# Cotton Growth and Yield Quality Responses to the Application of Chemical Topping Agents via Unmanned Aerial Vehicles

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**Abstract** [**Objectives**] To determine the optimal concentration of topping agents applied by unmanned aerial vehicles (UAVs) to effectively regulate cotton growth and improve production efficiency. [**Methods**] A field experiment was conducted in Shihezi City, Xinjiang, employing a randomized block design. Five UAV-based chemical topping treatments were applied at dosages of 0.300, 0.525, 0.750, 0.975, and 1.200 L/hm$^2$, designated as H1, H2, H3, H4, and H5, respectively. Additionally, manual topping (CK1) and tractor topping (CK2) treatments, both at a concentration of 0.750 L/hm$^2$, were included as control treatments. During the first 20 d following topping, parameters including primary agronomic traits of cotton (plant height, leaf age, number of fruit branches), dry matter accumulation and distribution, leaf area boll load (LAB), root-to-shoot ratio (RSR), leaf mass area (LMA), and leaf area index (LAI) were examined. At harvest, yield components, lint cotton yield, harvest index, and fiber quality were evaluated. [**Results**] Twenty days after topping, the concentration of the topping agent applied via UAV did not significantly affect cotton leaf age or the number of fruit branches. Additionally, no significant differences in plant height were observed among the five concentration treatments compared to CK2. However, plants treated with H1 exhibited significantly greater height compared to those treated with H5 and CK1, indicating that H1 was the least effective in controlling vegetative growth. Total dry matter accumulation (TDM), boll dry matter accumulation (BDM), LAB, and LMA all demonstrated an initial increase followed by a decrease as the spraying concentration increased. The highest TDM and reproductive organ dry matter ratio (RRDM) were observed in the H3 treatment. No significant differences were found among treatments for LMA, RSR, or LAI; however, LAB and single boll weight were greatest in the H3 treatment. Fiber quality parameters, including fiber length uniformity, micronaire (MIC), specific strength, and fiber maturity, initially increased and then decreased with increasing spraying concentration, whereas fiber elongation rate exhibited the opposite trend. The H3 treatment yielded the highest average fiber length uniformity and specific strength. [**Conclusions**] At optimal spraying concentrations, UAV-based application more effectively controls vegetative growth, promotes dry matter accumulation and distribution in cotton bolls, increases single boll weight, and enhances the MIC, specific strength, and fiber elongation rate of cotton fibers compared to manual and tractor spraying of topping agents. In summary, the use of UAVs for spraying chemical topping agents is recommended, with a suggested dosage range of 0.750 and 0.975 L/hm$^2$.

**Key words** Unmanned aerial vehicles (UVAs), Chemical topping, Cotton, Dry matter accumulation, Seed cotton yield, Fiber quality

## 1 Introduction

Topping is a critical stage in the cotton production process[1]. Currently, the apical portion of the main cotton stem is predominantly removed manually, and the method effectively reduces plant height as well as the growth of leaves and branches[2]. Moreover, the frequency of topping can be adjusted in accordance with the developmental stage of the cotton, while the intensity and timing of topping can also be regulated. Manual topping demands substantial human and material resources, exhibits low efficiency, incurs high costs, and increases the risk of pest and disease transmission. Given the current context of limited labor availability and escalating expenses, this method is no longer appropriate to meet the requirements of efficient cotton production[3]. Numerous mechanical topping techniques exist, such as hydraulic control topping, laser topping, mechanical lifting topping, mechanical rotary cutting topping, and machine vision topping. Although the underlying principles of these methods differ, all necessitate uniform cotton growth, consistent plant height, and level terrain to maximize the benefits of mechanical topping and attain optimal results[4]. Consequently, these techniques are not well-suited for large-scale implementation. Chemical topping is a technology that has gained widespread promotion in recent years. Compared to manual topping, chemical topping can enhance several agronomic traits within a certain range, including the number of bolls per plant, plant height, number of fruit branches, and leaf area index. Additionally, it can modify the cotton plant architecture[5-8], leading to increased dry matter accumulation and cotton yield. Shi *et al.*[9] demonstrated that chemical topping regulates the canopy structure of cotton, suppresses apical dominance, and consequently increases cotton seed yield. Tung *et al.*[10] demonstrated that chemical topping can retard the senescence of cotton reproductive organs and enhance their biomass. Yang Chengxun *et al.*[11] showed that chemical topping can modify the plant architecture of cotton, alter canopy structure and light distribution, optimize the photosynthetic efficiency of the population, and increase cotton yield. Xu

