Optimization of variables for maximizing efficacy and efficiency in aerial spray application to cotton using unmanned aerial systems

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Abstract: Aerial spraying can support efficient defoliation without crop contact. With the recent introduction to unmanned aerial system (UAS) for aerial spraying in China, there is a need to determine the optimum application variables to achieve high efficacy and efficiency with low costs. The present research involved field studies across two annual cotton production seasons in North Xinjiang, China. Four factors, including volume rate (A), tank mix including spray adjuvants (B), flight altitude (C), flight speed (D) and three levels of L_9 (3^4) orthogonal arrays were carried out to optimize the application parameters for three types of UASs. These included different numbers of rotors as follows: four-rotors, six-rotors and eight-rotors. Spray coverage, distribution uniformity (coefficient of variation (CV) of droplet coverage), rates of cotton defoliation and boll opening, application efficiency and cost were measured and assessed. Results showed that: (1) the rates of defoliation and boll opening by aerial cotton defoliant application could meet the requirement of cotton mechanized harvesting; (2) the optimal scenario for the three UASs was $A_3B_2C_1D_3$, Volume rate (A_3): 48 L/hm^2; Tank mix and concentration (B_2): (Tuotulong 225 + Sujie 750 + Ethephon 2250) mL/hm^2, Flight altitude (C_1): 1.5 m, and Flight speeds (D_3) for unmanned helicopters with four-rotors, six-rotors and eight-rotors were 3.12 m/s, 2.51 m/s and 3.76 m/s, respectively. These results can provide guidance for cotton defoliant aerial spraying in China using UAS.

Keywords: unmanned aerial system (UAS), unmanned aerial vehicle (UAV), unmanned electric helicopter (UEH), cotton defoliant, aerial spraying, parameter optimization

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1 Introduction

Cotton production is a labor-intensive, low efficient and time-consuming process. In addition to planting, most cotton production processes, including cotton harvesting are mostly dependent on manual work in China. In recent years, with rising costs of labor and agricultural materials, cotton production is in need of mechanization[1]. Chemical cotton defoliant sprays, which can promote the process of cotton defoliation, providing important support to cotton mechanical harvesting[2].

Agricultural aviation is common for chemical spraying in cotton and other crops in many parts of the word. Hopkins et al.[3] tested aerial application with ultra-low-volume (undiluted) technical insecticides and successfully suppressed populations of cotton aphid. Chester et al.[4] studied the occupational exposure and drift hazard of aerial application of paraquat to cotton in California, USA. Martin et al.[5] researched aerial electrostatic spray deposition and canopy penetration in cotton. In addition, aerial pesticide spraying has been applied in Swaziland[6], Australia[7], Brazil[8] and other countries. Xin et al.[9] studied the effects of dosage and spraying volume on cotton defoliants efficacy using Unmanned Aerial Vehicle (UAV) in China. Unmanned Aerial System (UAS) has been developing rapidly in spraying in China in recent years[10]. With advantages through vertical take-off and landing without a runway, high performance efficiency, low flight altitude, operating flexibility and ready adaptation to different application environments, mini-micro UAS have being increasingly used in crop spraying for many crop varieties[11]. Numerous studies have been reported on aerial spraying for plant protection in rice, maize, wheat and other crops. However, currently, in China, cotton defoliant application is mostly performed by ground sprayers, which only offer limited efficacy and efficiency of cotton defoliant application. Aerial spraying has great potential in cotton defoliant spraying. However, the potential of aerial pesticide application is still not fully realized in China[12].

Efficacy and efficiency of aerial spraying are significantly influenced by spraying application parameters (atomizer or nozzle

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type, spray pressure, flight altitude and speed)[13], the physical and chemical properties of the tank mix[14] and the meteorological conditions such as air temperature, relative humidity, wind velocity and direction[15]. Hewitt et al.[16] have shown the relative effects of the nozzle and application parameters compared to the tank mix physical properties in affecting the size spectrum of the droplets in sprays applied by air. Zhang et al.[17] have researched the influence of application parameters of unmanned aircraft on droplet deposition, showing that the optimum application parameters for a UAV WPH 642 were flight altitude of 2 m and flight speed of 1.5 m/s when spraying rice crop with 0.01% w/w dye in water.

