrics, including Mean Squared Error (MSE) and R-squared were calculated for both models. The combination resulting in the minimum predicted whiteflies is identified for each model. The modal equation of PLSR is represented as:

$$y = xB + E$$

Where y, Response matrix; x, Predictor matrix; B, Matrix of regression coefficients; E, Residual matrix.

The standard equation of ANN can be represented as:

$$y = f(W_2.f(W_1.x + b_1) + b_2)$$

Where x, Input vector; W_1 and W_2, Weight matrices for the connections between input-hidden and hidden-output layers, respectively, b_1 and b_2 are bias vectors; f, Activation function applied element-wise; y, Output vector.

The experiment was conducted using factorial completely randomised design (F-CRD). The General Linear Model (GLM) was used for the analysis of variance with the help of SPSS20 software (SPSS Inc., IBM Company, Chicago). Means with significant f-values at $p \leq 0.05$ were separated using Tukey's honestly significant difference (HSD) post hoc test at $\alpha \leq 0.05$.

RESULTS AND DISCUSSION

Effect of different sprayers on droplet parameters: The analysis of oil- and water-paper using Dropscan software revealed the droplet density of different sprayers used in the experiment (Table 3). The highest droplet density was observed as 81.67 drops/cm^2 of the air-assisted drop-up sprayer (T_3) while the lowest was 24.43 drops/cm^2 of the UAV sprayer (T_7). The droplets density of other sprayers were 67.10 drops/cm^2 for the auto rotate gun sprayer (T_2), 66.24 drops/cm^2 for the electrostatic sprayer (T_4), 56.52 drops/cm^2 for the power knapsack gun sprayer (T_5), 51.97 drop/cm^2 for the engine powered knapsack gun sprayer (T_5) and only 38.56 drops/cm^2 for the high clearance boom sprayer (T_1). Tukey's honestly significant difference post hoc test ($\alpha \leq 0.05$) showed significant effect on the droplet density of sprayers. Moreover, analysis of the variance of all the sprayers have significantly effects on droplet density. The adaxial surface of leaves had higher droplet density than the abaxial surface of leaves for the three positions of cotton plants', i.e. top, middle, and bottom canopy. Droplet densities of the top and bottom adaxial leaf surfaces were not statistically significant at $p \leq 0.05$, nevertheless, other positions of plant leaves differ significantly. However, the analysis of variance in the droplet density differs significantly for the adaxial and abaxial surfaces of all three leaves positioned on the cotton plant.

The largest droplets size observed was 488.39 µm from the high clearance boom sprayer while the smallest was 103.38 µm for the UAV sprayer. It was due to the nozzle orifice size and the nozzle discharge rate of the high clearance sprayer and UAV sprayer. The operating pressure of the high clearance boom sprayer was 18 kPa, which is used to operate 14 nozzles on a wide boom, and for the UAV sprayer, the operation pressure was 4 kPa, used to operate four nozzles on a single boom. From the statistical analysis of variance, the sprayer's droplet size differed significantly. However, the comparison of homogeneous subsets (Table 3) of auto-rotate gun sprayers with an air-assisted boom drop-up sprayer droplet size was not significantly different while other sprayers have significant effects on droplet size. The adaxial surface of the leaves gets a large number of drops, and the abaxial surface of the leaves gets a small number of drops for all three positions of the canopy of the cotton plant. Large-size drops travel less distance because more gravitational force acts on large-size drops. However, drops of a small size also travel for a shorter distance due to wind drag force and high temperature. It was observed that the abaxial surfaces of the leave of the bottom position of the plant hit a medium drop size of 240.64 µm, and above or below the size of drops do not reach the target. However, at other canopy heights, drop sizes were significantly different from each other. Regardless of it, from ANOVA, leaves height on cotton plant drop size had a significant effect.