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Shouzhen *et al.* [12] demonstrated that appropriately reducing the irrigation amount of cotton, combined with the rational application of chemical topping agents, does not significantly affect cotton yield or lint percentage. The use of tractors to spray chemical agents for topping offers advantages such as time efficiency, labor reduction, cost savings, and increased operational efficiency compared to manual spraying. Besides, this method can enhance the potential quality of cotton to some extent[8,13]. However, it is susceptible to issues such as missed spraying, over-application, and mechanical damage. Besides, the diversity of topping agents employed imposes specific requirements on cotton growth as well as water and fertilizer management. Furthermore, the use of these agents may also lead to pesticide contamination in cotton fields, thereby diminishing cotton quality and adversely affecting the economic returns for cotton farmers[14-15].

The advancement of unmanned aerial vehicle (UAV) technology has ushered in a "green revolution" within the agricultural sector through the application of UAV spraying techniques. These methods have been extensively employed for the application of insecticides to control pests on crops such as wheat[16], rice[17], corn[18], and cotton[19], as well as for the chemical regulation of growth using agents like mepiquat chloride and chlormequat chloride[20]. The application of chemical topping agents on cotton via UVAs offers several advantages, including water and pesticide conservation, time and labor saving, high efficiency, and precise, quantitative spraying. Furthermore, the topping process does not cause mechanical damage to the cotton, and multiple applications can be employed to address any deficiencies. This method represents a promising future development trend in cotton topping[21]. The application of cotton chemical topping agents via UAVs integrates the benefits of manual topping, mechanical topping, and tractor spraying. This method is characterized by rapid topping speed, high efficiency, low water consumption, minimal crop damage, capability for all-weather spraying, directional application, and adjustable dosage. Additionally, it does not impose stringent requirements on the uniformity of cotton growth. The application practice also exhibits several deficiencies, including the tendency of the solution to drift and insufficient penetration, specific requirements related to weather conditions and operator skills, limited operational endurance, high maintenance costs, and the absence of comprehensive standards. Most of the chemical topping agents applied via UAVs in the cotton-growing regions of Xinjiang remain in the experimental and demonstration phases. Since the concentrations of these agents are primarily determined by referencing tractor spraying standards, they are generally set too high. This not only prolongs the topping process but also limits the agents' applicability across different contexts. Furthermore, owing to the diverse range of UVA models and the numerous types of topping agents, there exist substantial variations in dosage, application frequency, corresponding UVA models, and crop plant spacing configurations for each topping agent. Additionally, different combinations and environmental conditions significantly influence the efficacy of these agents, necessitating long-term and continuous research and refinement. Consequently, the research team led by the author conducted experiments over two consecutive years to investigate the effect of varying concentrations of chemical topping agents applied via UVAs on the growth, yield, and quality of cotton. The study aims to provide a scientific foundation for the use of chemical topping agents sprayed by UVAs in cotton cultivation and offer valuable insights for the development of simplified and efficient cotton cultivation practices.