The optimization of various parameters of aerial cotton defoliant spraying has significant importance for improving cotton production, but not many reports about this research have been published so far. The present study is aiming to improve the efficacy and efficiency of aerial spraying using three typical UAS models in China. These sprayers would be used to study the relative effects of different application and tank mix systems in aerial cotton defoliant spraying, to support future optimization by applicators of application volume rate, tank mix and concentration, flight altitude and flight speed to be considered when spraying. Four-rotor aircraft would be used for verifying the feasibility of cotton defoliant aerial spraying using UAS and optimizing parameters range in the first year of study, four-rotor, six-rotor and eight-rotor aircraft would be used for efficacy evaluation and parameters optimization in the second year of study.

2 Materials and methods

2.1 UAS for cotton defoliant spraying

Cotton defoliant aerial spraying applications were performed by multiple-rotor UASs (Figure 1).

a. YR-GSF06

b. TXA-Xiangnong

c. YR-AU 15

Note: Four-rotor UAS (model no. YR-GSF06) and eight-rotor UAS (model no. YR-AU15) were provided by Xinjiang Tianshan Yuren Agricultural Aviation Technology Co., Ltd, China. The six-rotor UAS (model no. TXA-Xiangnong) was provided by Guangzhou Tianxiang Aviation Technology Co., Ltd, China.

Figure 1 Three types of UAS used in the experiments

The specifications of three UASs are shown in Table 1. UAS consist of spray bar, water-pump, water-pipe, nozzle and other components. Four flat-fan nozzles distribute on four spray bars of YR-GSF06, with space of 0.5 m, and perpendicular to the aircraft axes. Five flat-fan nozzles distribute on four spray bars of TXA-Xiangnong, with space of 0.5 m, and perpendicular to the aircraft axes. Six flat-fan nozzles distribute equidistantly along spray bar and perpendicular to the aircraft axis of YR-AU 15, with space of 0.5 m.

Table 1 Specifications of three types of UAS for experiments. Normally, size, weight, total volume, payload, nozzle, nozzle angle, liquid flow rate, spray pressure, application swath width and flight velocity are the main parameters which influence the application efficacy and efficiency

Parameters	UAS		
	YR-GSF06	TAX-Xiangnong	YR-AU 15
Size/mm×mm×mm	2185×2185×375	2396×600×300	3800×3800×850
Weight/kg	8.8	10	16.5
Payload/L	10	16	18
The number of Nozzles	four flat-fan nozzles	five flat-fan nozzles	six flat-fan nozzles
Nozzle orifice/mm	0.6	0.6	0.6
Nozzle angle	vertical	vertical	vertical
Nozzle orientation	downward	downward	downward
Flowrate/L min^{-1}	9.6 (2.4×4)	12.0 (2.4×5)	14.4 (2.4×6)
Spray swath width/m	3-5	4-6	5-7
Time of endurance/min	13	13	12
Flight speed/m s^{-1}	0-8	0-6	0-8

The swath widths of three UASs were measured before the experiments. For this assessment, five rows with 21 equally spaced deposition locations were put in place. The aircraft sprayed over the central cards. Swath widths were evaluated based on the swath width analysis method described by Zhang et al.[18]

2.2 Tank mix

A tank mix in pesticide application includes one or more active ingredient products in a carrier such as water or oil, as well as any adjuvants intended to enhance the performance of the spray. Some of the most common cotton defoliants and adjuvants in China were used in this study, as follows: (1) Cotton defoliant Tuotulong, active ingredient 36% w/w Thidiazuron+18% w/w Diuron, provided by Bayer Crop Sciences, Monheim, Germany; (2) cotton defoliant Ruituolong, active ingredient: 80% w/w Thidiazuron, provided by Jiangsu Repont Pesticide Factory, China; (3) adjuvant Sujie, active gradient: 335 g/L Lecithin + 345 g/L methylacetic missible oil, provided by Kunsheng Agricultural Development Company, Fujian Province, China; (4) adjuvant Kesheng, a non-ionic adjuvant, active ingredient 30% w/w Tebuconazole + w/w 30% thiram, provided by Jiangsu Kesheng Group Limited Liability Company; (5) dedicated adjuvant for Ruituolong, an organosilicone adjuvant, provided by Repont Pesticide Factory, China; (6) Ethephon, 40% w/w Ethephon.

2.3 GNSS (Global Navigation Satellite System) station

A Beidou GNSS with RTK differential positioning technology and bidirectional wireless radio station was mounted on each aircraft. The plane and vertical accuracies of this station were $10+5\times D\times10^{-7}$ mm and $20+1\times D\times10^{-6}$ mm, respectively, where D is the actual measuring distance, km[19]. The trajectories, coordinates, flight altitudes and speeds of aircraft were recorded by the mobile station systems carried by itself.

