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Research article

Evaluation of unmanned aerial vehicle for effective spraying application in coconut plantations

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ABSTRACT

Unmanned aerial vehicle (UAV) pesticide application in recent years owing to its importance such as time saving, reduction in human drudgery and also reduction in pesticides application rate. UAV has a great potential to address the problem involved in manual chemicals spraying in tall crops like coconut plantation where at present operation performed by manual climbing involves lots of drudgery and life risk. The current study aimed to understand the most influencing spraying parameters, such as spray height and spray time of the UAV sprayer on droplet characteristics such as spray droplet size, spray coverage and spray deposition at different layers (spindle, middle and bottom) of coconut tree canopy. The selected spray height (1, 2 and 3 m) and spray time (5, 8 and 11 s) significantly affects ($p < 0.05$) the droplet size (μm), spray coverage (%) and spray deposition (μl cm^{-2}). In spray droplet size, the treatment T4, T5, T7 and T8 were recorded recommended droplet size of 50–400 μm in all layer of the coconut tree canopy. In spray coverage, the nearest value for recommended spray coverage of 10–20 % was observed for T1 and T5 treatment in all layer of the coconut tree canopy. The maximum penetration efficiency of 34.41 % had achieved at spray height of 2m and spray time of 8s (treatment T5). Based on performance of selected parameter, the spray height of 2 m and spray time of 8 s (treatment T5) was found best for spraying operation using UAV in coconut tree. The results showed the performance of the UAV offers best alternative for spraying operation on coconut tree and also this system will drastically reduce application time, labour requirement and improved the safety of coconut farmers.

1. Introduction

Cocos nucifera, commonly known as coconut tree is cultivated extensively in the tropical and subtropical climate for its nuts and oils with centre of origin as central Indo-Pacific region. Apart from its usage as oil, coconut also have important role as food, fuel, building material, cosmetics, medicinal and also craft industry. More than 90 nations cultivating coconuts, with that Asia and the Pacific regions accounting for more than 89 % of global production. With an annual production of more than 21,500 million nuts, India ranks first

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among countries that produce coconuts (CDB, 2021). Even though coconut is a sturdy perennial palm, it is affected by a wide array of insects, mites, rodents and many lethal and debilitating diseases throughout its life span causing an average of 20–25 % loss every year (CDB, 2021). Though many diseases and pests are reported on coconut, diseases such as bud rot caused by *Phytophthora palmivora*, basal stem rot caused by *Ganoderma lucidum,* root wilt caused by phytoplasma, and pests like rhinoceros beetle (*Oryctes rhinoceros*), red palm weevil (*Rhynchophorus ferrugineus*), leaf eating caterpillar (*Opisina aernosella*) and invasive rugose spiralling whitefly (*Aleurodicus rugioperculatus*) are economically very important in India. Other problems include mite, rodents, fruit rot, leaf spots and leaf blights (Namboothiri et al., 2019). For the management of these pests and diseases, various sustainable pest/disease management strategies have been worked out and done successfully under field conditions. Community based approach of management of pest/diseases in coconut is the only practical and successful method as majority of pest and pest problems needs prophylactic management in a wider area. This requires trained manpower, chemicals, time and climbing equipments as most of the management strategies are to be carried out in and around the crown portion of the coconut palm. For curative measures of management, spot applications of chemicals are recommended, that too in huge quantities. For example, prophylactic spraying of 300 ml of Bordeaux mixture per palm on the inner most leaf axils of the coconut crown before onset of monsoon (late May or early June) are the recommendation for the management of bud rot disease in coconut [1]. The traditional method of management of major pests and diseases requires climbing on to the coconut crown area and spot application of chemicals/bio agents on leaf axils, spindle leaves, nuts, and inflorescence or on all parts by spraying with the help of sprayers. The climbing task becomes more arduous depending on the height of the palm. The average height of the tree is between 18 and 25 m with 3.5 m of average leaf length. Due to tall tree and topographic restrictions, ground spraying machinery is also difficult to operate for coconut tree. Apart from these difficulties, scarcity of coconut climbers and their high wage for climbing charges forces the farmers to leave no option for the timely adoption of management strategies leading to more crop loss. Unmanned Aerial Vehicles (UAV) has a great potential to support and address these issues to control pest and disease especially for tall tree and complex topographic like coconut plantations [2,3]. UAV assisted spraying will be of great advantage over manual spraying as it will impart highest level of precisions saves lot of time, no risk of life to workers and also limits the use of pesticides. Furthermore, spot application of chemicals could also be targeted through UAV. The important parameters of UAV sprayer like spray height [4,5], spray time have significant influence on spray droplet size [6–8], droplet deposition [9,10], coverage, distribution uniformity [11] and drift [12,13]. So far, extensive research has made on field crops and orchard crop using UAV based sprayer [4,14,15] but very limited work has been done in plantation crops like coconut tree in India.