## 2 Materials and methods

**2.1 Overview of the test site and test materials** This experiment was conducted in the experimental field of the Cotton Research Institute at the Xinjiang Academy of Agricultural and Reclamation Science (44°18′52″ N, 85°58′50″ E) in 2021 and 2022. The preceding crop in the two-year experimental field was cotton, and the soil was characterized as clay loam with medium fertility (Table 1). The cotton variety used in the study was Jinken 1565, supplied by the Xinjiang Academy of Agricultural and Reclamation Science. The biological topping agent, Smart Control Expert, was supplied by Beijing Shennongyuan Biotechnology Development Co., Ltd. Fig. 1 illustrates the temperature and precipitation data during the cotton growing season (April to October) in Shihezi City, Xinjiang, from 2021 to 2022. All data were obtained from the Shihezi Meteorological Bureau. From July to August 2021, the weather was predominantly hot and rainy, with the maximum temperature reaching 40.7 ℃, the minimum temperature recorded at 16.9 ℃, and an average daily precipitation of 2.56 mm. In contrast, the same period in 2022 experienced drier conditions with infrequent rainfall, a maximum temperature of 38.7 ℃, a minimum temperature of 13.1 ℃, and an average daily precipitation of 0.23 mm.

**Table 1 Nutrient content and pH of test soil**

| Year | Organic matter//g/kg | Available P//mg/kg | Available K//mg/kg | Alkai-hydrolyzable N//mg/kg | pH |
|---|---|---|---|---|---|
| 2021 | 9.61 | 12.34 | 381.75 | 61.96 | 8.3 |
| 2022 | 9.63 | 12.39 | 376.32 | 61.52 | 8.4 |

**2.2 Experimental design** The experiment included five concentration treatments of a topping agent applied via UAVs: 0.300 (H1), 0.525 (H2), 0.750 (H3), 0.975 (H4), and 1.200 L/hm$^2$ (H5). Additionally, two control treatments were established, consisting of manual topping (CK1) and tractor topping (CK2), both at a concentration of 0.750 L/hm$^2$. Each treatment was replicated three times. The area of each plot measured 460 $m^2$ (length 100 m, width 4.6 m). Buffer rows were established between plots, and the treatments were arranged in a randomized block design. On July 9, 2021, and July 7, 2022, both the UAV and control treatment topping agents consisted of the biological topping agent Smart Control Expert. The formulation comprised 5 parts figarin, 5 parts emulsifier, 15 parts xylene, 1 part prosperity control agent, 0.5 parts pollination agent, 0.5 parts swelling agent, 0.5 parts 4-chlorophenoxyacetic acid, 0.2 parts microbial compound agent, 0.5 parts microbial metabolite, and 3 parts flumetralin. The product was supplied in 500 mL bottles by Beijing Shennongyuan Biotechnology Development Co., Ltd. The UAV utilized was the XAG P30, manufactured by Guangzhou XAG Technology Co., Ltd., characterized by an electric multi-rotor configuration. The total weight of the vehicle was 16.1 kg, with a maximum liquid carrying capacity of 16 kg. It was equipped with four SNZ-14000A rotary centrifugal nozzles, which produced atomized particles ranging in size from 90 to 300 μm. The UAV exhibited a maximum spray flow rate of 5.6 L/min and achieved a maximum flight speed of 7 m/sec, with an effective spray width varying between 2 and 6 m. The tractor utilized was a Lovol M750H-D type tractor equipped with a backpack medicine tank. The medicine tank had a maximum capacity of 2.0 t, operated at a speed of 5 km/h, and featured a spray width of 14 m. The cotton sowing dates in 2021 and 2022 were on April 18. An ultra-wide film measuring 2.05 m in width, with one film covering six rows (66 cm + 10 cm), was utilized for machine-harvested cotton planting. The planting width was 4.56 m, and the plant spacing was 0.1 m. The drip tape system was arranged with one film covering three pipes, resulting in a theoretical planting density of $25.5 \times 10^4$ plants/$hm^2$. Throughout the entire growth period of cotton, no base fertilizer was applied. Instead, top-dressing fertilizers were administered as follows: 705 kg/$hm^2$ of urea (N 46%), 345 kg/$hm^2$ of monoammonium phosphate ($P_2O_5$ 60%), and 360 kg/$hm^2$ of potassium sulfate ($K_2O$ 52%), all applied with water droplets. The total irrigation volume amounted to 5 475 $m^3/hm^2$. Drip irrigation was conducted 10 times at intervals of 8 – 10 d, with each application delivering between 450 and 600 $m^3/hm^2$. Other management practices were implemented in accordance with local field cultivation standards.