2.4 Weather station

Meteorological conditions such as wind velocity, wind direction, air temperature and relative humidity are important factors affecting aerial and ground spraying. Given the dynamic nature of meteorological variables in the field, an ideal experimental design would be to apply all treatments simultaneously. However, this is usually not practical[20]. The flight route of the aircraft when spraying each treatment was set according to the local ambient wind direction. Meteorological variables were monitored using a Watch Dog Weather Station with sensors at a height of 4 m above ground. The weather station was positioned approximately 100 m downwind of the flight line directly alongside the sampling line[21,22].

2.5 Deposition cards

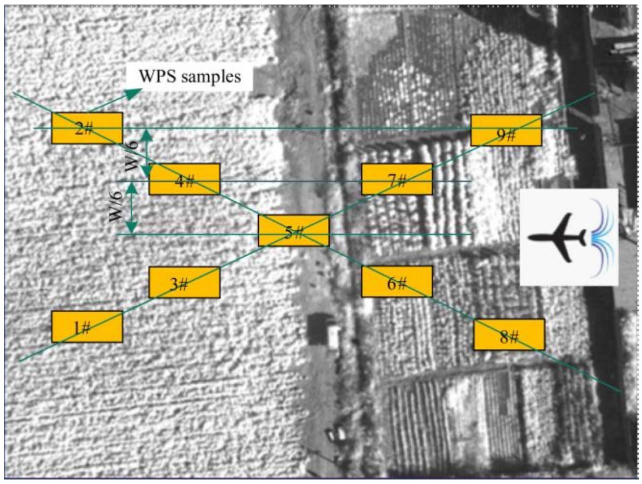
Spray coverage was assessed using deposition cards known as Water Sensitive Paper (WSP)[23] with the size of 26 mm×76 mm, provided by Syngenta. This paper is coated with a layer of Bromoethyl Blue which changes in color from yellow to blue when hydrated by water droplets, thereby, spray characteristic values such as droplet size, coverage, deposition density, deposition rate and other values could be obtained by image processing and other methods[24].

2.6 Experimental site arrangement

Cao et al.[25] suggested that the optimal dates for cotton defoliant spraying in north Xinjiang are normally around 5-15 September. On this basis, the spray applications were made on 5 September and the assessment dates for ranking cotton defoliation and boll opening rates were 5 September to 5 October. The test field is in the cotton base of China National Cotton Group, located at 87°17′87″E; 44°40′94″N, Changji Autonomous Prefecture, Xinjiang Uygur Autonomous Region, China. Field with uniform, orderly and stable vigor cotton plants was selected as experimental plots. The cotton variety for experiments was No. 9813 of Chinese cotton, which is one of main cotton varieties in North Xinjiang. The cotton plants were in boll opening stage, with average plant height of 50 cm and plant density of 14800 plants/hm^2.

27 plots were setup for experiments (nine plots × three UAS), and the layout of each plot was 8 m×100 m, as shown in Figure 2. Nine sampling points were set for each experimental plot and arranged as a ‘X-shape’ layout. WSPs were placed in the lower region of the cotton canopy for assessing spray deposition, 10 cm above ground. Two contrast plots[26] (CK: control check group, and tractor spraying group) were set for cotton defoliation and boll opening rates contrasting with aerial spraying plots. The cotton plants in the CK plot were in natural growth without cotton defoliant application, and the Tractor Plot was sprayed by a ground boom application system had five flat fan nozzles (orifice 0.6 mm) per side spaced at 0.5 m intervals. The swath width was 5 m and spray pressure was 300 kPa. The spray mixture comprised two active ingredient products (Tuotulong 225 + Ethephon 2250) mL/hm^2. The application volume rate was 180 L/hm^2, the forward velocity of the tractor was 1.2 m/s. $L_9(3^4)$ orthogonal arrays[27] were carried out for parameter optimization for three UAS. Factors and levels of orthogonal tests are shown in Table 2.

40-80 L/hm^2 volume rate was observed as the optimal range of volume rate in the first year of study, then 48 L/hm^2, 72 L/hm^2, and 96 L/hm^2 volumes rates were setup as spraying volumes in the second year of study. Tuotulong performed better than other cotton defoliant in cotton defoliation on No. 9813 of Chinese cotton, and it was selected in the second year of study. It was observed in the first year of study that the optimal flight altitude for aerial spraying using UAS was 1.5-2.0 m. Pressures of 200 kPa, 300 kPa and 400 kPa corresponded to respective application volume rates of 48 L/hm^2, 72 L/hm^2 and 96 L/hm^2. It should be noted that at higher spray pressures, the droplet size would be expected to get smaller which in turn could improve coverage based on prior research.



