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Chemical topping improves the efficiency of spraying harvest aids using unmanned aerial vehicles in high-density cotton

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ABSTRACT

The cotton defoliation strategy is highly appreciated in Xinjiang, where mechanical harvesting is limited by a large proportion of green leaves and unopened bolls at harvest due to an insufficient temperature sum. Because of a high plant density, the application of defoliants (harvest aids) by tractors is less efficient; thus, unmanned aerial vehicles (UAVs) for spraying harvest aids are becoming more and more popular. However, it is unknown if this method affects spraying quality and whether the spray is affected by the cotton plant type that was shaped by chemical topping. This study aims to address if chemical topping could enhance defoliation when harvest aids is sprayed using UAV. Field experiments were carried out in 2019 and 2020 in Alaer, Xinjiang, China. The topping treatments included manual topping (MT) as the control and chemical topping (CT) that inhibit apical growth of the stem by foliar application of mepiquat chloride (MC) at 90 (MC90), 180 (MC180), or 270 (MC270) g ha^{-1} in mid-July. The harvest aids was sprayed in mid-September using UAVs. The average droplet deposition and deposits of harvest aids within the canopy in CT and MT were not different in 2019. However, the average droplet deposition and deposits of CT were much higher than those of MT in 2020. Both droplet deposition and deposits decreased with canopy height, and the droplet distribution performance of CT was better than that of MT. The droplet deposition and deposits in the upper and middle canopy of CT were significantly higher than those of MT in 2020. At 21 days after harvest aids application, the number of leaves per plant in CT was significantly lower than that in MT, while there was no difference between the amounts of MC. CT did not affect boll opening. Moreover, the yield and quality were not affected by harvest aids application using UAVs and CT. We concluded that spraying harvest aids using UAVs combined with CT improved management efficiency and economic benefits by saving labor, without loss of cotton yield and quality. Our results demonstrate that applying harvest aids using UAVs in cotton with CT could improve the quality of defoliation and provide a reference for optimizing cotton managements globally.

1. Introduction

Cotton (*Gossypium hirsutum* L.) is an important economic crop in China and is the main raw material for the textile industry. The Xinjiang Uygur Autonomous Region in northwest China has become a major cotton-growing area (Tian et al., 2018). In 2018, the region measured 2.5 million hectares, with a total production of 5.1 million tons, accounting for 74.2% of the entire cotton-planting area and 83.7% of the total production in China (WNBS. PRC, 2018). In recent years, the quality of machine-harvested cotton in Xinjiang has not improved due to the lack of efficient defoliants and the development of new technologies. According to a survey, 43% of the cotton-processing companies in Xinjiang were not willing to purchase machine-harvested cotton (Zhang et al., 2015) because of the large number of leaves mixed in with the

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seed cotton.

Xinjiang is located in the inland of northwest China, with an arid climate and a short frost-free period, and the temperature resource greatly restricts the duration of cotton growth (Dai and Dong, 2014; Feng et al., 2017). The possible duration of cotton growth in Xinjiang is much shorter than in other cotton-producing areas of China and the United States (Jost and Cothren, 2000; Mao et al., 2014). To overcome these drawbacks and ensure quick canopy establishment, cotton in Xinjiang is planted with a high planting density, ranging from 16.5 to 22.5 plants m^{-2}, which is around twice that in the North China Plain (Feng et al., 2017; Meng et al., 2021). As a result, at harvest time, there is a substantial number of green leaves remaining in cotton plants, and the leaf area index (LAI) is high at 3.0–3.7 (Yang et al., 2019). This increases the difficulty of defoliation and opens bolls when machine harvesting is applied. The dense plant population and green leaves often prevent harvest aids from reaching the lower canopy. Therefore, harvest aids and spraying methods have attracted much attention for their contributions to harvest aids efficacy and environmental pollution (Liu et al., 2015; Meng et al., 2019).

As a new emerging technology, UAVs have become popular for spraying plant protection products in China. This spraying method has many advantages, such as reducing water use, decreasing pesticide pollution, causing less harm to crops and soil, increasing efficiency, and lowering costs (Chen et al., 2021; Meng et al., 2018). Pesticides applied by UAVs exhibit the most uniform distribution in the rice canopy, enhancing insecticidal efficacy (Qin et al., 2016). UAVs are also used in maize (Qin et al., 2014), wheat (Wang et al., 2019), fruit trees (Meng et al., 2020), and cotton. The flight height, spray volume, and droplet size affect spray penetration in the cotton canopy and the uniformity of droplet distribution (Chen et al., 2021). Two sprayings are suggested for harvest aids (Xin et al., 2018). Adding aviation spray adjuvants can improve defoliant droplet deposition and increase the defoliation rate and bolls opening rate (Xiao et al., 2019). The benefits of UAV applications in cotton include reducing labor costs and geographical restrictions without harm to operators (Chamata, 2017; Lan et al., 2008; Yu et al., 2016). However, it is unclear if the harvest aids sprayed by UAVs would affect cotton yield and fiber quality and if they can meet the requirements of machine harvesting.