The highest area coverage percentage was 33.49% for the high-clearance boom sprayers, while the lowest area coverage was 5.97% for the UAV sprayer. In high clearance boom, hydraulic force is used for high volume application rate of spray solution, which produces a large size of drops and causes more area coverage (%), and the UAV sprayer uses a low volume application rate nozzle, which causes a lower area coverage drop (%). Low-volume electrostatic sprayers and UAV sprayers have less area coverage % as compared to high-volume application rate sprayers, i.e. high clearance boom sprayers, auto-rotate gun sprayers, and air-assisted drop-up sprayers. However, the sprayer treatments T_1, T_2, T_4, T_5 and T_7 have significant effect on area coverage (%). Overall, the variance analysis showed that all sprayers had a significant effect on area coverage percentage. The maximum area of coverage was observed at 40.86% at top canopy of the plant's adaxial surface of the leaf. However, the lowest area coverage (%) was observed as 11.44% at bottom canopy of the plant's abaxial surface of the leaf. The reason for the highest area coverage (%) was the large size of drops with more droplet density, and another reason for it was no hindrance between the sprayer drop and the targeted leaves. Hence, the sprayer drop directly fell over the adaxial surface of the leaves. The leaves' area coverage (%) had a significant difference except for the top abaxial and bottom adaxial surface of leaves' height on the plant canopy. Analysis of variance of coverage area

(%) also had significant on leaf and leaf height differences at plant canopy.

The deposition of spray was found highest as 32.02 µL/cm² for the air-assisted drop-up sprayer (T_3) and the lowest was 13.10 µL/cm² for the knapsack sprayer. The higher deposition was due to higher number of drops/cm², while the lower was due to the larger size of drops that caused runoff on the paper's surface. The analysis of variance showed a significant difference in the effect of sprayers on the volume of spray material deposition. However, on comparing all sprayers in pairs (Table 3), the volume of spray deposition differed significantly except for the electrostatic and UAV sprayers. The adaxial surface of leaves got more deposition than the abaxial surface of leaves. For spray volume deposition at the top and middle height of the adaxial leaves surface, it was not significant

Table 3 Observed means and standard deviations of droplet parameters among different sprayers

Sprayer	Droplet parameters			
	Drop/cm²	VMD (µm)	Coverage (%)	Deposition (µL/cm²)
T_1	38.56^{b} ± 16.69	488.39^{f} ± 253.66	33.49^{e} ± 30.85	20.26^{c} ± 16.68
T_2	67.10^{e} ± 23.24	172.26^{c} ± 74.08	27.99^{d} ± 15.48	26.20^{d} ± 13.06
T_3	81.67^{f} ± 11.69	163.55^{c} ± 70.30	26.72^{cd} ± 15.97	32.02^{e} ± 12.32
T_4	66.24^{e} ± 35.72	138.81^{b} ± 33.86	16.16^{b} ± 8.88	17.26^{b} ± 5.66
T_5	56.52^{d} ± 24.79	420.63^{d} ± 110.99	25.15^{c} ± 12.41	26.45^{d} ± 12.48
T_6	51.97^{c} ± 21.25	474.01^{e} ± 232.34	31.58^{e} ± 14.96	13.10^{a} ± 6.39
T_7	24.43^{a} ± 27.80	103.38^{a} ± 212.07	5.97^{a} ± 18.47	18.29^{b} ± 12.45
Oil and water paper positions	Drops/cm²	VMD (µm)	Coverage (%)	Deposition (µL/cm²)
Top adaxial	77.86^{e} ± 29.50	303.78^{c} ± 193.80	40.86^{d} ± 14.92	32.49^{e} ± 9.57
Top abaxial	55.70^{c} ± 21.40	183.72^{a} ± 85.84	17.44^{c} ± 7.09	19.36^{c} ± 5.95
Middle adaxial	69.44^{d} ± 22.36	405.98^{e} ± 302.40	41.21^{d} ± 26.86	31.48^{e} ± 11.37
Middle abaxial	46.34^{b} ± 24.79	193.03^{a} ± 139.16	14.25^{b} ± 5.53	14.68^{b} ± 6.25
Bottom adaxial	54.54^{c} ± 22.34	353.74^{d} ± 251.95	18.01^{c} ± 10.92	24.06^{d} ± 14.73
Bottom abaxial	27.39^{a} ± 16.55	240.64^{b} ± 140.00	11.44^{a} ± 5.46	9.56^{a} ± 4.05

Means followed by the same lowercase letters are not significant different ($p \leq 0.05$).

VMD, Volume median diameter.