UAV spraying tests were carried out in this study, to better understand the effects of spray height and spray time on spray droplet size (VMD), spray coverage (%), droplet deposition (μl cm^{-2}), and penetration efficiency (%) at different layers (spindle, middle and bottom) of coconut tree canopy of UAV spraying methods. This study will give in-depth knowledge for the optimization of the sprayer parameters for coconut tree using UAV sprayer.

2. Materials and methods

2.1. Unmanned aerial vehicle

The E610P hexacopter plant-protection UAV sprayer (M/s. EFT Electronic Technology Co., Ltd., China) with a payload capacity and take-off load capacity of 10 L and 25 kg respectively was used in the study. The maximum flight height, flight speed, self-weight flight time and flight control distance were 25 m, 0-8 ms^{-1}, 25 min and 1.4 km, respectively, during operation. This UAV's six-blade propeller design, lowers the frame's vibration during the spray operation and also enhances the flight stability. Furthermore, high downwash airflow generated by the UAV helps in penetration of spray deposition into the crops canopy. Four flat fan nozzles (model: 2020A-132, make: M/s. Ningbo Licheng Agricultural Spray Technology Co., Ltd., China) is fixed under the rotor wings and maximum spray pressure generated by the system was 0.39 mpa. Flight control of UAV has manual control using remote-controlled type with Radio Master Link, controlled via radio frequency at 2.4 GHz and Auto-Pilot control based on the drone's flight position from GPS route planning with emergency landing option, which uses decision data received from the satellite. To provide the necessary power for the UAV system, the UAV sprayer has two LiPo batteries with six cells each and a capacity of 16,000 mAh with charging time of 30 min. Spray liquid was atomized into tiny spray droplets using a T-Jet nozzle after being pressurized by a brushless direct current motor (BLDC) attached water pump.

2.2. Experimental plot and design

The experiment was conducted at MAWA Plot, ICAR-Central Plantation Crops Research Institute, Kasaragod, India (12 31 50 N, 74 58 8 E). The average height of coconut tree was 12 m, the tree age was 11 years, and the row spacing and plant spacing was 7.5 m.

In this study, the spray height was selected as 1, 2 and 3 m to avoid spray drift due to wind speed and to increase the spray deposition inside canopy as reported by many researchers (Wang et al., 2018: Zhang H. et al., 2020, Yallappa et al., 2022). Another reason for selection of low spray height was due to most of coconut cultivation was near to coastal area where high wind velocity was observed. In the experiment, the spray characteristics was recorded during the wind speed of 1.0 ± 0.4 ms^{-1} to reduce the ill effect. The hovering method of UAV spraying was carried out in the experiment for 5 s, 8 s and 11 s at the top of the spindle. The droplet deposition was found not satisfactory on coconut tree during flight operating speed hence, it was planned to hover the UAV for 5 s, 8 s and 11 s at the top of the coconut tree. During the experiment, the measurements comprised following parameters like spray droplet size, spray coverage and droplet deposition in the different layer of tree (spindle, middle and bottom) and ground loss were recorded. Water-sensitive paper (WSP, Syngenta Crop Protection AG, Basel, Switzerland) of size 50 mm × 50 mm was selected as the droplet collector. The layout of the experimental area is shown in Fig. 1.

2.3. Environmental condition

During the experimental study, various meteorological parameters such as, air temperature, relative humidity, wind velocity and rainfall at Mawa Plot, ICAR-Central Plantation Crops Research Institute, Kasaragod, India were recorded in order to avoid the negative effects of weather on the performance of the spraying operation shown in Table 1.

2.4. Spray sampling

2.4.1. Sampling of spray deposition

As presented in Table 2, nine treatments with selected spraying height and spraying time are performed for evaluating droplet distribution and nine coconut trees are for data collection. The canopy of each coconut tree was divided into three layers, i.e., spindle, middle (14th leaf) and bottom layer. In each layer, the 50 × 50 mm Water sensitive paper (WSP) cards were fixed on the top surface of leaf using the paper clip to collect spray droplets on sensitive side. The spray characteristics such as spray droplet size, spray coverage and spray deposition in target area were collected and analyzed using DepositScan® Software developed by United States Department of Agriculture.

2.4.2. Sampling of ground level

During the spraying operation, the spray materials are not completely deposited in the coconut tree canopy layers. Some of the spray materials pass through the different layers of canopy and are deposited on the ground, causing soil pollution. To catch the spray droplets that fell to the ground, four WSP around the tree were set up on the ground beneath each target coconut tree. To measure spray droplet deposition in the ground, a WSP with a size of 50 × 50 mm was fixed on flat iron plates attached to square iron rods at each collection location.