Droplet deposition distribution and pesticide efficacy with UAV application are affected by plant architecture (Meng et al., 2020), and the cotton plant type is greatly determined by chemical topping. Chemical topping with a high amount of mepiquat chloride (MC), as a labor-saving technology, is applied on a large scale in China (Dai et al., 2022; Nie et al., 2021) and results in a different cotton canopy compared to manual topping (Liang et al., 2020; Yu et al., 2021). Thus, the efficacy of harvesting aids sprayed by UAV might differ between chemical topping and manual topping.

The objectives of this study were (i) to determine the effects of spraying harvest aids with UAVs on manual topping and chemical topping by quantifying the droplet deposition distribution within the cotton canopy; and (ii) to explore if UAV spraying quality affects cotton yield and fiber quality in relation to chemical topping and a high population density.

2. Materials and methods

2.1. Experimental site

Field experiments were conducted in Alaer (40°29'N, 80°50'E) in Southern Xinjiang, China, in 2019 and 2020. Alaer is located on the edge of the Taklimakan Desert and has a warm temperate inland desert climate with little precipitation and high radiation. The soil in the experiment site is sandy loam with a pH of 7.9, a total N of 0.72 g kg^{-1}, available P of 17.1 mg kg^{-1}, available K of 253 mg kg^{-1}, and organic matter content of 3.13 g kg^{-1} in the top 0–30 cm of the soil layer. The weather conditions of Alaer during the cotton-growing season (April–October) in 2019 and 2020 are shown in Fig. 1.

2.2. Experimental design and management

The cotton topping experiment was arranged in a completely randomized block design with three replicates. Topping modes include manual topping and chemical topping. Manual topping was to remove the top buds of the main stems manually after peak flowering (Dai et al., 2014). Chemical topping was conducted via foliar spraying of MC in three different amounts, i.e., 90 (MC90), 180 (MC180), and 270 (MC270) g ha^{-1}, in mid-July, and 150 mL ha^{-1} special additives were added to the solution to improve spraying quality. The chemical topping agent was sprayed by an electric knapsack sprayer. In addition to the heavy application of MC for chemical topping, 450 g ha^{-1} MC was applied eight times to restrict the vegetative growth of cotton plants for each plot according to farmers' traditional practice. Each plot included 12 rows in a narrow-wide row spacing; alternatively 10 + 66 cm that designed for machine-harvest, and the total plot area was 68.4 m^2 (15 m long × 4.6 m wide). The planting density was 19.5 plants m^{-2} in 2019 and 18.0 plants m^{-2} in 2020. The cotton cultivar was medium-maturing 'Yuanmian 11', and it was planted on April 10, 2019 and on April 13 in 2020. The harvest dates for cotton were October 15, 2019 and October 10, 2020.

To evaluate the droplet deposition distribution of harvest aids in the cotton canopy, 2250 g ha^{-1} Xinsaili, a newly developed defoliation aid of 10% thidiazuron and 40% ethephon, was sprayed by UAVs on September 14, 2019 and on September 17, 2020.

The experiment was irrigated with a surface drip-irrigation system under plastic film mulching. Irrigation was applied eight times throughout the cotton-growing season, with an amount of 4560 m^3 ha^{-1} in 2019 and 5100 m^3 ha^{-1} in 2020. Fertilizers were applied according to local farmers' practices; at sowing, 80 kg ha^{-1} N, 130 kg ha^{-1} P_2O_5, and 35 kg ha^{-1} K_2O were applied, and during both cotton-growing seasons, 200 kg ha^{-1} N, 93 kg ha^{-1} P_2O_5, and 61 kg ha^{-1} K_2O were applied with drip irrigation. Insect pests, weeds, and diseases were controlled in a timely manner according to farmers' practices.

2.3. Plant protection UAV and environmental condition monitoring

In this study, we selected two different types of plant protection UAVs. The T16, powered by a 17,500 mAh–51.8 V battery (DJI Technology Co., Ltd., Shenzhen, China) and equipped with six rotors and eight pressure nozzles, was used in 2019. The XP2020ST, powered by an 18,000 mAh–48.1 V battery (XAG Co., Ltd., Guangzhou, China) and equipped with four rotors and four centrifugal nozzles, was used in 2020. Both UAVs used the Global Navigation Satellite System (GNSS) and Real-Time Kinematic (RTK) navigation technology. The accuracy of the flying height and velocity was controlled to remain within the centimeter level. The working parameters of the two UAVs during spraying are presented in Table 1. The accuracy of the flight height and velocity was achieved by well-trained professionals. To prevent droplets from drying quickly and to reduce drift, harvest aids spraying stopped at high noon and when the wind speed was more than 3 m s^{-1}. To ensure spraying efficiency and quality and to reduce drift, we monitored the environmental parameters during application using an air quality detector (4.0XS, Green Source Co., Ltd) and a digital anemometer (PM6252A, Shenzhen Huayi Smart Measurement Technology Co., Ltd). The temperature, relative humidity, and wind speed during spraying were 29.2 °C, 38%, and 0.5 m s^{-1}, respectively, in 2019, and 26.4 °C, 35%, and 0.65 m s^{-1}, respectively, in 2020.