Note: 27 treatment plots were setup, and nine water sensitive paper samples were setup in bottom of cotton plants for droplets collection in each plot. 27 plots represented 27 treatments (nine treatments for each UAS respectively). The intervals of samples are W/6, W is the swath width of aircraft.

Figure 2 Layout of the plots

Table 2 Four factors: Volume rate (A), Tank mix and concentration (B), Flight altitude (C), Flight speed (D), and three levels of $L_9(3^4)$ orthogonal arrays[24] was used for sprays optimization of cotton defoliant spraying using three types of UAS

Level	Factor A	Factor B	Factor C	Factor D
	Volume rate/L hm^{-2}	Tank mix and concentration/mL hm^{-2}	Flight altitude/m	Flight speed/m s^{-1}
1	96	Tuotulong 225+Ethephon 2250	1.5	1.0
2	72	Tuotulong 225 + Sujie 750 +Ethephon 2250	2.0	2.0
3	48	Tuotulong 225+Kesheng 750 +Ethephon 2250	2.5	3.0

2.7 Data processing and sprays assessing methods

After spraying, WSP samples were collected and placed in sealed bags once dry. They were scanned to produce 600 dpi digital images using a Canon 4200F scanner in the laboratory. DepositScan[28] software was used to obtain the droplet deposition characteristic values from the images. Spray application quality is commonly assessed by the droplet size spectrum, deposition density, percentage coverage and distribution uniformity across the swath[29,30]. In the present study, cotton defoliant sprays were assessed based on droplet coverage and CV[31,32]. CV was calculated to evaluate the distribution uniformity of droplets at each sampling point using the follow calculation formulae[33]:

$$CV = \frac{SD}{\bar{X}} \times 100\% \tag{1}$$

$$\bar{X} = \frac{\sum X_i}{n} \tag{2}$$

$$SD = \sqrt{\frac{\sum X_i^2 - \frac{(\sum X_i)^2}{n}}{n-1}} \tag{3}$$

where, SD is the standard deviation of sampling points of each experimental plot; X_i is the droplet coverage at sampling points (the percentage of droplets on WSP); $\bar{X}$ is the mean value of droplet coverage at each sampling point; n is the number of sampling points in each experimental plot.

Cotton defoliation and boll opening rates of experimental plots and control plots were assessed after 7 d, 14 d, and 25 d of spraying, using the following equations:

$$Cotton\ defoliation\ rate = \frac{L_a - L_i}{L_a} \times 100\% \tag{4}$$

$$Boll\ opening\ rate = \frac{opening\ boll\ number}{boll\ number} \times 100\% \tag{5}$$

where, L_a is the number of leaves before cotton defoliant spraying; L_i is the number of leaves after i days of cotton defoliant spraying. Gray correlation analysis[34] was used for parameter optimization in this study. Gray correlation analysis can overcome the partiality of range and variance analysis. The following steps were carried out:

(1) Sequence setting: in this step, the reference sequence was set as $X_0=\{X_0(1), X_0(2), \ldots X_0(n)\}$, while experimental plot sequences were set as $X_i=\{X_i(1), X_i(2), \ldots X_i(n)\}$, where i is the test number, which is from 1 to 9, and n is the index number which is 7 in this study.

(2) Data dimensionless procession: in this step, indices were processed to be dimensionless using the equation $X_i = \frac{X_0(n)}{X_i(n)}$.

(3) Sequential difference value calculation: in this step, the difference values between experimental plot sequence and reference sequence were calculated to obtain the minimum and maximum difference values.

(4) Correlation coefficients between experimental plot sequences and reference sequence were calculated by the equation:

$$\eta_i(k) = \frac{\min_j \min_i |x_0(l) - x_j(l)| + P \max_j \max_i |x_0(l) - x_j(l)|}{|x_0(k) - x_j(k)| + P \max_j \max_i |x_0(l) - x_j(l)|} \tag{6}$$

where, $\eta_i(k)$ is correlation coefficient; $|x_0(k)–x_j(k)|$ is the absolute difference value between No. k index of No. j experimental plot and the value of No. k index of reference sequence; $\min_j \min_i |x_0(l) - x_j(l)|$ and $\min_i |x_0(l) - x_j(l)|$ were the minimum difference values of two-stage and one-stage respectively; $\max_j \max_i |x_0(l) - x_j(l)|$ is the two-stage maximum difference value; P is the resolution ratio, the value of P was set to 0.5 in this study; $|x_0(l)|–x_j(l)|$ is the absolute difference value between No. l index of No. j of experimental plot and the value of No. l index of reference sequence.

