Effects of citrus tree-shape and spraying height of small unmanned aerial vehicle on droplet distribution

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Abstract: In order to explore the droplet penetration of spraying with unmanned aerial vehicle (UAV) on citrus trees with different shapes, the tests were carried out at different working heights. The material was five years old Cocktail grapefruit (*Citrus paradisi cv*. Cocktail) grafted on Trafoliata (*Poncirus trifoliata* L. Raf.) and the type of UAV sprayer used was the 3W-LWS-Q60S. A solution of 300 times Ponceau 2R diluents liquid instead of pesticide was used for citrus fields spraying and the droplets were collected by paper cards. Droplets deposition parameters were extracted and analyzed using digital image processing after scanning the cards. The results showed that: 1) For the trees with round head shape canopy, the droplet depositions of the upper, middle and lower layers had a significant difference at 0.05 level. The droplet deposition had the best effect when the working height was 1.0 m, where the average droplet deposition densities were 39.97 droplets/cm^2 and the average droplet size was 0.30 mm, but the droplet coverage (3.19%) was lower than that at the working height of 1.5 m (4.27%). 2) Under three different working heights of UAV, the tree with open center shape can obtain higher droplet deposition density at all three layers than that with the round head shape canopy. It was especially prominent when the working height was 1.0 m, as the middle layer increased by 49.92%. However, the higher range of droplet deposition density meant larger fluctuation and dispersion. 3) The open center shape canopy and the 1.0 m working height obviously improved the droplet coverage rate and droplet density in the citrus plant. For these parameters of open center shape citrus tree, there was no obvious difference in the front and rear direction, but in the left and middle part of the tree crown, the difference reached a 0.05 significant level. Considering droplet deposition characteristics and the spray uniformity, the UAV performed better when working on open center shape plants at a 1.0 m working height.

Keywords: citrus, tree shape, unmanned aerial vehicle (UAV), droplet deposition
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1 Introduction

Citrus is one of the most important fruit crops in the world, especially in China, where the citrus originated from[1]. There has been consistent growth in citrus acreage and annual production in recent years. In 2013,

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the planting area of citrus was 2 422 000 hm^2 and the annual output was 33 210 000 t. The planting area of citrus and annual output in 2013 increased by 5.03% and 4.83%, respectively, as compared to 2012, and 5.86% and 13.19%, respectively, as compared to 2011[2]. The citrus has become a critical crop in the south of China. In recent years, China's citrus yield and quality has gained sustainable improvement, due to mostly spraying work. However, diseases and insect pests are still the main constraint on the development of the citrus industry[3,4]. It seems that chemical spraying is still the most effective method for disease and pest control. However, the traditional small knapsack sprayer has not adapted to the sudden diseases and pests in the process of fruit cultivation and the demands that plant protection machinery being efficient, time saving, labor saving, safe and eco-friendly[5]. Aviation plant protection machinery and its related technology will be the future development direction of plant protection and agricultural mechanization[6,7]. The research and development of aviation plant protection technology have been accelerated by the government support and market needs, especially regarding the UAV.

Recent years, researchers from China and other countries put much concentration on study of UAV spraying[8-13], and have laid a solid foundation for agricultural aviation applications. The aerial spraying drift and deposition effectiveness are impacted by many complex factors, such as airplane types, working height and weather conditions, etc[14,15]. Fritz et al.[16-19] conducted several research analyses of spraying drift on the aerial application systems. In addition, many researchers emphasized the importance of optimal spraying parameters in UAV's[20-23]. The rotor UAV is a kind of UAV which has many advantages, such as its small size, high flexibility, no requirement for takeoff site and driver, frequent takeoffs and landings under high temperatures[24-27]. In addition, it showed a good performance under hilly terrains, complex canopy structures of citrus trees and even severe turbulence below the UAV rotor.