2.4.3. Penetration efficiency

Penetration efficiency in the vertical direction at different layers of the coconut tree canopy was calculated as follows to evaluate the performance of droplet uniformity of the UAV sprayer [16].

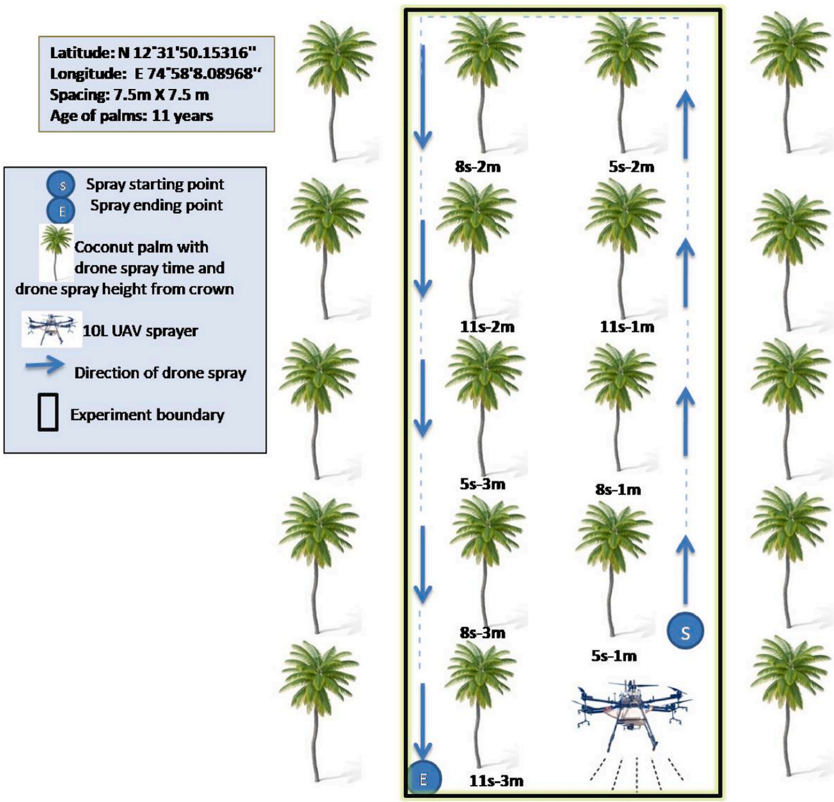

Fig. 1. Experimental plot layout for UAV spray test.

Table 1
Meteorological data during the UAV spray test in Mawa Plot, ICAR-CPCRI.

Date	
Time	: 6–8 AM (21-03-2023 to 23-03-2023)
Location	: Mawa Plot, ICAR-Central Plantation Crops Research Institute, Kasaragod, India
Environmental parameters	Air temperature, °C: 28.5 ± 1.5
	Relative humidity, %: 70 ± 2
	Wind velocity, ms^{-1}: 1.0 ± 0.4
	Rainfall, mm: Nil

Table 2
A summary of operational parameter and its treatments number.

Number of treatments	Spray height (H), m	Spray time (T), s
T1	1	5
T2	1	8
T3	1	11
T4	2	5
T5	2	8
T6	2	11
T7	3	5
T8	3	8
T9	3	11

$$Dp = \frac{D_b}{D_s + D_m} \times 100 \quad (1)$$

where, D_p (%) represents the percentage used as a value to judge droplet penetration of the UAV sprayer; D_s, D_m and D_b, represents the droplet deposition (μl cm^{-2}) on spindle, middle and bottom layer of canopy. The higher the D_p value the better the penetrations through the different layer of the tree canopy.

An ANOVA and Duncan test was carried out to evaluate the spray droplet size, spray coverage and deposition data at different layers of coconut tree canopy with three spray height and three spray time, at a significance level ($p < 0.05$). The statistical analyses using the SAS Statistics software for were performed.

3. Results and discussion

3.1. The effect of spray height (H) and spray time (T) on droplet size (VMD)

The UAV sprayed at three height (1, 2, 3 m) and three spray time (5,8,11 s) and droplet sizes (VMD) collected using WSP were analyzed. The data analysis showed that main effect and their interaction effects were statistically significant on droplet size ($p < 0.05$) in all the layers (spindle, middle and bottom) of the coconut tree, as shown in Table 3.