2.4. Measurements

2.4.1. Yield and fiber quality

To determine the final seed cotton yield and yield components, open bolls of ten representative plants in the center eight rows in a

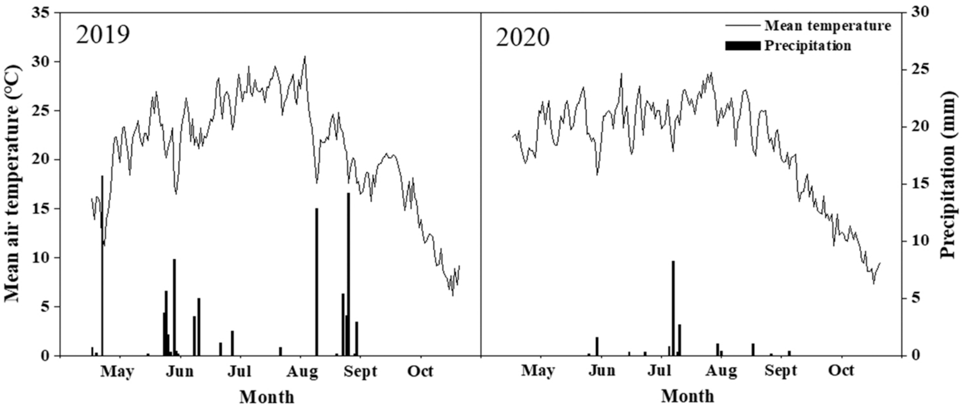

Fig. 1. Daily mean air temperature and precipitation during cotton-growing seasons in 2019 and 2020 at Alaer, China.

Table 1
Working parameters of unmanned aerial vehicles (UAVs) during harvest aid application in 2019 and 2020.

Year	UAV type	Parameters							
		Number of propellers	Nozzle type	Number of nozzles	Spraying width (m)	Spraying height (m)	Driving speed (m s^{-1})	Tank capacity (L)	Spraying volume (L ha^{-1})
2019	DJI T16	6	Pressure nozzle	8	4.6	2.5	4	16	19.5
2020	Jifei XP2020	4	Centrifugal nozzle	4	4.6	2.5	5	20	22.5

subsampling area of 24.3 m^2 per plot were counted to obtain the number of open bolls per plant, then all open bolls of subsampling area were manually harvested to determine the seed cotton yield by weight. Ninety bolls from the sample area were randomly collected per plot to measure the average boll weight and lint percentage on October 13, 2019 and on October 8, 2020. Then, fiber samples (30 g) obtained in each plot were sent to the Supervision, Inspection and Test Center of Cotton Quality, Ministry of Agriculture, Anyang, China, to determine fiber quality using a high volume instrument (HVI).

2.4.2. *Growth and development*

Ten cotton plants were successively marked from the center four rows in each plot before harvest aids were applied. Then, the plant height and canopy width of tagged cotton were measured using a portable scale, and the length from the ground to the shoot apex and the maximum horizontal width of the cotton canopy were considered the plant height and canopy width, respectively. The green leaves, number of open bolls, and total bolls of the 10 marked plants were counted before harvest aid application and were counted at 7, 14, and 21 days

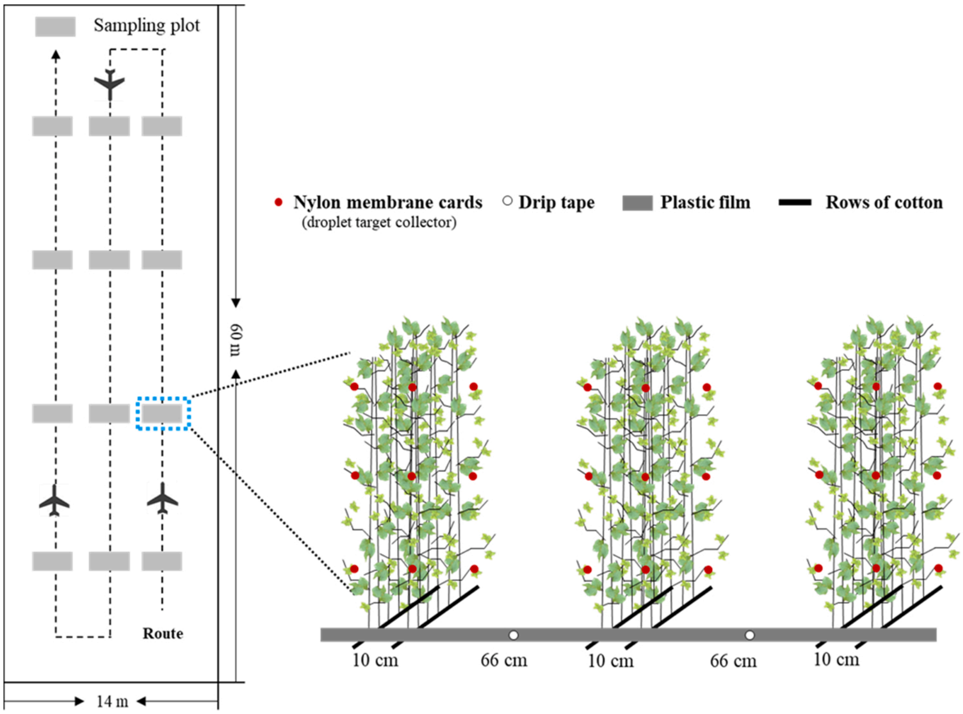

Fig. 2. Unmanned aerial vehicle (UAV) flight route and layout of sampling points within the cotton canopy in 2019 and 2020.

after spraying. The LAI was measured with an LAI-2000 canopy analyzer (Li-COR Inc., Lincoln, NE, USA) (Yang et al., 2019) in each plot before harvest aid application. The measurements were repeated at least three times to minimize errors within each plot.