Scientific pruning techniques can control tree size, adjust the proportion of twig and leaf distribution, improve the efficiency of light ventilation, strengthen the accumulation of carbohydrates, and improve the abundance of blooms and fruit[28,29]. Reasonable canopy structures of trees maintained by proper training and pruning is also necessary for the UAV spraying application. The effects of different citrus tree shapes and UAV operation altitude on droplet deposition were comparatively studied in the research. The optimal combination of the parameters was determined through experiments, which can provide a reference for UAV application and agronomic techniques.

2 Materials and methods

2.1 Testing instruments

The four-rotor UAV (3W-LWS-Q60S, Zhuhai Crop Guardian Aerial Plant Protection Co., Zhuhai City, China) was used in this experiment and its key parameters are as follows: the container capacity 6 L, spray swath 4.0-6.0 m, relative flight height to canopy 0.5-3.0 m, operation speed 0-8.0 m/s, particle size ranges from 80 μm to 120 μm. There are four conical spray nozzles arranged in a row, and its spray volume is 1000-1300 mL/min. Both the working height and operating speed can be adjusted according to the requirements.

The Digital Plant Canopy Imager (CI-110, CID Bio-Science, Inc. Camas, USA) was also used in this experiment. The CI-110 Digital Plant Canopy Imager consists of an auto-leveling image capturing probe and arm with 24 Photosynthetically Active Radiation (PAR) sensors, built-in USB interface for an optional palm-top computer, and CI-110 software. The leaf area index (LAI) was calculated by the CI-110 with the canopy image (768×494 pixels) captured from a self-leveling PENTAX lens of 170° fisheye.

2.2 Experimental materials

The Cocktail grapefruit (*Citrus paradisi* cv. Cocktail) grafted on Trafoliata (*Poncirus trifoliata* L. Raf.) rootstock was used in this experiment. The plant row spacing is 5 m and the plant spacing is 3.5 m. The average diameter and height of the plant crown were 3.0 m. The healthy plants with consistent growth in the flat lands were chosen as test materials. The materials of field test are showed in Figure 1.

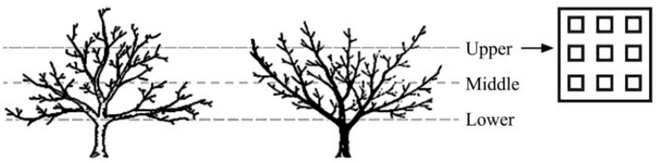
a. UAV used in the experiment b. Cocktail grapefruit canopy

Figure 1 Materials of field test

2.3 Experimental treatment

The experiment was conducted on April 4, 2015 at Qianlishan Agricultural Co. Ltd in Wan'an County, Jiangxi province. The spray experiment was designed as six treatments with five replications. The droplet distribution effect of citrus tree with natural round type and open center shape was tested under the condition of same operating speed (1.0 m/s) and three working heights (e.g. the distance between the UAV and the top of the canopy were 0.5 m, 1.0 m and 1.5 m, respectively). In order to avoid the test error caused by droplet drift, a row of plants was left as a protected area between two different treatments.

The top, middle (2/3 plant height), and lower (1/3 plant height) parts of citrus trees crown were flagged by hanging nine white pulp paper cards from inside to outside parts of the plants (Figure 2). Each sampling paper card size was 76 mm×50 mm which was nearly the same size as a grapefruit leaf. The spray solution was 300 times Ponceau 2R (99.5% purity). Paper cards were collected one by one in zip lock bags after spraying and dried.



a. Round bead shape b. Open center shape

Figure 2 Different citrus tree shapes and sampling scheme

The parameters including the droplets coverage rate, droplets deposition density, droplets size and droplets deposition uniformity were analyzed.