### 2.3 Measurement items and methods

**2.3.1** Determination of agronomic traits. Three points exhibiting uniform growth were randomly selected from each plot. From each point, 10 cotton plants (5 from the inner rows and 5 from the outer rows) were chosen for fixed-point and fix-time observations. Plant height, leaf age, and the number of fruit branches were measured at 0, 5, 10, 15, and 20 d following the application of the topping agent.

**2.3.2** Accumulation and distribution of dry matter. Following the application of the topping agent at intervals of 0, 5, 10, 15, and 20 d, three uniformly growing points were selected from each plot. At each point, two cotton plants exhibiting uniform growth (one from the inner row and one from the outer row) were collected and transported to the laboratory. The plants were then separated into roots, stems, leaves, buds, flowers, and bolls. Subsequently, the samples were subjected to blanching in an oven at 105 ℃ for 30 min, followed by drying at 80 ℃ until a constant weight was attained, after which they were weighed. The leaf area boll load (*LAB*)[22] and root-to-shoot ratio (*RSR*)[23] of the cotton plants were calculated using the following formulae.

$$LAB\ (g/m^2) = (BM/LA) \times 1\,000 \quad (1)$$

$$RSR\ (\%) = RW/AFW \times 100 \quad (2)$$

In Formula (1), *BM* denotes the dry weight of a single bell, while *LA* represents the leaf area. In formula (2), *RW* refers to the root fresh weight, and *AFW* indicates the above-ground fresh weight. Forty small circular leaf samples, each with a diameter of 1.5 cm, were obtained using a puncher, carefully avoiding the main veins. The leaves were blanched at 105 ℃ for 30 min and subsequently dried at 80 ℃ until a constant weight was achieved. The dry mass of the leaves was then measured, and the leaf mass area (*LMA*, g/$m^2$) was calculated using the following formula[24].

$$LMA\ (g/m^2) = LDM/LA \times 1\,000 \quad (3)$$

In Formula (3), *LDM* denotes the dry mass of the leaf, while *LA* signifies the leaf area.

**2.3.3** Leaf area index (LAI). The LAI of cotton was measured using the punching method[25], employing a puncher with a diameter of 1.5 cm.

**2.3.4** Yield and its components. One day prior to the cotton harvest, sample plots measuring 6.67 $m^2$ were selected from each plot, with three replicates per plot. The number of plants and bolls in these sample plots were recorded, allowing for the calculation of cotton planting density and the number of bolls per plant. At multiple plots, 10 cotton plants exhibiting uniform growth were selected, and all bolls were harvested. This procedure was repeated three times. The harvested bolls were subsequently weighed and ginned to investigate the weight of single bolls, lint percentage, and overall yield. Additionally, the harvest index (*HI*) was calculated according to the formula: $HI = SCY/BY$, where *SCY* represents the seed cotton yield and *BY* denotes the biological yield[26].

**2.3.5** Fiber quality. One day prior to the cotton harvest, a total of 60 bolls were collected from each treatment, comprising 20 bolls from the bottom, 20 from the middle, and 20 from the top of the plants. This sampling procedure was repeated three times. The samples were subsequently submitted to the Cotton Quality Supervision, Inspection, and Testing Center of the Ministry of Agriculture and Rural Affairs for analysis of fiber length, fiber length uniformity, micronaire (MIC), specific strength, elongation rate, maturity, and short fiber index.

**2.4 Data analysis** Microsoft Office Excel 2013 and SPSS 26.0 (Chicago, USA) were utilized for data reduction and analysis of variance. Duncan's multiple range test was employed for multiple comparisons. Origin 2021 (OriginLab, Northampton, USA) was used for graphical illustrations.