From Fig. 2, the size of the droplets sizes gradually increased with an increase in the spray time from 5, 8 and 11 s at targeted layers for all spray height. The data showed that the droplet size of the upper layer was the highest followed by middle and bottom layer under the same treatment. This may be because the larger droplets cannot easily penetrate inside coconut leaf pore space and falls on upper layers of canopy, while the smaller droplets are more capable of easily penetrating into the canopy and reaches the bottom layers. Similar result was reported by Wang et al. [17] and Li et al. [18]. From Fig. 2, it was also observed that the size of the droplets gradually decreased with an increase in the spray height from 1 to 3 m at target layer for all spray time. This showed that the increase in the UAV spray height from 1 to 3 m, lead to a secondary breakup of droplet size leading to reduction in the spray droplet and another reason may be due to the effect of downwash airflow further decreases the size of droplets.

In Duncan test, the significant difference of VMD was not observed for treatment T4 and T8 at spindle, T5 and T9 at middle and at

Table 3
ANOVA of spindle, middle and bottom layer for droplet size (μm), VMD.

Source	DF	Mean Sum of Squares		
		Spindle	Middle	Bottom
H	2	43205.48*	46768.41*	42695.36*
T	2	35867.28*	23167.88*	15449.33*
H*T	4	826.18*	2050.87*	1601.83*

Here '*' denotes level of significance ($\alpha = 5\%$)).

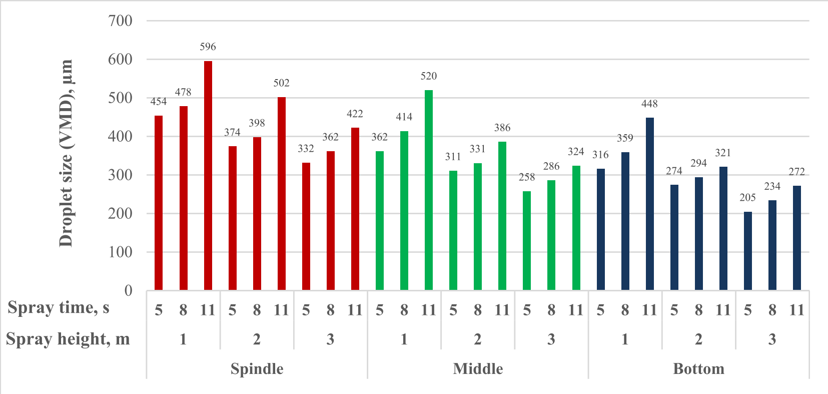

Fig. 2. Comparison of droplet size (VMD) for selected spray height and spray time on different layers of coconut tree.

bottom (T1 and T6; T4 and T5) (Table 4). The maximum droplet sizes of 596 ± 24.17 μm, 520 ± 14.53 μm, 448 ± 12.11 μm were observed at spindle, middle and bottom layer respectively at treatment T3. The minimum droplet sizes of 332 ± 4.49 μm, 258 ± 9.53 μm, and 205 ± 3.9 μm were observed at spindle, middle and bottom layer, respectively for treatment T7. In overall the highest droplet size in the experiment was observed at treatment T3 (596 μm) at spindle layer and lowest droplet size was observed at treatment T7 (205 μm) at bottom layer. This again indicates that the density of branches and leaves in the coconut tree canopy blocking the larger droplets at spindle layer and allowing fine droplets to settle at middle and at bottom layer of coconut tree. In ground sprayer, the effective droplet size to control pest and diseases in tree was reported as 50–400 μm. The UAV sprayer effective droplet size with less drift was reported as 200–400 μm ([19]; Chen et al.,2022; wang et al., 2023) because below 200 μm the droplets drifts and above 400 μm showed less effective for pest control. In our study, the treatment T4, T5, T7 and T8 recorded recommended droplet size in all layers of the coconut tree canopy.

3.2. The effect of flight height and spray time on spray coverage in the canopy

The UAV sprayed at three height (1, 2, 3 m) and three spray time (5, 8, 11 s) and spray material were collected in WSP and analyzed (Table 5). The data analysis showed statistically significant difference in coverage percentage ($p < 0.05$) for the main and interaction effect on different layers of coconut tree (spindle, middle and bottom). The results showed that maximum spray coverage of 31.90 %, 27.40 % and 14.58 % were observed at spindle, middle and bottom layers for treatment T3. The minimum coverage of 9.70 % and 7.61 % were observed at spindle and middle layer and at bottom layer it was observed for treatment T9 (4.10 %). The overall highest spray coverage in the experiment was observed as 31.90 % for treatment T3 at spindle layer and lowest spray was observed as 4.10 % for treatment T9 at bottom layer, respectively. In all the case, the spray coverage was recorded highest at spindle layer followed by middle and bottom layer. This confirms that the denser the branches and leaves, it considerably reduces the penetration of spray material at bottom layer. This observation revealed canopy structure is one of the most important factors influencing the spray coverage (Wang et al., 2023; [20], 2018). In Duncan test, significant difference of spray coverage was not observed in treatment T2 and T6, T4 and T7 at spindle, T2 and T6 at middle. For lower layer, treatment T4 and T7, T5 and T6 showed no significant difference (Table 6).