2.4.3. Droplet deposition distribution

Droplet deposits and deposition of harvest aids in the plant canopy measure spray quality and efficacy (Meng et al., 2019; Zhu et al., 2011). In this study, droplet deposition, deposits, and distribution uniformity of harvest aids in the cotton canopy using UAVs with low-volume spraying were evaluated by setting nylon membrane cards at different canopy positions (Fig. 2).

When applying harvest aids, UAVs flew along a route of 4.6 m width, including six rows of sampling areas (Fig. 2). In a route, nylon membrane cards (NMCs), the droplet target collector, were placed in six rows and evenly distributed in the downwind field of the UAVs. The cotton canopy was divided into three levels according to plant height, and nine pieces of NMCs were attached to cotton leaves with double-sided tape in each of the upper, middle, and bottom layers of the canopy. The test zone contained three replicates, and 27 NMCs were collected in each layer. Then, a new target oligonucleotide code (TOC) method was used to detect the droplet deposition distribution. The TOC method is based on a reverse dot-blot strategy (Romano et al., 2001; Saiki et al., 1989). The TOC and harvest aids were added to the tank before application, and the spray droplets were captured, identified, and displayed by color through a base complementary pairing and signal amplification process. The NMCs were scanned in a laboratory (CanoScan LiDE 220, Japan), and the droplet deposits and deposition of harvest aids were analyzed by the DepositScan program (USDA, USA).

2.5. Statistical analyses

The experimental data were analyzed using one-way analysis of variance (ANOVA) using SPSS 21.0 (SPSS Inc., Chicago, IL, USA). Duncan's test was used for multiple comparison at the 95% probability level. Origin 2018 (Origin Lab Co., Northampton, MA, USA) was used to plot the figures.

3. Results

3.1. Yield and fiber quality

Compared with manual topping, the cotton yield, yield components, and fiber quality were not affected by chemical topping, and also did not interact with year. The number of bolls, lint percentage, seed cotton yield, and fiber quality (fiber length, strength, and micronaire) differed between the two years and were higher in 2020 than in 2019, except for fiber length and strength, which were lower in 2020 (Table 2).

3.2. Morphological growth

The final plant height differed between manual topping and chemical topping. The plant height of chemical topping (93.3 cm) across the two years was 16.9% higher than that of manual topping (79.8 cm). The plant height in chemical topping decreased with MC doses (Fig. 3A, B). The plant height in 2019 was higher than that in 2020. The canopy width of chemical topping was, on average, 8.8% shorter than that of manual topping (Fig. 3C, D).

3.3. Leaves and bolls

The LAI before harvest aid application was much higher in 2019 than in 2020 (Fig. 4). Before spraying, there were 29.6 and 23.5 leaves per plant, on average, in 2019 and 2020, respectively. LAI was not significantly different between the two topping treatments in either year.

Within 7 days of spraying, leaf numbers showed no differences between the two topping treatments. Then, the leaf numbers of chemical topping decreased quickly. At 14 days after spraying, the number of leaves per plant in chemical topping was, on average, 18.7% lower than that in manual topping. At 21 days after spraying, the number of leaves

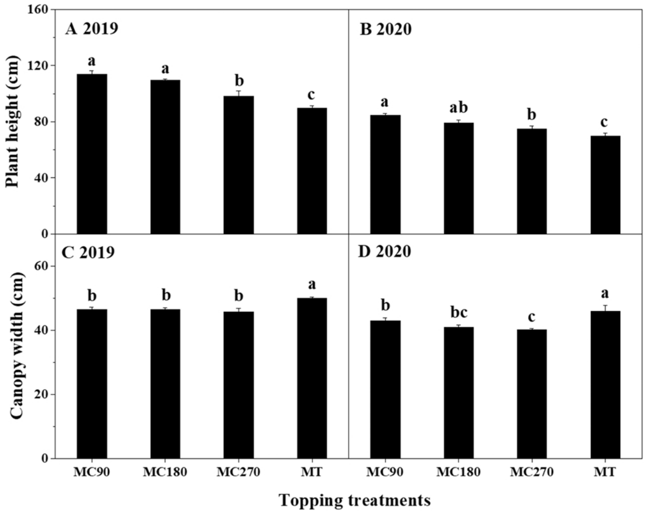

Fig. 3. Plant height and canopy width of cotton in chemical topping (e.g., MC90) and manual topping (MT) in 2019 and 2020. MC indicates mepiquat chloride, and the subsequent number is the application amount (g ha^{-1}).

Table 2
The effect of topping modes and harvest aids on cotton quality, yield, and yield components in 2019 and 2020.