Treatment details are given under Materials and Methods.

Table 4 Comparison of treatments using pyriproxifen 100 g a. i./ha chemical against whitefly

Treat-ments	Water used (L/ha)	No. of whitefly adults/three leaves				
		BS	3 DAS	5 DAS	7 DAS	10 DAS
T_1	800	30.46^{a} [5.52]	15.46^{a} [3.93] (49.24)	18.90^{ab} [4.34] (37.95)	10.12^{ab} [3.15] (66.77)	8.50^{a} [2.89] (72.09)
T_2	800	40.07^{c} [6.33]	21.43^{a} [4.61] (46.51)	24.89^{ab} [4.95] (37.88)	13.87^{b} [3.72] (65.38)	8.60^{a} [2.93] (78.53)
T_3	1,000	37.64^{bc} [6.13]	22.85^{a} [4.78] (39.29)	26.83^{b} [5.18](28.72)	8.69^{ab} [2.94](76.91)	8.60^{a} [2.93] (77.15)
T_4	15	33.63^{abc} [5.80]	18.11^{a} [4.25] (46.15)	19.21^{ab} [4.37] (42.87)	9.77^{ab} [3.12] (70.94)	7.40^{a} [2.72] (77.99)
T_5	300	31.17^{ab} [5.58]	18.15^{a} [4.26] (41.77)	15.94^{a} [3.98](48.86)	8.19^{a} [2.86](73.72)	7.87^{a} [2.80](74.75)
T_6	300	29.08^{a} [5.39]	19.19^{a} [4.38] (34.01)	20.43^{ab} [4.51] (29.75)	11.15^{ab} [3.33] (61.65)	10.44^{a} [3.23] (64.09)
T_7	20	33.81^{abc} [5.81]	16.26^{a} [4.02] (51.90)	17.30^{a} [4.16] (48.83)	9.38^{ab} [3.06] (72.26)	9.08^{a} [2.95] (73.14)
T_8 (Control)	-	40.97^{c} [6.40]	37.32^{b} [6.10] (9.78)	40.53^{c} [6.36] (1.07)	33.66^{c} [5.79] (17.84)	35.52^{b} [5.95] (13.30)

Figures in [] parentheses are square root transformed values and () are percentage reduction. Means followed by the same lowercase letters are not significant different ($p \leq 0.05$). BS, Before spraying; DAS, Days after spraying.

Treatment details are given under Materials and Methods.

different but was significantly different between the plant canopy leaves surfaces. Inspite of this, from the ANOVA, all the sprayer and leaves position had significant effects on sprayer volume deposition for all heights of the canopy and leaves adaxial and abaxial surfaces. Charged spray droplets increased deposition nearly 2–3 times on adaxial and abaxial surfaces of top canopy leaves, compared to uncharged spray. The spray application method unaffected the canopy penetration of the spray into the lower layers of the plant foliage (Martin and Laheef 2017).

Bio-efficacy of different sprayers to control whitefly: Population of whitefly adults a day before the spray treatment was quite uniform and above the economic threshold level (ETL) (Table 4). However, three days after the spray, the whitefly population reduced considerably in all the treatments which was statistically at par with untreated control (T_8) of 37.32/3 leaves. After the 7th and 10th days of spray application, the population of whiteflies was drastically reduced in all treatments. Moreover, it was also observed that all the technology treatments had significant control as compared to the control treatment (No sprayer) to reduce whitefly adult populations. The statistical analysis all sprayers' technology treatments had significantly reduced whitefly population at 3, 5, 7, and 10 DAS at 5% of the significance level. Overall, we can say that the different treatments have different effects on reducing the whitefly population.

Partial Least Squares Regression (PLSR) and Artificial Neural Network (ANN): The models PLSR and ANN were employed to predict the population of whiteflies based on various parameters. The PLSR model yielded MSE of 10.72 and R-squared value of 0.67, indicating moderate level of predictive accuracy. The optimal parameters identified were sprayer technology as drone sprayer and 10 day after treatment, with predicted minimum number of whiteflies at 7 DAS. Conversely, the ANN model showed better performance with MSE of 8.31 and R-squared value of 0.74. The optimal parameters for ANN were engine power gun sprayer at 10 DAS, predicting a minimum of 8.00 whiteflies. The higher R-squared value of ANN suggests its better capability in capturing the variance in the dataset compared to PLSR. The scattered plots depicted a positive correlation between the actual number of whiteflies and the number predicted by a PLSR and ANN models (Fig. 1). The data points cluster closely around the diagonal line, indicating good agreement between the predicted and actual values.