In Fig. 3, the spray coverage gradually increased with an increase in the spray time from 5, 8 and 11 s at target layers for all spray height expect at spray height of 3 m. Increased trend of spray coverage with spray time may be due to longer exposure time of spray material. At spray height of 3 m, the spray coverage increased from 5 s to 8 s and further increases in spray time decreased the spray coverage. The reason may be due to the complex distribution of the overall leaf inclination angle of coconut tree, . In Fig. 3, it was also

Table 4
Means, standard deviation and coefficient of variations (CV) of VMD on spindle, middle, and bottom layer.

Treatment	Spray droplet size (μm), VMD		
	Spindle	Middle	Bottom
T1	454 ± 7.78^{d}	362 ± 8.16^{d}	$316{\pm}2^{c}$
T2	478 ± 12.50^{c}	414 ± 7.83^{b}	359 ± 11.65^{b}
T3	596 ± 24.17^{a}	520 ± 14.53^{a}	448 ± 12.11^{a}
T4	374 ± 6.41^{g}	311 ± 8.86^{f}	274 ± 11.85^{d}
T5	398 ± 5.38^{f}	331 ± 12.53^{e}	294 ± 5.83^{d}
T6	502 ± 8.15^{b}	386 ± 3.48^{c}	321 ± 12.44^{c}
T7	332 ± 4.49^{h}	258 ± 9.53^{h}	205 ± 3.9^{g}
T8	362 ± 6.20^{g}	286 ± 3.35^{g}	234 ± 3.37^{f}
T9	422 ± 0.38^{e}	324 ± 2.92^{e}	272 ± 10.54^{e}
CV	2.541	2.188	3.176

The different letters in each column after mean value are significantly different at a level of 5 %.

Table 5
ANOVA of spindle, middle and bottom layer for coverage (%).

Source	DF	Mean Sum of Squares		
		Spindle	Middle	Bottom
H	2	240.9*	162.3*	128.62*
T	2	474.3*	370.1*	54.54*
H*T	4	8.14*	3.28*	16.81*

Here '*' denotes level of significance (α = 5%).

Table 6
Means, standard deviation and coefficient of variations (CV) of spindle, middle and bottom for coverage (%).

Treatment	Spray coverage (%)		
	Spindle	Middle	Bottom
T1	19.70 ± 0.803[e]	15.10 ± 0.180[e]	9.70 ± 0.087[d]
T2	28.30 ± 0.820[b]	23.20 ± 0.190[b]	13.90 ± 0.423[b]
T3	31.90 ± 1.380[a]	27.40 ± 0.76[a]	14.58 ± 0.144[a]
T4	10.20 ± 0.397[g]	8.70 ± 0.118[g]	5.31 ± 0.154[f]
T5	21.20 ± 0.118[d]	18.20 ± 0.376[d]	13.28 ± 0.310[c]
T6	28.20 ± 0.964[b]	22.40 ± 0.649[b]	13.05 ± 0.531[c]
T7	9.70 ± 0.123[g]	7.61 ± 0.319[h]	5.20 ± 0.072[f]
T8	17.10 ± 0078[f]	13.20 ± 0.57[f]	6.80 ± 0.026[e]
T9	22.60 ± 0.021[c]	19.80 ± 0.535[c]	4.10 ± 0.087[g]
CV	1.795	1.400	1.236

The different letters in each column after mean value are significantly different at a level of 5 %.

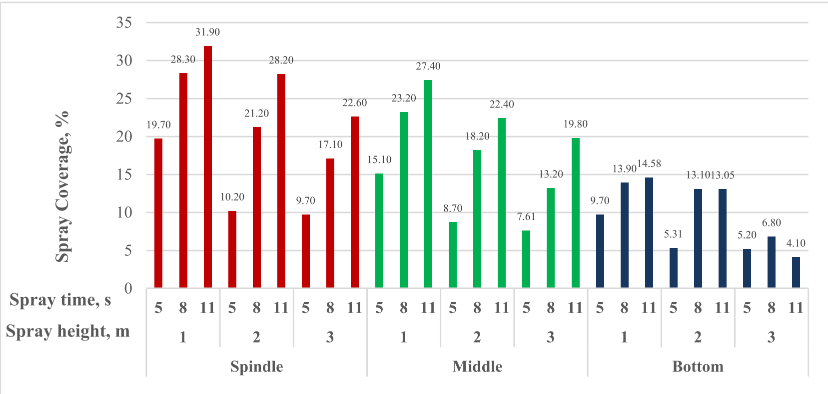

Fig. 3. Comparison of coverage (%) for selected spray height and spray time on different layers of coconut tree.

observed that the spray coverage gradually decreased with an increased in the spray height from 1 to 3 m at targeted layers for all spray time. It was observed that the increased in height of spray increases the width of spray hence the spray material was distributed more on lateral direction than the vertical downward direction. This result confirmed that the higher the spray height larger the coverages of the outside layers than those of the middle and bottom layers (Meng et al., 2022). On other hand, this may be due to natural wind speed

Table 7
ANOVA of spindle, middle and bottom for spray deposition (μl cm^{-2}).