Year	Treatment	Boll number (bolls m^{-2})	Boll weight (g boll^{-1})	Lint percentage (%)	Seed cotton yield (kg ha^{-1})	Fiber length (mm)	Fiber strength (cN tex^{-1})	Micronaire
2019	MC90	80.0 a	6.4 a	38.9 a	3690 a	31.5 a	35.1 a	3.6 a
	MC180	73.8 a	6.4 a	39.6 a	3832 a	31.8 a	35.1 a	3.6 a
	MC270	73.7 a	6.2 a	40.2 a	3932 a	31.4 a	35.6 a	3.9 a
	MT	87.7 a	6.2 a	40.5 a	3773 a	30.8 a	35.0 a	4.1 a
2020	MC90	103.6 a	6.1 a	44.4 a	5034 a	29.9 a	33.4 a	4.8 a
	MC180	93.7 a	6.2 a	44.3 a	4914 a	30.0 a	33.9 a	4.9 a
	MC270	98.7 a	6.2 a	43.9 a	4836 a	29.4 a	32.8 a	4.9 a
	MT	95.3 a	6.2 a	44.8 a	4967 a	29.9 a	32.5 a	4.9 a
Source of variance								
Year (Y)		*	ns	*	*	*	*	*
Treatment (T)		ns	ns	ns	ns	ns	ns	ns
Y×T		ns	ns	ns	ns	ns	ns	ns

The same lowercase letters indicate no significant difference between treatments within the same year at $a = 0.05$. MC indicates mepiquat chloride, and the subsequent number is the application amount (g ha^{-1}). MT indicates manual topping. ns means non-significant, while * indicates a significant difference at $a = 0.05$.

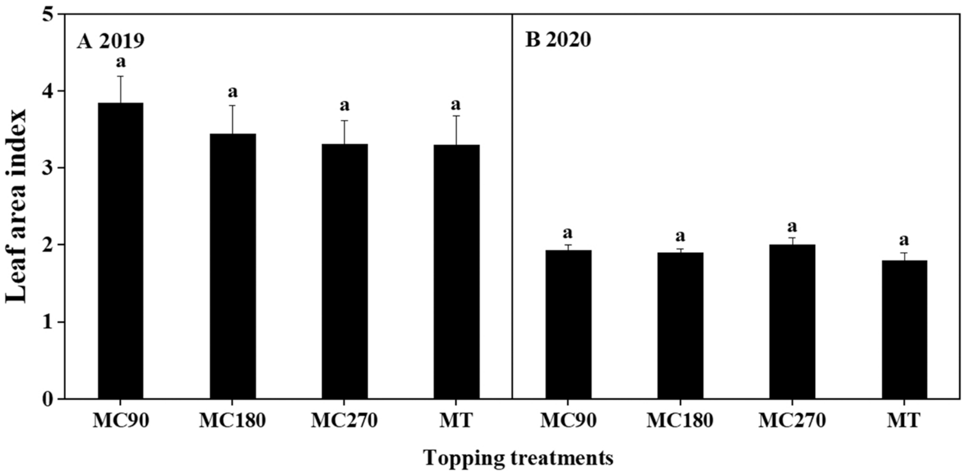

Fig. 4. Leaf area index (LAI) before harvest aid application on September 9, 2019 and on September 10, 2020. MC indicates mepiquat chloride, and the subsequent number is the application amount (g ha^{-1}). MT indicates manual topping.

per plant was 5.1 in MC90, 4.9 in MC180, and 4.1 in MC270, on average, which was much lower than that in manual topping (7.0 leaves) (Fig. 5A, B).

At the time of harvest aid application, the number of open bolls was much lower in 2019 than in 2020. In 2019, the number of open bolls increased rapidly after spraying and showed no significant difference between chemical and manual topping (Fig. 5C). In 2020, because almost all bolls were open before spraying, there was no significant difference between the two topping treatments (Fig. 5D).

3.4. Droplet deposition and deposits

The average droplet deposition was 0.23 μL cm^{-2} in MC90, 0.22 μL cm^{-2} in MC180, and 0.20 μL cm^{-2} in MC270; these values were higher than in manual topping (0.09 μL cm^{-2}) in 2020 (Fig. 6B). The average deposits were 28.9 points cm^{-2} in MC90, 30.0 points cm^{-2} in MC180, and 29.4 points cm^{-2} in MC270 and were higher than in manual topping (18.6 points cm^{-2}) in 2020 (Fig. 6D). The droplet deposition and deposits were slightly higher in chemical topping treatments than in manual topping; however, they did not differ significantly in 2019 (Fig. 6A, C).