Economics of sprayer's application: Different sprayers have varying costs associated with initial investment, and operation matinees expenses can significantly impact its economic viability. The field efficiency was calculated as 50%, which was a little below the recommended (55–65%) (Kumar *at al.* 2020b). The actual field capacity of the sprayers was found to be T_1: 1.78 ha/h, T_2: 1.42 ha/h, T_3: 1.46 ha/h, T_4: 0.06 ha/h, T_5: 0.40 ha/h, T_6: 0.08 ha/h and T_7: 1.25 ha/h. The cost of operation varied and ranged between ₹196.37–998.29/ha of sprayers. The height cost of operation was observed in the case of air assisted electrostatic sprayer followed by knapsack sprayer, drone sprayer, powered knapsack sprayer, auto-rotate gun sprayer, air-assisted drop-up boom sprayer and high clearance sprayer. The total cost of the operation of the drone for spraying was ₹720/ha. From the data presented in Fig. 2, an engine-powered knapsack gun sprayer offered a modest 20% cost saving with no significant time or labour savings. Air assisted electrostatic sprayer showed negative percentages across all categories, indicating a potential increase in time (-33%), labour (-160%), and cost (-130%) as compared to the knapsack sprayer. Tractor-operated auto-rotate gun, air-assisted drop with boom, high clearance boom, and drone sprayers exhibited substantial savings in time, labour, and cost, making them more efficient alternatives to the knapsack sprayer. High clearance boom and drone sprayers stand out with significant savings across all three parameters, making them potentially more cost-effective and time-efficient choices for agricultural applications. Chen *et al.* (2020) reported that in recent years, use of UAV spraying with low