Source	DF	Mean Sum of Squares		
		Spindle	Middle	Bottom
H	2	3.27*	2.07*	0.89*
T	2	3.77*	1.23*	0.69*
H*T	4	2.65*	0.17*	0.11*

Here '*' denotes level of significance (α = 5%).

which drift the spray material in higher spray height compare to lower spray height, another reason may be due to residence time of spray droplets in air.

3.3. The effect of flight height and spray time on spray deposition

From table, significant differences ($p < 0.05$) were observed for average spray deposition of main and interaction effect of spray height (H) and spray time (T) on the different location of coconut tree (Table 7).

In Duncan test, except treatment T2 and T6 at spindle layer all other treatment showed significant difference of spray deposition at different layer of coconut tree (Table 8). The maximum spray deposition of 2.60 ± 0.028 μl cm^{-2}, 2.05 ± 0.087 μl cm^{-2}, and 1.44 ± 0.021 μl cm^{-2} were observed in spindle, middle and bottom layers, respectively at treatment T3. The minimum droplet sizes of 0.50 ± 0.013, 0.40 ± 0.010 and 0.27 ± 0.010 μl cm^{-2} was observed in spindle, middle and bottom layers respectively at treatment T7. The overall highest spray deposition in the experiment was 2.60 ± 0.028 μl cm^{-2} for T3 treatment at spindle layer and lowest spray deposition was observed as 0.27 ± 0.010 μl cm^{-2} for T7 treatment at bottom location. From Fig. 4, it was revealed that the increase in spray time the spray deposition increased.

From Fig. 4, it was also observed that the increase in spray height the amount of spray deposition decreased. The release height of UAV droplets of tall trees was at higher altitude, lesser the force of air speed creates by UAV on top layer hence the penetration of spray material was restricted. This is also confirmed with the study of Wang et al., (2019), it was reported the higher the altitude, the weaker the downwash airflow of the rotor at the top of canopy, and more easily sprayed droplets can drift with the crosswind. As expected, the spindle layer had recorded highest spray deposition followed by middle layer and bottom layer for all treatment. During the droplet deposition on the canopy, the branches and leaves on the upper layer of coconut tree block the larger spray material, while the fine droplets with smaller amount of spray material pass through the pores of the branches and leaves and settle into the middle and bottom layer.

3.4. Penetration efficiency (D_p)

Percentages of droplet deposition at different layer in the coconut canopy was calculated and shown in Fig. 5 for further analysis of droplet distribution in the different layers. The results demonstrated that an increase in the spray time from 5 s to 8 s improved the penetration efficiency and slightly reduced with further increase in spray time to 11 s in all spray height. This confirmed that a high spray time for same spray height does not necessarily increase the penetration efficiency. In high spray time, the larger spray droplets are prone to runoff from the leaves at spindle layer rather increasing the penetration efficiency where else lower penetration efficiency in less spray time at all spray height is due to insufficient amount of spray material released on different layer. The maximum penetration efficiency of 34.41 % had achieved for T5 treatment and shown significantly difference compared with other treatment. In UAV sprayer, increased penetration efficiency may be due to the downwash air speed causes disturbance to the canopy, changes the original branch and leaf structure, and the pore space of the canopy becomes larger. Additionally, the downwash air speed increases the movement velocity of the spray droplets and enhances the kinetic energy of the droplets to transport to the canopy. The higher the D_p value is the better the penetration efficiency of UAV sprayer. Based on the performance, the highest PE valve was recorded for T5 treatment i.e. for spray height of 2m and spray time of 8 s and it was recommended for pesticide application using UAV sprayer in coconut tree.

3.5. The effect of flight height and spray time on ground loss

The effects of different spray height (1, 2, 3 m) and spray time (5, 8, 11 s) on the ground loss of pesticides under tree canopies were analyzed. The data analysis showed statistically significant difference in VMD, coverage and deposition ($p < 0.05$) on ground level (Table 9).

3.6. Droplet size at ground layer

The maximum droplet size was observed for treatment T3 (243 ± 5.64 μm) followed by treatment T2 (238 ± 3.65 μm) and these treatments had no significant difference (Table 10). Similarly, the treatment T1 and T5 was observed with no significant difference. The lowest droplet size of 124 ± 8.48 μm was recorded for treatment T9. Increased in spray height gradually decreased the droplet size at ground layer. This may be due to lesser the height of UAV higher the disturbance created to canopy structure due to downwash speed of UAV and increased the droplet movement along pore space of leaf to reach the ground.