(5) Correlation degrees: these aimed to observe the correlation level of different indices. The correlation degrees of each index for the three aircraft were calculated using the following equation:

$$r_i = \frac{1}{n}\sum_{k=1}^{n}\eta_i(k) \tag{7}$$

where, r_i is the correlation degree of index i.

(6) Weight coefficient calculation, correlation degrees were uniformized to obtain the weight coefficient of each index.

Spraying efficacy was assessed by droplet coverage, distribution uniformity, rates of cotton defoliation and boll opening. Working cost including tank mix cost and battery power consumption. The cost of water, Tuotulong, Ethephon, Sujie and Kesheng are 0.0028 CNY/L, 0.15, 0.06, 0.26 and 0.14 CNY/mL respectively. Working efficiency is calculated by spraying swath width and flight speed of aircraft by the following equation:

$$E=S\times W \tag{8}$$

where, E is efficiency, m^2/s; S is flight speed, m/s; and W is swath width, m.

Droplet coverage, CV, cotton defoliation rate, boll opening rate, battery consumption, pesticide cost and working efficiency were set as seven indices for parameter optimization and numbered from 1# to 7#. Reference sequence and seven index sequences were set for the analysis of gray correlation degree.

3 Results and discussion

Experimental scenarios and results of three UASs are shown in Table 3. Statistical analysis, based on parameters of droplet coverage and distribution uniformity (CV), was assessed for four factors (Volume rate, Tank mix and concentration, Flight altitude and Flight speed).

3.1 Influence of meteorological variables on spray

As shown in Table 3, the CV of most experimental plots were under 40%, except in the 6th experimental plot of YR-GSF06, the CV was 40.46%. For the 5th and 6th experimental plots of TAX-Xiangnong, the CVs were 44.90% and 42.16% respectively. The meteorological data show that the wind velocity during the periods of these three experiments was 4 m/s, and the wind direction was not stable, suggesting that the uniformity of droplet distribution is influenced by the wind velocity and variability of wind direction. The observed increase of CV with wind velocity suggested that the droplet distribution became non-uniform when the wind velocity exceeded 4 m/s and the wind direction was not stable.

3.2 Analysis of cotton defoliation and boll opening rates

After 25 d of cotton defoliant application, the cotton defoliation and boll opening rates of CK group were 28% and 76% respectively, while respective values for the tractor plot were 84% and 70%. Figure 4 shows that all experimental plots (sprayed by aircraft) have greater cotton defoliation and boll opening rates than the CK plot. Most experimental plots have greater cotton defoliation and boll opening rates than the tractor spraying plot, except the cotton defoliation rates of 1st, 4th and 6th plots sprayed by YR-GFS06, 4th and 6th sprayed by TXA-Xiangnong. The 1st, 4th and 7th plots sprayed with YR-AU 15 show slightly lower defoliation and boll opening rates than respective values of the tractor plot. It was noticed that the 1st plot of YR-GFS06 and YR-AU 15, and 4th plot of three types of aircraft were sprayed without adjuvant. The wind velocity of 6th plots of YR-GFS06 and TXA-Xiangnong exceeded 4 m/s. The 7th plot of YR-AU 15 was sprayed without adjuvant and at the flight altitude of 2.5 m. Because these experimental plots leaded to relative lower cotton defoliation, it is proved that, adjuvant could improve spraying efficacy, high wind velocity (exceed 4 m/s) results in lower spraying efficacy, and 2.5 m flight altitude is not appropriate for cotton defoliant aerial spraying using UAS.

Overall, the high rates of cotton defoliation and boll opening incidence support the concept that the UAS in this study can be effectively used to spray cotton crops, whereas the control samples which were sprayed by ground rigs showed lower overall spray performance (Figures 3 and 4).