## 3 Results and analysis

**3.1 Effect on primary agronomic traits of cotton** As presented in Table 2, there was no significant interaction effect between the topping treatment and the year on the primary agronomic traits of cotton. In 2021, 20 d after topping, the plant height of treatments H1, H2, and CK2 was greater than that of CK1; additionally, the leaf age of H1 exceeded that of CK1. Furthermore, the number of fruit branches in the five UAV treatments and CK2 was significantly higher than that in CK1. In 2022, only the plant height, leaf age, and number of fruit branches in H1 were greater than those in CK1. These findings indicate that the topping treatment significantly influences plant height and leaf age, with the H1 treatment notably enhancing the number of fruit branches.

**Table 2 Primary agronomic traits of cotton under various topping treatments**

| Days after topping | Treatment | 2021 | | | 2022 | | |
|---|---|---|---|---|---|---|---|
| | | Plant height//cm | Leaf age | Number of fruit branches | Plant height//cm | Leaf age | Number of fruit branches |
| 0 | H1 | 79.29 a | 16.60 a | 10.22 a | 77.38 a | 16.58 a | 10.17 a |
| | H2 | 79.31 a | 16.67 a | 10.22 a | 77.83 a | 16.33 a | 10.25 a |
| | H3 | 78.94 a | 16.89 a | 10.67 a | 77.04 a | 16.08 a | 10.17 a |
| | H4 | 79.66 a | 16.78 a | 10.55 a | 77.76 a | 16.17 a | 10.25 a |
| | H5 | 78.90 a | 16.89 a | 10.33 a | 77.66 a | 16.42 a | 10.17 a |
| | CK1 | 79.57 a | 16.89 a | 10.56 a | 77.51 a | 16.75 a | 10.50 a |
| | CK2 | 79.23 a | 16.44 a | 10.56 a | 77.07 a | 16.67 a | 10.58 a |
| 5 | H1 | 83.86 a | 17.33 a | 11.11a | 83.51 a | 17.00 a | 11.08 a |
| | H2 | 83.20 a | 17.33 a | 10.89 a | 82.35 a | 16.67 a | 10.83 a |
| | H3 | 82.62 a | 16.89 a | 10.78 a | 79.72 a | 16.58 a | 10.58 a |
| | H4 | 82.29 a | 16.89 a | 10.55 a | 79.30 a | 16.48 a | 10.50 a |
| | H5 | 81.46 a | 17.22 a | 10.33 a | 79.43 a | 17.25 a | 10.58 a |
| | CK1 | 81.18 a | 16.89 a | 10.56 a | 78.94 a | 16.75 a | 10.50 a |
| | CK2 | 82.21 a | 17.22 a | 11.11 a | 80.19 a | 17.17 a | 11.00 a |
| 10 | H1 | 85.72 a | 18.00 a | 12.00 a | 84.43 a | 18.08 a | 11.50 a |
| | H2 | 85.55 a | 17.89 a | 11.89 a | 84.14 a | 17.58 a | 11.25 a |
| | H3 | 84.73 a | 17.55 a | 11.56 ab | 82.29 a | 17.33 a | 11.17 a |
| | H4 | 84.14 a | 17.33 a | 11.33 ab | 81.29 a | 17.25 a | 11.08 a |
| | H5 | 83.37 a | 17.56 a | 11.22 ab | 81.09 a | 17.25 a | 11.08 a |
| | CK1 | 83.17 a | 16.89 b | 10.56 b | 80.30 a | 16.75 b | 10.50 a |
| | CK2 | 84.06 a | 18.44 a | 11.89 a | 82.16 a | 18.42 a | 11.25 a |
| 15 | H1 | 87.99 a | 18.89 a | 12.11 a | 87.02 a | 18.67 a | 11.67 a |
| | H2 | 87.30 a | 18.45 ab | 12.00 a | 86.36 a | 18.42 ab | 11.33 ab |
| | H3 | 86.80 a | 18.22 ab | 11.89 a | 84.25 a | 18.17 ab | 11.17 ab |
| | H4 | 86.16 a | 18.00 ab | 12.56 a | 83.02 a | 18.08 ab | 11.08 ab |
| | H5 | 85.39 a | 17.78 ab | 11.44 a | 82.63 a | 17.92 ab | 11.08 ab |
| | CK1 | 83.85 a | 16.89 b | 10.56 b | 80.90 a | 16.75 b | 10.50 b |
| | CK2 | 85.87 a | 18.67 ab | 12.00 a | 83.63 a | 18.42 ab | 11.33 ab |
| 20 | H1 | 89.99 a | 18.89 a | 12.11 a | 88.53 a | 18.92 a | 11.67 a |
| | H2 | 87.96 ab | 18.67 ab | 12.00 a | 87.25 ab | 18.42 ab | 11.33 ab |
| | H3 | 87.39 abc | 18.33 ab | 11.89 a | 85.17 ab | 18.17 ab | 11.17 ab |
| | H4 | 86.61 abc | 18.11 ab | 11.56 a | 84.67 ab | 18.08 ab | 11.08 ab |
| | H5 | 85.92 bc | 17.78 ab | 11.44 a | 83.77 ab | 17.92 ab | 11.08 ab |
| | CK1 | 84.13 c | 16.89 b | 10.56 b | 81.42 b | 16.75 b | 10.50 b |
| | CK2 | 88.77 ab | 18.67 ab | 12.00 a | 85.58 ab | 18.42 ab | 11.33 ab |
| Source of variation | Year ($Y$) | * | * | * | | | |
| | Treatment ($T$) | ** | * | * | | | |
| | $Y \times T$ | NS | NS | NS | | | |