The ratio of leaf surface area to unit ground surface area, called the Leaf Area Index (LAI), is an important parameter which controlling many biological and physical processes, such as transpiration, photosynthesis, and respiration cycles. To ensure the accuracy and efficiency of the data, the LAI of the citrus tree was deemed to be the average value as computed after measuring three times in different directions under the citrus crown. The LAI was measured by the CI-110 Digital Plant Canopy Imager under the operating steps as follows: First, simply position the CI-110 under the desired leaf canopy. Second, the auto-leveling fisheye camera lens (170°) will display a live image of the canopy for accurate data collection. It captures the desired canopy image; which can be used to compute LAI. Finally, the correlation between droplet deposition densities and LAI was analyzed by statistical software.

Meteorological parameters were measured during treatments using the Meteorograph in the orchard.

Table 1 Meteorological parameters of different treatments

Working height/m	Temperature /°C	Humidity /%	Wind speed /m·s^{-1}	Wind direction
0.5	20.7	60	0.4	WSW
1.0	23.9	44	0.9	SW
1.5	25.1	44	2.2	S

2.4 Data collection and analysis

1) Parameters of droplet deposition distribution

The parameters of droplet deposition distribution, such as droplet coverage, droplet deposition density and droplet size were analyzed by the image processing software Image J.

Droplet coverage: The percentage of the chemical area covered on the paper card.

Droplet deposition density: The number of droplet deposition per unit area on the paper card.

Droplet size: That is, the length's mean diameter which is the sum diameter divided by the number of particles.

2) Droplet deposition distribution uniformity

The coefficient of variation (CV) was used for evaluating the uniformity of droplet deposition distribution. The formula for calculating CV is:

$$V = \frac{S}{\bar{X}}, \quad S = \sqrt{\frac{\sum_{i-1}^{n}(Xi - \bar{X})^2}{n-1}} \tag{1}$$

where, S stands for the standard deviation; Xi is the sample card's droplet deposition density, the coverage rate and particle size, respectively; $\bar{X}$ is the average value of Xi; n is the total number of sampling cards.

3) Leaf area index (LAI)

CI-110 plant canopy analyzer with analysis software was used for measuring the LAI of trees with different types (natural round and open center shapes).

4) Statistical analysis

EXCEL software was used for data analysis and diagrams drawing. SPSS17.0 software was used for the variance and correlation analysis.

3 Results and discussion

3.1 Droplet distribution of UAV spraying on the citrus round shaped crown trees

Table 2 shows the droplet distribution results of UAV spraying on the citrus round shape plants at different spraying heights. It not only reflects the droplet distribution along the height direction of the citrus plants, but also reflects the influence of different working heights on the droplet deposition effect.

Table 2 Effect of droplet deposition distribution at different heights on citrus canopy

Working height/m	Canopy layer	Droplet coverage rate/%	droplet deposition density/droplets·cm^{-2}	Droplet size/mm
0.5	Upper	4.34±0.51b	37.04±5.98b	0.41±0.11a
	Middle	2.82±0.61ab	25.22±0.44b	0.56±0.19a
	Lower	1.08±0.14a	5.58±0.30a	0.77±0.07a
1.0	Upper	4.50±1.14b	54.85±4.24b	0.25±0.03a
	Middle	3.13±0.73ab	33.32±4.93b	0.30±0.03a
	Lower	1.94±0.14a	31.73±0.81a	0.34±0.11a
1.5	Upper	7.07±2.03b	52.63±7.37b	0.54±0.14a
	Middle	4.51±1.73b	23.71±7.21ab	0.63±0.12a
	Lower	1.22±0.36a	9.42±4.29a	0.81±0.09a

Note: The data in the table are mean ±SD. Data followed by different small letters are significantly different among different treatments at α<0.05 level by Duncan's new multiple range test.

The results of statistical analysis indicate that the droplet deposition density and the droplet coverage rate between the upper and middle layers have no significant difference, but the droplet deposition density and droplet coverage rate of the lower canopy were relatively lower. The droplet particle sizes at the three canopy layers had no significant difference. The general trend of droplet distribution decreased with the citrus canopy height. Thus, it can be seen that most droplets on the surface and outside canopy had weak penetration and poor deposition effects due to interaction of citrus leaves and branches. Therefore, the implementation of aerial mechanization in the orchard requires a further combination of agronomic technology at the same time.