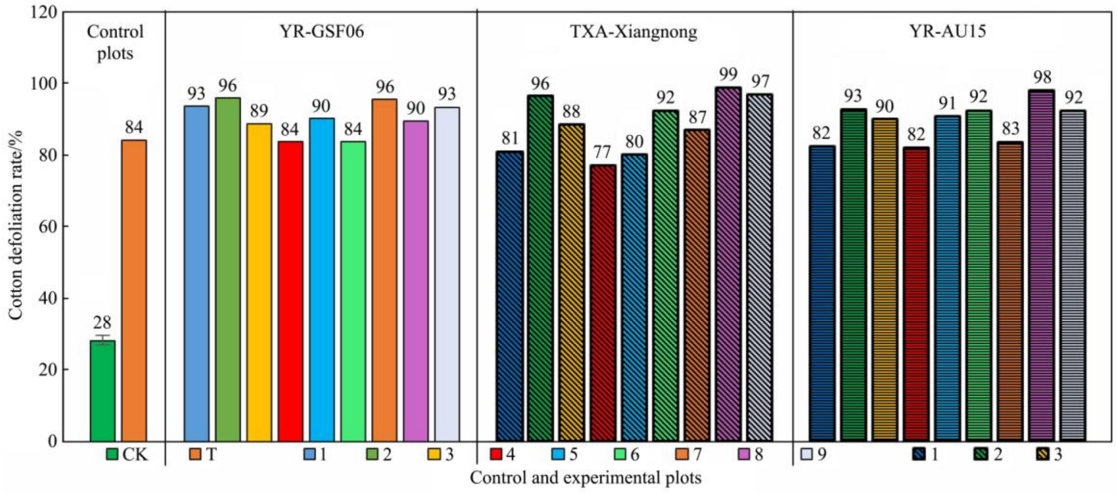
Table 3 Experimental scenarios and results of three UASs

UAS	Test No.	VR/L hm^{-2}	TM/mL hm^{-2}	FA/m	FS/m s^{-1}	DC/%	CV/%	PC/V	C/CNY	E/m^2 s^{-1}	OR
YR-GSF06	1	1(96)	1(Tuotulong 225)	1(1.5)	1(1.42)	10.51	37.82	1.35	169.0188	4.26	0.7370
	2	1(96)	2(Tuotulong 225 +Sujie 750)	2(2.0)	2(2.33)	16.01	30.74	1.46	364.0188	9.32	0.7130
	3	1(96)	3(Tuotulong 225 +Kesheng 750)	3(2.5)	3(3.12)	10.52	33.90	1.52	274.0188	15.60	0.7088
	4	2(72)	1(Tuotulong 225)	2(2.0)	3(3.12)	4.32	25.07	1.11	168.9516	12.48	0.7559
	5	2(72)	2(Tuotulong 225 +Sujie 750)	3(2.5)	1(1.42)	3.08	20.46	1.21	315.2016	7.10	0.6704
	6	2(72)	3(Tuotulong 225 +Kesheng 750)	1(1.5)	2(2.33)	4.04	40.46	1.00	247.7016	6.99	0.5531
	7	3(48)	1(Tuotulong 225)	3(2.5)	2(2.33)	1.84	27.42	0.92	168.8844	11.65	0.7615
	8*	3(48)	2(Tuotulong 225 +Sujie 750)	1(1.5)	3(3.12)	1.59	34.74	0.80	266.3844	9.36	0.8140*
	9	3(48)	3(Tuotulong 225 +Kesheng 750)	2(2.0)	1(1.42)	2.48	25.14	0.88	221.3844	5.68	0.7432
TXA-Xiangnong	1	1(96)	1(Tuotulong 225)	1(1.5)	1(1.31)	10.92	15.42	2.84	169.0188	5.24	0.7927
	2	1(96)	2(Tuotulong 225 +Sujie 750)	2(2.0)	2(2.01)	13.96	25.25	2.74	364.0188	10.05	0.7523
	3	1(96)	3(Tuotulong 225 +Kesheng 750)	3(2.5)	3(2.51)	11.84	19.97	2.94	274.0188	15.06	0.7919
	4	2(72)	1(Tuotulong 225)	2(2.0)	3(2.51)	3.62	44.90	2.10	168.9516	12.55	0.7529
	5	2(72)	2(Tuotulong 225 +Sujie 750)	3(2.5)	1(1.31)	5.04	42.16	1.82	315.2016	7.86	0.6601
	6	2(72)	3(Tuotulong 225 +Kesheng 750)	1(1.5)	2(2.01)	4.81	14.54	1.77	247.7016	8.04	0.7832
	7	3(48)	1(Tuotulong 225)	3(2.5)	2(2.01)	1.47	26.24	1.25	168.8844	12.06	0.7940
	8*	3(48)	2(Tuotulong 225 +Sujie 750)	1(1.5)	3(2.51)	2.48	28.37	1.11	266.3844	10.04	0.7941*
	9	3(48)	3(Tuotulong 225 +Kesheng 750)	2(2.0)	1(1.31)	3.51	29.20	1.00	221.3844	6.55	0.7938
YR-AU 15	1	1(96)	1(Tuotulong 225)	1(1.5)	1(2.08)	7.63	30.35	2.85	169.0188	10.40	0.7987
	2	1(96)	2(Tuotulong 225 +Sujie 750)	2(2.0)	2(2.79)	9.43	29.37	2.47	364.0188	16.74	0.7901
	3	1(96)	3(Tuotulong 225 +Kesheng 750)	3(2.5)	3(3.76)	5.86	29.06	2.94	274.0188	26.32	0.7841
	4	2(72)	1(Tuotulong 225)	2(2.0)	3(3.76)	4.65	32.92	2.19	168.9516	22.56	0.8114
	5	2(72)	2(Tuotulong 225 +Sujie 750)	3(2.5)	1(2.08)	4.27	32.63	2.54	315.2016	14.56	0.7384
	6	2(72)	3(Tuotulong 225 +Kesheng 750)	1(1.5)	2(2.79)	6.08	17.86	1.94	247.7016	13.95	0.8176
	7	3(48)	1(Tuotulong 225)	3(2.5)	2(2.79)	3.10	30.69	1.23	168.8844	19.53	0.8121
	8*	3(48)	2(Tuotulong 225 +Sujie 750)	1(1.5)	3(3.76)	1.65	35.48	0.90	266.3844	18.80	0.8194*
	9	3(48)	3(Tuotulong 225 +Kesheng 750)	2(2.0)	1(2.08)	5.03	38.46	1.53	221.3844	12.48	0.7660