3.7. Spray coverage at ground layer

The highest and lowest spray coverage was observed for treatment T3 as 18.20 ± 0.397 % and treatment T4 as 5.60 ± 0.057 % (Table 10). In Duncan test, significant difference of spray coverage was not observed between treatment T1 and T7 and for treatment T5 and T6. As the spray time increased from 5 s to 11 s the spray coverage on WSP was also observed increased trend except at spray height of 3 m. From Table 10 and it was also observed that the increased in spray height the spray coverage on WSP was decreased except for spray time 5 s. This may be due to the more coverage on outside of the canopy and also may be due to spray drift as reported by [6].

Table 8
Means, standard deviation and coefficient of variations (CV) of deposition on spindle, middle and bottom layer.

Treatment	Spray deposition (μl cm^{-2})		
	Spindle	Middle	Bottom
T1	0.95 ± 0.005^f	0.79 ± 0.010^g	0.49 ± 0.015^g
T2	1.98 ± 0.07^b	1.52 ± 0.010^c	1.11 ± 0.010^b
T3	2.60 ± 0.028^a	2.05 ± 0.087^a	1.44 ± 0.021^a
T4	1.31 ± 0.030^d	1.22 ± 0.042^e	0.61 ± 0.010^e
T5	1.44 ± 0.023^c	1.35 ± 0.010^d	0.96 ± 0.021^d
T6	1.97 ± 0.026^b	1.67 ± 0.046^b	1.00 ± 0.000^c
T7	0.50 ± 0.013^h	0.40 ± 0.010^i	0.27 ± 0.010^i
T8	0.72 ± 0.029^g	0.50 ± 0.021^h	0.39 ± 0.010^h
T9	1.16 ± 0.018^e	0.91 ± 0.026^f	0.56 ± 0.021^f
CV	29.84	3.489	1.941

The different letters in each column after mean value are significantly different at a level of 5 %.

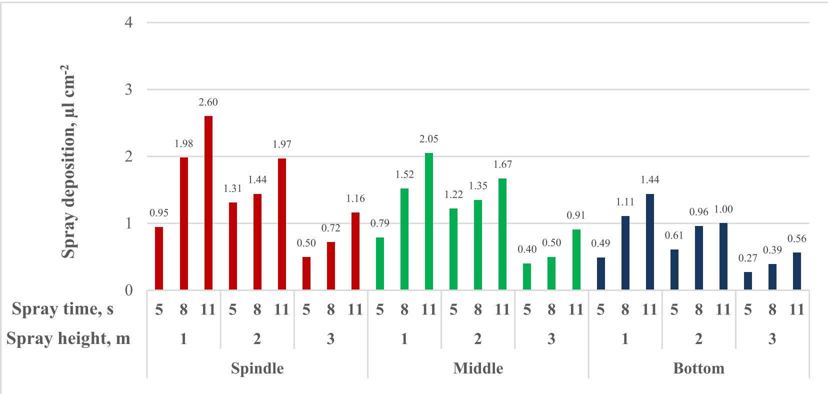

Fig. 4. Comparison of deposition (μl cm^{-2}) for selected spray height and spray time on different layers of coconut tree.

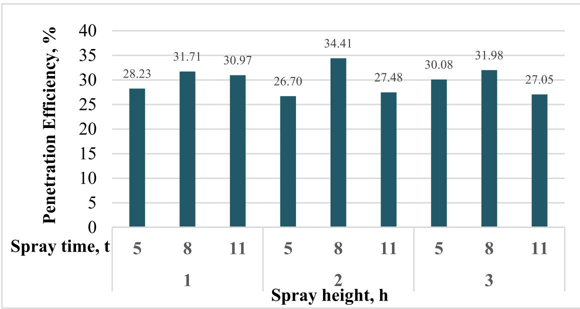

Fig. 5. Penetration efficiency for different treatment on selected layers of coconut tree.

Table 9
ANOVA of ground layer.

Source	DF	At ground level		
		VMD, μm	Coverage, %	Deposition, μl cm^{-2}
H	2	19385.82*	83.58*	2.07*
T	2	433.23*	86.96*	1.77*
H*T	4	1114.26*	21.87*	0.89*

Here '*' denotes level of significance ($\alpha = 5\%$).

Table 10
Means, standard deviation and coefficient of variations (CV) of VMD, spray coverage and spray deposition at ground layer.