The associations between droplet deposition parameters and working height were examined using the average value of each citrus canopy layer droplet deposition parameters representing the droplet deposition. Table 2 indicates that the droplet deposition density and coverage rate in citrus canopy were the lowest when the working height was 0.5 m and the discrete level of data is greater; this may be due to when the UAV acts on shorter distances to the citrus canopy, the powerful jets of the UAV bounce the spray off the branches of the big citrus trees, making it difficult for the leafs to capture droplets and thus causing unsatisfying droplet deposition effects. The general trend of droplet deposition density on each layer citrus plants were greater when the working height was 1.0 m than that of the operation height was 0.5 m and 1.5 m, but its droplet coverage rate (3.19%) was slightly lower than that of the 1.5 m operation height (4.27%). The droplet diameters at the 1.0 m operation height were significantly lower when contrasted with the working height at 1.5 m. From the overall trend, droplets on the targets had the maximum dispersion at 1.5 m working height, where the range of droplet coverage rate was 5.85% and the range of droplet density was 43.21 droplets/cm^2. The optimal characteristics of droplets on the targets are a higher coverage rate, larger deposition density, and smaller droplet diameter[30]. So, the optimal operation height was 1.0 m, which had a better UAV spraying effect. According to these results, it follows that proper flight height affects the droplet deposition effect of UAV spraying. A higher altitude induces a wide spraying span and droplet drift, and a lower altitude causes a narrow spraying span as most of those droplets concentrated in the upper canopy, while the inside regions had fewer or no droplet deposition. Thus, the working height of the UAV has a great effect on the droplet deposition distribution of the citrus canopy.

3.2 Effect of different plant shapes on droplet density

Complex citrus canopy structures compounded the trouble of adequate droplet penetration. The droplet deposition density decreased as the LAI increased. These results determined that significant negative correlations were found between leaf area index and droplet deposition density, r=−0.73, as shown in Figure 3. Therefore, proper pruning of the citrus canopy will help to reduce the canopy leaf area index and effectively improve the droplet deposition density of UAV spraying.

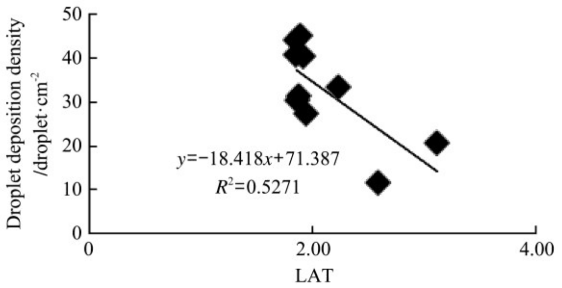


Figure 3 Correlation analysis between droplet deposition density and LAI

Using the results shown in Figure 3, we changed the citrus plant shape from a round head shape to an open center shape and got a lower LAI. These agronomic measures were carried out to increasing the droplet deposition density. Figure 4 shows the comparative analysis results of droplets deposition density by UAV spraying on the round head shape and the open center shape crown. As a whole, the droplet deposition density of the 1.0 m working height reached record levels. From the specific perspectives, under the condition of the three working heights, the maximum droplet deposition density of round shape trees was 54.85 droplets/cm^2, with a minimum value of 5.58 droplets/cm^2 and a range of 49.27. The maximum droplet deposition density of the open center shape was 69.28 droplets/cm^2, with a minimum value of 19.46 droplets/cm^2, and a range of 49.82. This means that an open center shape canopy can improve the droplet deposition density in each layer of the citrus crown to some extent, but it also has a large discrete degree.