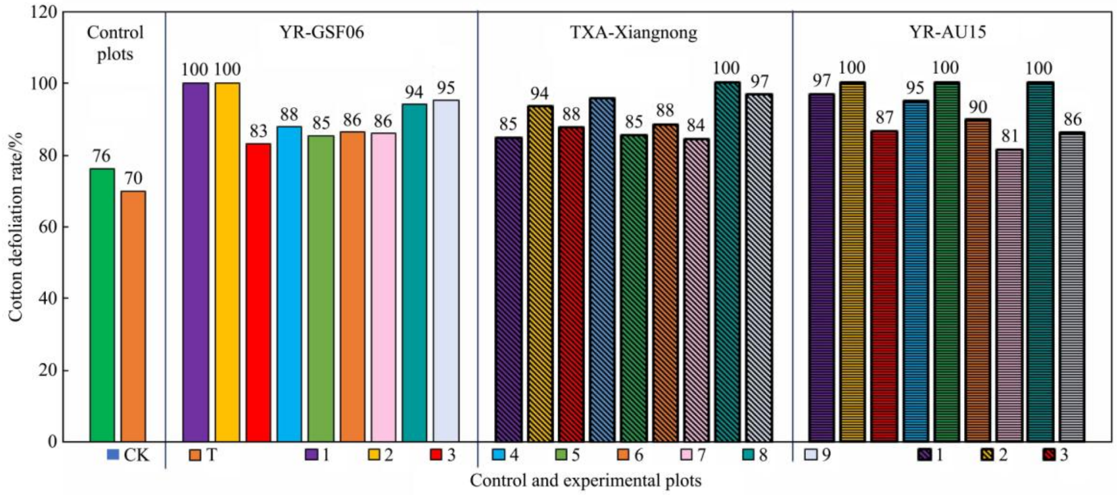
Note: $L_9(3^4)$ orthogonal arrays were performed by YR-GSF06, TXA-Xiangnong and YR-AU 15 respectively, each UAS has performed nine treatments of cotton defoliant spraying, parameters and results of each treatment are listed. VR, Volume Rate; TM, Tank Mix and concentration; FA, Flight Altitude; FS, Flight Speed; DC, Droplet Coverage; CV, Coefficient of Variance; PC, Power Consuming; C, Cost; E, Efficiency; OR, Overall rating (Score).