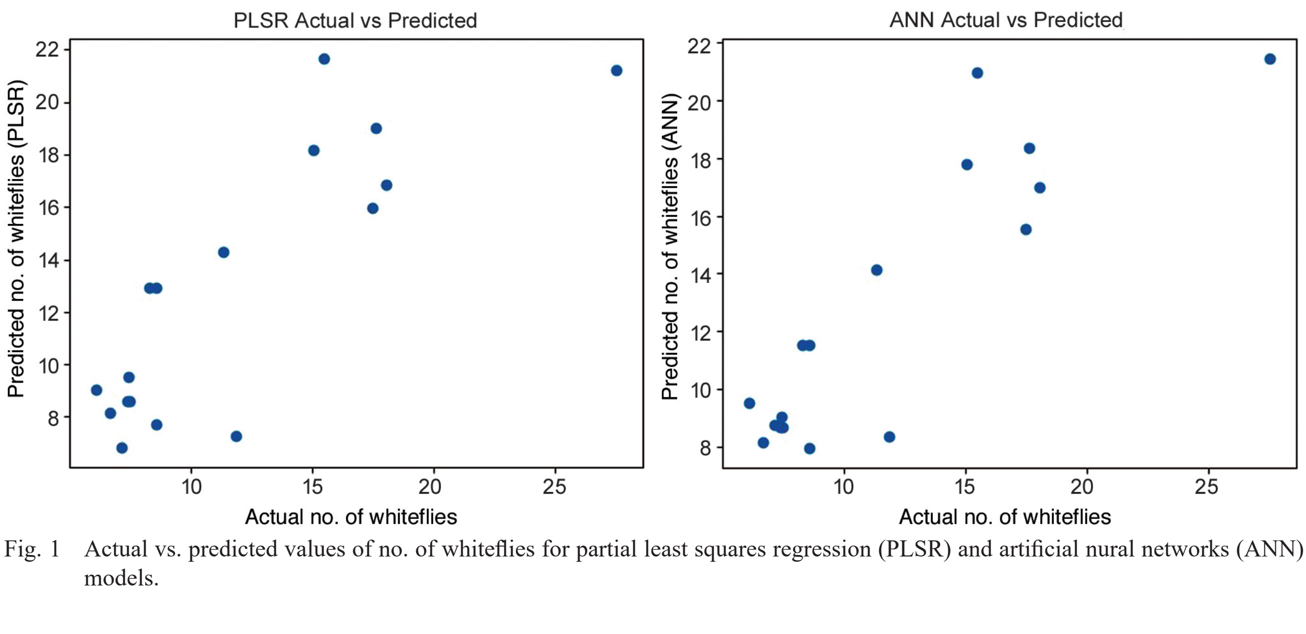

Fig. 1 Actual vs. predicted values of no. of whiteflies for partial least squares regression (PLSR) and artificial nural networks (ANN) models.

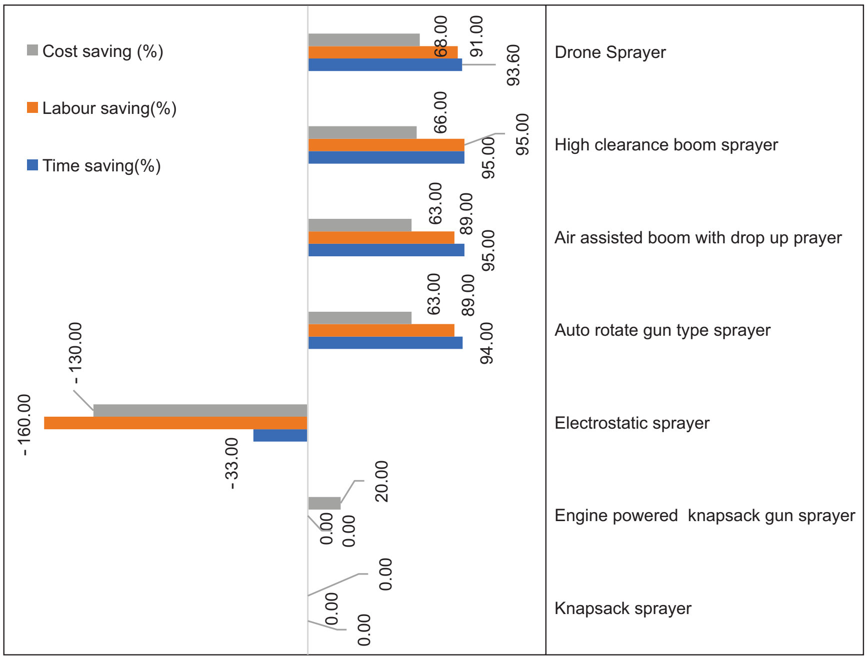

Fig. 2 Operation economics of different sprayers over knapsack sprayer by straight-line depreciation method.

altitudes and low volume has increased the application of chemicals to control pests in different crops because it saves time, energy, and drudgery of operation with less chance of chemical contact to operator as well as avoiding soil structure damage by controlling traffic over field surface.

Based on the field experiments, evaluation of different spraying technologies, and the data analysis performed using ANOVA, ANN, and PLSR techniques, it was concluded that drone sprayer produced the lowest droplet density (24.43 drops/cm²), smallest droplet size (103.38 µm), and minimum area coverage (5.97%), whereas the high-clearance boom sprayer generated the largest droplets (488.39 µm) and highest coverage (33.49%); the air-assisted drop-up sprayer achieved the highest spray deposition (32.02 µL/cm²); droplet density, coverage, deposition, and size. The results were significantly influenced by sprayer type, leaf surface (adaxial>abaxial), and canopy position, demonstrating the combined effect of design and crop architecture on spray distribution. All sprayer technologies significantly reduced whitefly populations compared to the control treatment, with substantial reductions observed at 7 and 10 DAS, demonstrating their bio-efficacy despite differences in spray characteristics. The ANN model (R^2 = 0.74; MSE = 8.31) outperformed PLSR (R^2 = 0.67; MSE = 10.72) in predicting whitefly populations. High-clearance boom and drone sprayers showed noteworthy time, labour and cost savings over knapsack sprayers. Future research should target enhanced canopy penetration, AI-based spray optimisation, drift minimisation, and validation under diverse crop and climatic conditions.

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