The relatively simple canopy structure of the open center shape citrus plants with a lower LAI obtained a better droplet deposition, but the thin canopy lacked the leaves to resist the strong airflow of the UAV as the leaves were buffeted by the wind. There are also inevitable accidental errors occurring in the pruning process, and the different levels of pruning contribute to the large discrete degree of droplet deposition density and non-uniform distribution. Perhaps some effective measures, such as more optimal operating parameters and mechanical pruning, rather than human pruning, could reduce the unfavorable influence of these uncertain factors. Mechanical pruning easily gets the same size tree crown, which could minimize the artificial error[31,32]. It is also an effective method to reduce cost and labor intensity in the orchard management process.

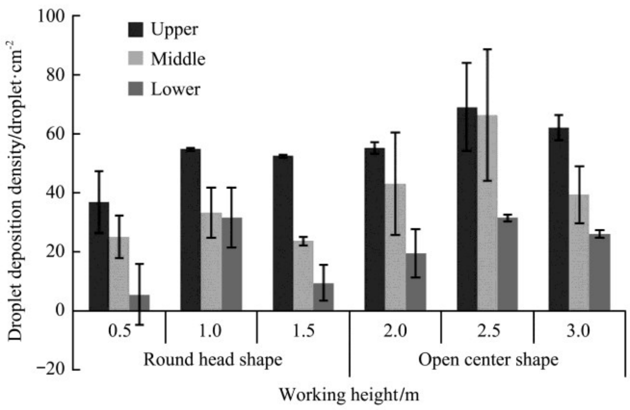


Figure 4 Effects of different citrus tree shapes on the droplets density of UAV spraying

In Table 3, the droplets deposition distribution of the round shape crown was compared with that of the open shape with a working height of 1.0 m. The CV is often used as an indicator of droplet deposition distribution uniformity and the variance of mean value was analyzed. There are statistically significant differences in the droplet deposition density between the upper, middle and lower layers of the round shape canopy at 5% level conditions, but there was no obvious difference of droplet deposition density between the upper and middle layers of open shaped trees under 5% level conditions.

Table 3 UAV droplets deposition distribution of different tree shape with 1 m working height

Crown types	Layers	Droplet deposition density/droplets·cm^{-2}	Percentage change/%	CV/%
Round head shape	Upper	54.85±4.24b	—	13.40
	Middle	33.32±4.93a	—	25.63
	Lower	31.73±0.81a	—	4.43
Open center shape	Upper	69.28±10.07b	+20.83	25.16
	Middle	66.54±12.84b	+49.92	33.43
	Lower	31.54±5.62a	-0.60	30.86

Note: The data in the table are mean ±SD. Data followed by different small letters are significantly different among different treatments at α<0.05 level by Duncan's new multiple range test.

We can see that droplet deposition density in the middle layer was effectively improved with the open center shape, but the droplet deposition density of the low layer was still significantly lower. The open shape canopy greatly raised the level of droplet distribution in the citrus canopy and the droplet deposition density of the middle canopy increased by 49.92%. However, the coefficient of variation on the open shape canopy is larger than that of the round shape canopy. The results reveal that the fluctuation and dispersion of droplet deposition density is larger and the uniformity of the droplet deposition distribution still needs to be improved.

These results suggest that the open center shape citrus tree is suitable for UAV spraying in the process of production management, but the larger fluctuation and dispersion data show poor uniformity. These consequences may be linked to the tree structure modifying that is difficult to maintain higher standards and unity. The standard and the unity of the open center shape crown are still to be improved.

3.3 Effects of droplet deposition distribution in different directions of trees with different tree shapes using UAV spray

The droplet distribution in different directions of citrus trees with different tree shapes at 1.0 m working height is shown in Table 4. Overall, the droplet coverage rate and droplet deposition density were improved by the open center shape, and there was no obvious difference of the droplet particle size among the different plant shapes. Under the round head shape canopy, the droplet coverage rates of the front and rear directions had no significant difference at the 5% level. There are statistically significant differences between these directions and the middle orientation, but the middle part has less droplet coverage rate. The droplet coverage rates showed no significant difference between the left, middle, and right parts of the plant crown. For the droplet coverage rate of the open center shape canopy, there are no significant differences between the front, middle and rear directions, but the left and middle parts had significant differences, and the middle part had the highest value, which was 5.27%. The droplet coverage rate has a low level and large discrete degree. For these two shapes, there were no obvious differences on the droplet density and diameter in the front, middle and rear part plants, but the differences of the droplet deposition density between the left, middle and right part reached a 0.5% significant level. Furthermore, the droplet deposition density of the middle layer in the open center shape tree crown reached a record level (66.26 droplets/cm^2). All in all, the droplet deposition of the middle part was significantly improved, and thus, droplet penetration also was improved by the open center shape crown.