Table 4 Meteorological data were collected and recorded by the weather station throughout the experimental treatments

UAS	Test No.	Temperature/ ℃	Relative humidity/%	Wind velocity/m s^{-1}	Wind direction
YR-GSF06	1	23	29	3	Southeast, steady
	2	22	30	1-3	Southeast, steady
	3	21	31	1-2	Southeast, steady
	4	22	32	2	East, steady
	5	23	30	1-3	Northwest, variable
	6	22	32	4	Northwest, variable
	7	21	33	3	East, steady
	8	22	32	1	East, steady
	9	22	32	1	East, steady
TXA-Xiangnong	1	22	32	3	East, steady
	2	23	32	2	Northwest, steady
	3	23	30	2	West, steady
	4	23	32	3	Northwest, variable
	5	23	32	4	Northwest, variable
	6	21	34	4	Northwest, steady
	7	22	33	1	Northwest, steady
	8	20	42	1-2	South steady
	9	22	33	3	Northeast, steady
YR-AU 15	1	21	38	2	Northwest, steady
	2	21	39	2	Northwest, steady
	3	21	38	2	Northwest, steady
	4	21	38	1-2	Northwest, variable
	5	21	37	1	Northwest, steady
	6	21	37	1	Northwest, steady
	7	21	42	1	Southeast, steady
	8	21	37	1	North, steady
	9	21	36	1	North, steady



a. Cotton defoliation rate



b. Boll opening rate

Figure 3 Cotton defoliation rate and boll opening rate of experimental plots and control plots were investigated on the spraying day, 7 d, 14 d, and 25 d after the spraying day

a. CK plot b. plot spraying with ground rig c. plot spraying with UAS

Figure 4 Plots of CK, spraying with ground rig and UAS after 25 d of cotton defoliant application

3.3 Spray optimization

The present paper provides an assessment of spray performance to help guide optimization of parameters which can be controlled by an applicator such as application technique, acceptable meteorological conditions, selection of application volume rate, tank mix and concentration, and the spraying system. It should be noted that this assessment is only a partial evaluation because any final decision-making on spraying will also depend on other factors such as cotton variety, UAS type and so on. The correlation degrees and weight coefficients[35] were calculated (Table 5).

Table 5 Correlation degrees and weight coefficients of seven indices

Aircrafts	Indices	1	2	3	4	5	6	7
YR-GSF06	Correlation degree	0.5268	0.5886	0.9000	0.8726	0.6648	0.7334	0.6181
	Weight coefficient	0.1074	0.1200	0.1835	0.1779	0.1356	0.1495	0.1260
TXA-Xiangnong	Correlation degree	0.6889	0.6170	0.9297	0.9212	0.6023	0.7502	0.7283
	Weight coefficient	0.1315	0.1178	0.1775	0.1759	0.1150	0.1432	0.1390
YR-AU 15	Correlation degree	0.7386	0.6326	0.9709	0.9441	0.5294	0.7624	0.7797
	Weight coefficient	0.1379	0.1181	0.1812	0.1762	0.0988	0.1423	0.1455

Overall rating of different experimental plots of three UASs are shown in Table 3. It could be concluded from the overall rating that the optimum parameters for the three UAS were: Volume rate (A_3): 48 L/hm^2, Tank mix and concentration (B_2): (Tuotulong 225 + Sujie 275 + Ethephon 2250) mL/hm^2, Flight altitude (C_1): 1.5 m, Flight speeds (D_3) for YR-GSF06, TXA-Xiangnong and YR-AU 15 were 3.12 m/s, 2.51 m/s, 3.76 m/s respectively.

4 Conclusions

Incremental field experiments have been conducted across a two year period to evaluate the relative spraying performance of aerial cotton defoliant applications using UASs of four-rotor, six-rotor and eight-rotor. Orthogonal test arrays of $L_9(3^4)$ were carried out for the field experiments. Gray correlation analysis was used for evaluating spraying efficacy and efficiency in order to recommend optimal setups and application scenarios.

It was observed that: (1) cotton defoliant aerial spraying using UAS is feasible and providing logistical advantages over ground spraying; (2) the optimal scenarios for the three aircraft under the use conditions in this study involve the application of a tank mix containing (Tuotulong 225 + Sujie 750 +Ethephon 2250) mL/hm^2 at a total application volume rate of 48 L/hm^2, with an aircraft flight altitude of 1.5 m. Optimal flight speeds for the three aircraft were as follows: YR-GSF06, 3.12 m/s, TAX, 2.51 m/s and YR-AU 3.76 m/s. The results of this study will facilitate the development of cotton defoliant aerial spraying in China using UAS.

The authors have tested a range of application scenarios that is typical at the time of this study. It should be noted that there are many more choices available to applicators which may give different performance than that observed in the present study and we do not intend to recommend or endorse any products over others. Our research has provided examples of some application scenarios. Applicators have a wide, and ever-growing choice of systems for their specific spraying, and additional research in the future should test additional cases as appropriate.

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