3.5. Distribution of droplet deposition and deposits

As shown in Fig. 7, droplet deposition and deposits decreased with canopy height. At the upper and middle canopy layers, both droplet deposition and deposits of chemical topping, except for MC180 in 2019, were higher than those of manual topping in both years. At the bottom of

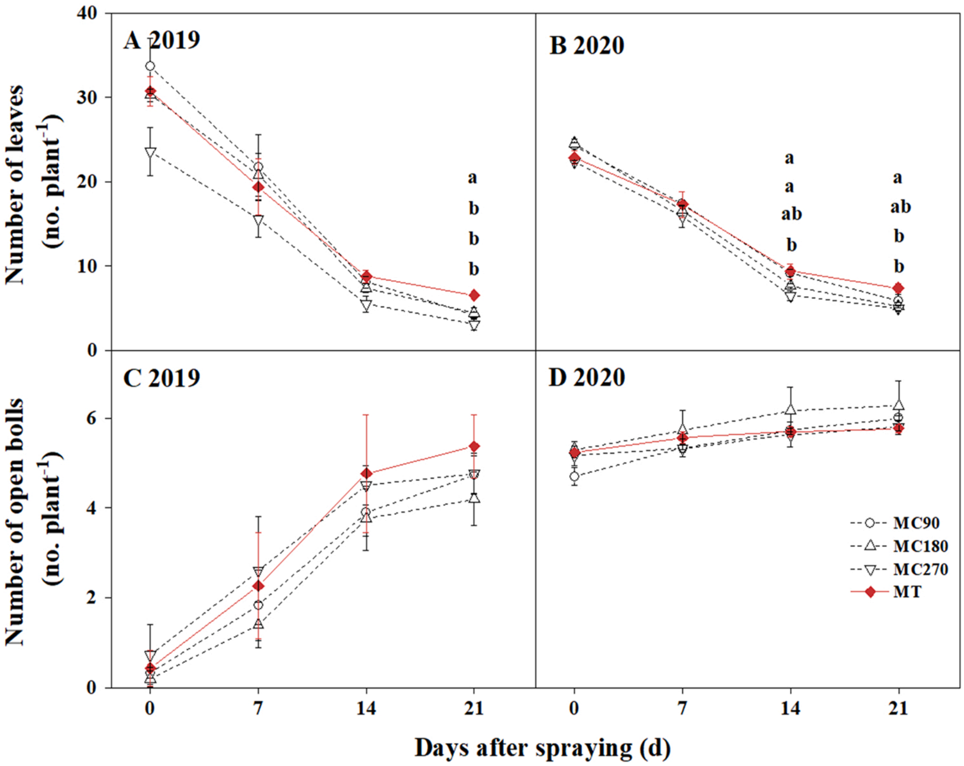

Fig. 5. Number of leaves and open bolls per plant after harvest aid application by unmanned aerial vehicle (UAV) in 2019 (A, C) and 2020 (B, D). MC indicates mepiquat chloride and the subsequent number is the application amount (g ha^{-1}), which presents chemical topping. MT indicates manual topping.

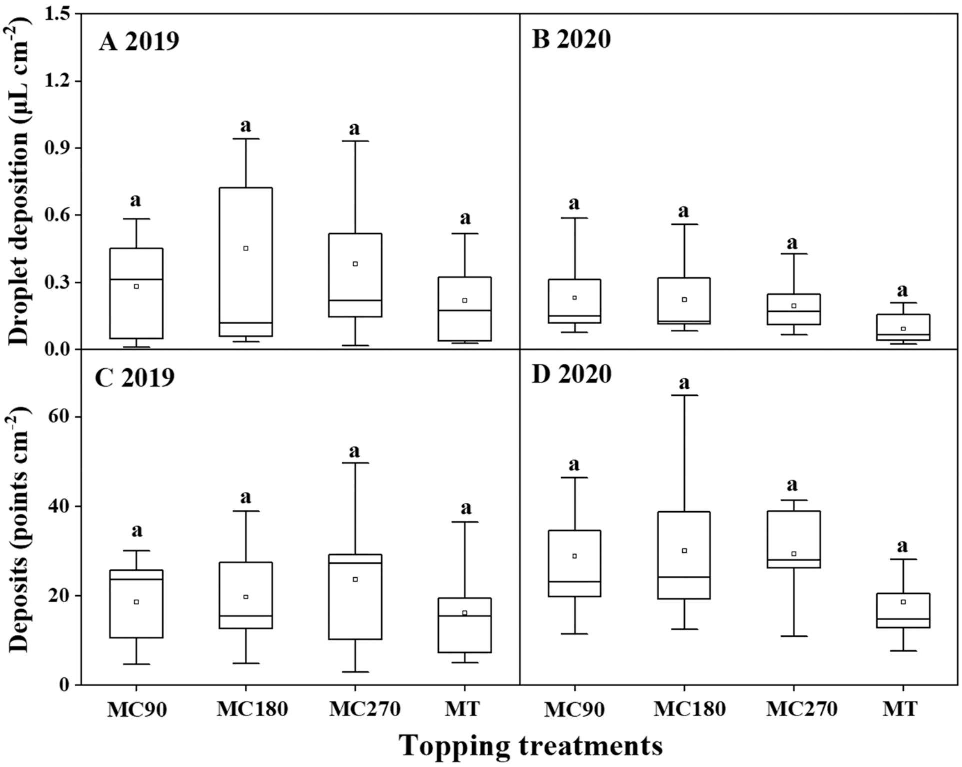

Fig. 6. The average droplet deposition and deposits in chemical and manual topping treatments in 2019 and 2020. MC indicates mepiquat chloride and the subsequent number is the application amount (g ha^{-1}), which presents chemical topping. MT indicates manual topping.