Treatment	VMD, μm	Coverage, %	Deposition, μl cm^{-2}
T1	199 ± 4.48^{b}	8.20 ± 0.02^{e}	0.45 ± 0.010^{f}
T2	238 ± 3.65^{a}	16.20 ± 0.42^{b}	2.26 ± 0.046^{a}
T3	243 ± 5.64^{a}	18.20 ± 0.397^{a}	1.82 ± 0.072^{b}
T4	184 ± 1.08^{c}	5.60 ± 0.057^{g}	0.54 ± 0.010^{e}
T5	199 ± 4.81^{b}	12.10 ± 0.273^{c}	0.86 ± 0.006^{d}
T6	172 ± 3.43^{d}	12.40 ± 0.237^{c}	0.89 ± 0.021^{d}
T7	146 ± 1.90^{e}	8.19 ± 0.00^{e}	0.39 ± 0.010^{g}
T8	132 ± 1.12^{f}	7.40 ± 0.140^{f}	0.26 ± 0.010^{h}
T9	124 ± 8.48^{g}	9.20 ± 0.288^{d}	1.19 ± 0.015^{c}
CV	2.190	2.352	3.096

The different letters in each column after mean value are significantly different at a level of 5 %.

3.8. Spray deposition at ground layer

In Duncan test, significant difference of spray deposition was not observed between treatment T5 and T6 (Table 10). The highest and lowest spray deposition was observed for treatment T2 2.26 ± 0.046 μl cm^{-2} and treatment T8 0.26 ± 0.010 μl cm^{-2}. There was no trend observed for selected spray height and spray time in spray deposition on ground. The reason for maximum penetration of droplets for T2 treatment may be due to high downwash airflow at spray height of 1 m causes high shaking effect of the branches and these transports spray droplets beyond the canopy structure.

In spray droplet size, the effective droplet size to control pest and diseases in tree was reported as 50–400 μm. In this study, the treatment T4, T5, T7 and T8 recorded recommended droplet size in all location of the coconut tree. In spray coverage, WSPs with coverage higher than 30 % were classified as over-sprayed. It is also reported that a high coverage does not necessarily imply a more effective spray application [21,22]. The recommended coverage rate for sprayer was 10–20 % [23]. In our experiment, the nearest value for recommended spray coverage in all location was observed for T1 and T5 treatment. In spray deposition, in the study showed acceptable for all selected parameters in all layer of coconut tree. The most influence parameters were penetration efficiency, the higher the D_p value is the better the penetration efficiency of sprayer and higher the uniformity of spray for effective control pest and diseases. Based on that the maximum penetration efficiency of 34.41 % had achieved for T5 treatment and shown significantly difference compared with other treatment. In overall, the performance of treatment T5 i. e spray height of 2 m and spray time 8 s was in acceptable range in term spray droplet size, spray coverage and spray deposition and penetration efficiency. The treatment T5 can be selected for tall crop having similar tree geometry of coconut tree. However, several aspects must be considered to determine the effect of other parameters such as Leaf Area Index at different growth stage of tree and spray dosage volume on the spray effect and spray drift in order to improve the spray performance of the plant-protection UAVs for coconut tree. The performance evaluated of UAV system must be conducted for pest control of coconut trees before the commercialization of the optimized operation strategy when compared to the traditional manual knapsack method.

4. Conclusion

In this study, the effects of three spray height (1, 2 and 3 m) and three spray time (5, 8 and 11 s) on the droplet size (VMD), spray coverage (%), deposition distribution (μl cm^{-2}) in the canopy layer and ground level were systematically analyzed to understand the spray characteristics on coconut tree. The selected spray height and spray time significantly affects the spray characteristics viz., droplet size, spray coverage and spray deposition. The droplet size, spray coverage, deposition distribution in the spindle layer was found higher than middle and bottom layer with increased in spray time in all spray height. Based on the analyzed data for selected spray height and spray time on selected spray characteristics, it is suggested to select the spray height of 2 m and spray time of 8 s (Treatment T5) for satisfactory performance of UAV sprayer for coconut tree. The mean droplet size, spray coverage, and spray deposition was found to be in acceptable range for the effective control of pest and diseases and similarly penetration efficiency of treatment T5 was found significantly higher compared to other treatments.

Data and code availability statement

Data will be made available on request.

CRediT authorship contribution statement

R. Pandiselvam: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Conceptualization. **Daliyamol:** Writing – original draft, Methodology, Investigation, Data curation. **Syed Imran S:** Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Vinayaka Hegde:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Data curation. **M. Sujithra:** Validation, Resources, Investigation, Funding acquisition, Formal analysis. **P.S. Prathibha:** Validation, Methodology, Investigation, Formal analysis, Data curation. **V.H.**

Prathibha: Methodology, Investigation, Formal analysis, Data curation. **K.B. Hebbar:** Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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