Table 4 Effect of droplet deposition distribution in different directions of trees with different tree shapes using UAV spray

Places	Droplet coverage rate/%		Droplet deposition density/droplets·cm^{-2}		Droplet size/mm	
	Round shape	Open shape	Round shape	Open shape	Round shape	Open shape
Former	2.31±0.44b	2.09±0.13a	31.74±4.51a	42.68±13.59a	0.28±0.08a	0.33±0.02a
Middle	1.82±0.16a	3.89±0.59a	19.67±3.82a	32.43±2.73a	0.27±0.04a	0.28±0.07a
Rear	2.10±0.14ab	3.21±0.75a	24.90±2.86a	30.60±5.19a	0.25±0.02a	0.38±0.01a
Left	2.34±0.37a	2.94±1.64a	7.46±0.63a	25.36±1.68a	0.25±0.01a	0.34±0.07a
Middle	4.41±1.38a	5.27±1.36b	30.55±4.74b	66.26±1.88c	0.21±0.02a	0.31±0.06a
Right	2.84±0.82a	3.87±0.88ab	17.85±0.10c	47.92±5.10b	0.36±0.02b	0.27±0.01a

Note: The data in the table are mean ±SD. Data followed by different small letters are significantly different among different treatments at α<0.05 level by Duncan's new multiple range test.

The droplet deposition results of the front, middle and rear parts reflected that the UAV had a stable performance in the operating process. According to the droplet deposition at the left, middle and right sides of plant crown, it shows that the open center shape had a better droplet distribution, but the pruning unity of open center shape citrus trees is the key to obtain uniform droplet distribution. In addition, the droplet is easily affected by crosswinds when the droplets fall. It could lead to droplet drift, deposition reduction, poor uniformity and large discrete degree. Combining the aerial adjuvant[33,34] and electrostatic nozzle[35,36] in the field test with the optimal spraying parameters maybe can reduce the crosswind effect. Moreover, the field test should pay attention to the proper weather condition, especially regarding wind speed.

4 Conclusions

The UAV spraying experiments were conducted to make clear the influences of citrus plant types on the aviation spraying at different working heights with regards to improving droplet distribution. The results showed that:

1) The UAV spraying could obtain the better droplet distribution at 1.0 m working height, which resulted in higher coverage, larger deposition density, smaller droplet diameter, smaller variation coefficient and uniform droplet distribution.

2) Citrus canopy leaf area index (LAI) was negatively related to droplet deposition density, and open center shape citrus trees could considerably increase the droplet distribution, especially in the citrus central canopy. Even though the CV of droplets density was larger and the droplet distribution is not uniform, the open center shape canopy may be more suitable for the UAV spraying. But the standard and the unity of pruning for the open center shape crown is still to be improved.

3) The droplet coverage rate and deposition density were improved by the canopy shape changing from a natural round shape to the open shape when the UAV operates at the 1.0 m height. The spray performance is stable along the flight direction in the operating process by this UAV. However, the droplet is easily affected by crosswinds and this could cause the droplet drift, deposition reduction, poor uniformity and large discrete degree.

The experiment demonstrated the effects of two important parameters on droplet distribution and combined the agronomic measures and agricultural machinery successfully which could effectively improve the droplet deposition distribution of UAV spraying. There also remain some shortcomings in this experiment, such as the lower droplet coverage rate, larger dispersion data, and next time, we will work to add some effective measures to improve droplet deposition.

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