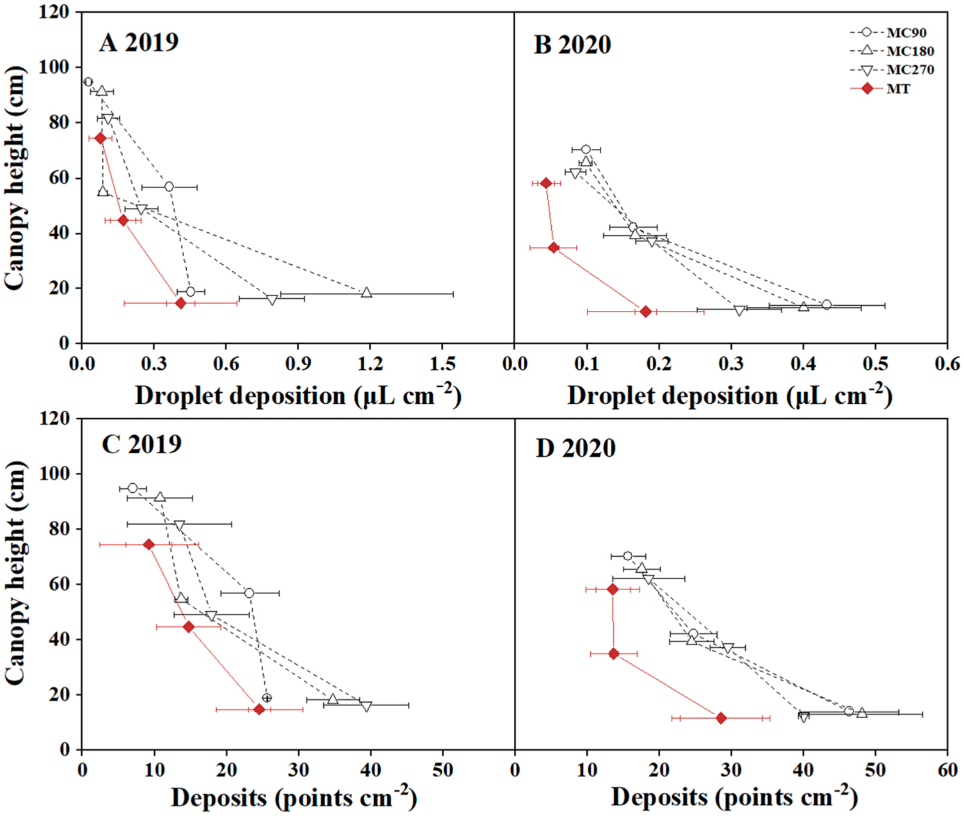

Fig. 7. Distribution of droplet deposition and deposits within the cotton canopy in 2019 and 2020. MC indicates mepiquat chloride and the subsequent number is the application amount (g ha^{-1}), which presents chemical topping. MT indicates manual topping.

the canopy, droplet deposition and deposits of chemical topping were much higher than in manual topping, especially in 2020. This demonstrated a strong penetration in chemical topping when using UAVs to spray the harvest aids.

4. Discussion

Spraying harvest aids using UAVs combined with chemical topping did not reduce cotton yield and quality. Chemical topping improved the distribution of droplet deposition and deposits within the canopy. At the upper and middle canopy, the droplet deposition and deposits in chemical topping were much higher than in manual topping, especially in 2020, demonstrating a deeper penetration and a better applying efficiency due to the morphological changes caused by the heavy application of MC. The improved quality in spraying harvest aids with chemical topping led to better defoliation and quicker boll opening, which benefited machine harvesting.

Our findings confirm that spraying harvest aids using UAVs did not affect cotton yield and fiber quality (Meng et al., 2019). In our study, although two types of UAVs were used because of the availability of plant protection services; this may not have affected our results. A field experiment of spraying harvest aids with four types of UAVs in Xinjiang has showed no differences on the effect of spraying quality and yield (Ma et al., 2016). Harvest aid application by UAVs can potentially be applied to replace tractors or knapsack sprayers due to their low cost and less labor input. The huge difference in fiber quality parameters, such as fiber length, fiber strength, and micronaire, in 2019 and 2020 was mainly attributable to the difference in weather conditions between the two years (Fig. 1; Table 2). In 2019, there was more precipitation, especially in August and September, which led to excessive vegetative growth in cotton. However, we observed a high mean air temperature and less precipitation in 2020, which led to drought during the cotton bolls opening period. As a result, bolls opened prematurely, greatly affecting the fiber quality.

Differing with previous findings that manual topping improved cotton yield and quality by accelerating the transportation of nutrients to bolls (Yang et al., 2008), our study showed that chemical topping achieved the same yield as manual topping. Additional organs continue to develop after applying chemical topping, and these organs would not contribute to the final yield because there is not enough thermal time for the maturation of young fruit; thus, the yield might decrease. However, chemical topping improves light use efficiency by extending the photosynthesis period and increasing the number of fruit branches (Liang et al., 2020; Yang et al., 2015). The disadvantage of chemical topping on excessive growth might be compensated for the advantage of light use. Cotton in chemical topping has more fruit branches, high plant height, and more assimilate portioning to fruit (Dai et al., 2022), which provides the possibility to increase the seed cotton yield.

A better efficacy of harvest aid application using UAVs was achieved with chemical topping because of morphological improvements. Leaves remaining in plants at harvest time increase the trash content of mechanically harvested cotton (Byrd et al., 2016). Spraying harvest aids using UAVs defoliates almost all leaves with chemical topping, obtaining better effects for the leaves at the bottom canopy and thus improving the fiber quality of machine-harvested cotton by reducing the cleaning time during the ginning process (Li et al., 2012a; Tian et al., 2017). We did not test the optimal application time for harvest aids, but a low yield would be obtained if harvest aids were applied between 20% and 40% open bolls (Snipes and Baskin, 1994). By applying harvest aids at 60% or greater of open bolls, the cotton yield and fiber quality could be increased (Bynum and Cothren, 2008; Du et al., 2013). Cotton growth duration in Xinjiang is much shorter than that in the United States and Australia due to an insufficient temperature sum; thus, many green leaves might remain at the time of harvest aids application (Feng et al., 2017; Jost and Cothren, 2000; Meng et al., 2021). However, the spraying of harvest aids using UAVs still achieves better performance in chemical topping. In 2019, there were few bolls opening at the time of harvest aids application, but new harvest aids used in this study showed a good performance in accelerating the process of boll opening. The effect of spraying harvest aids using UAVs would be affected by weather conditions that not only depend on suitable weather for UAV flights but also the air temperatures, affecting the function of harvest aids (Snipes and Wills, 1994). However, there is limited information available, and this topic requires further study.

The compact cotton plant achieved by chemical topping promoted the spraying efficiency of UAVs, i.e., deeper penetration of droplet deposition and deposits compared to manual topping. Previous studies have demonstrated that the efficiency of pesticide application by UAVs is not only affected by dosage, spraying parameters, and equipment but also by plant phenotypes (Lou et al., 2018; Qin et al., 2016; Tang et al., 2018). A compact cotton plant types can not only increase cotton yield by optimizing light utilization (Liang et al., 2020; Mao et al., 2014), but also can improve the efficacy of pesticide application, i.e., harvest aids sprayed by UAVs. In this study, chemical topping promoted a compact plant type due to a significant decrease in canopy width, which allowed more leaves in the middle and bottom canopy layers to be exposed to harvest aids, thus having a better defoliation efficacy (Figs. 5–7). The main compound of harvest aids, thidiazuron, a synthetic cytokinin-like molecule, cannot easily move from the leaf to other tissues (Huetteman and Preece, 1993); therefore, the deep penetration of the chemicals is a benefit. The half-life of thidiazuron in the field is about 10 days (Meng et al., 2019). The half-life of MC, the main compound of the chemical topping agent, in cotton plants and in soil was 2.5–3.9 days and 7.6–10.5 days, respectively (Li et al., 2012b). The reduced amount of chemical residue ensures the environmental tolerance of chemical topping and harvest aids.

The economic benefits of machine harvesting cotton are key issues in cotton production and are determined by labor cost, fertilizer cost, management cost, and the market price of seeds, pesticides, and seed cotton yield in different years (Guo et al., 2021). In China, manual topping, as a traditional cultivation practice, has been adopted for hundreds of years to control excessive vegetative growth (Dai et al., 2017; Mao et al., 2015). However, the rapid development of urbanization, labor shortages, and consequent high labor prices have brought great challenges to continuing this practice in China (Dai and Dong, 2014). The replacement of manual topping and the optimization of harvest aid efficacy are the most efficient ways to improve the yield, quality, and economic benefits of cotton in China. In this study, although chemical topping required additional pesticide input, which increased the cost of agricultural production, it was negligible compared to manual topping. Harvest aid application is traditionally performed by tractors or knapsack sprayers in China and requires more water and labor (Meng et al., 2019). When the tractors spray the harvest aids, machines may also damage cotton crops by rolling over the cotton plants and knocking off the bolls. Spraying harvest aids using UAVs overcomes these shortcomings and has a low cost at 60 CNY ha^{-1} in Xinjiang. However, the net revenues of spraying harvest aids by UAVs combined with chemical topping need to be investigated on a large scale to evaluate it more precisely. (Fig. 8).

5. Conclusion

Spraying harvest aids using a UAV did not affect cotton yield and fiber quality. Chemical topping increased droplet deposition and deposits in the cotton canopy, thus improving harvest aids efficiency. The optimal strategy of machine harvesting cotton in Xinjiang was identified as 180 g ha^{-1} MC application for chemical topping and spraying harvest aids using UAVs. Our results provide a promising alternative to help farmers manage their cotton with a low cost without sacrificing yield and quality. Moreover, this study further expanded the use of plant growth regulators in cotton production, being of great significance not only in China but also of great reference to other cotton-growing

Chemical topping **Manual topping**

Fig. 8. Cotton plants with chemical topping and manual topping at Alaer in 2020.

countries.

Author Contributions

M. D., Z. Z., and K. Y. designed the research; Y. L. and K. Y. performed the experiments with the assistance of Z. G., Y. L., S. P., L. D., and K. L.; K. Y. analyzed the data; W. T., X. L., L. Z., X. T., and Z. L. provided some important suggestions; K. Y. wrote the paper. All authors reviewed the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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