**NOTE** H1, H2, H3, H4, and H5 denote UAV spraying treatments with topping agent concentrations of 0.300, 0.525, 0.750, 0.975, and 1.200 L/hm$^2$, respectively. CK1 and CK2 represent manual and tractor spraying treatments, respectively, both applied at the same concentration of 0.750 L/hm$^2$ and serving as controls. Different lowercase letters in the same column denote significant differences among treatments at the same time point ($P < 0.05$). * and ** indicate significance at the 0.05 and 0.01 levels, respectively. NS denotes no significant effect.

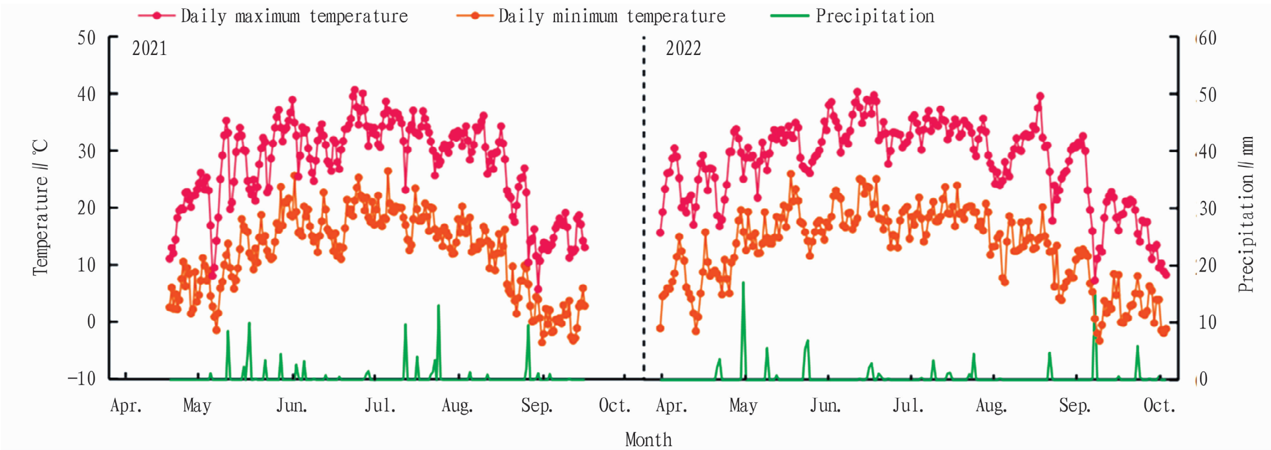
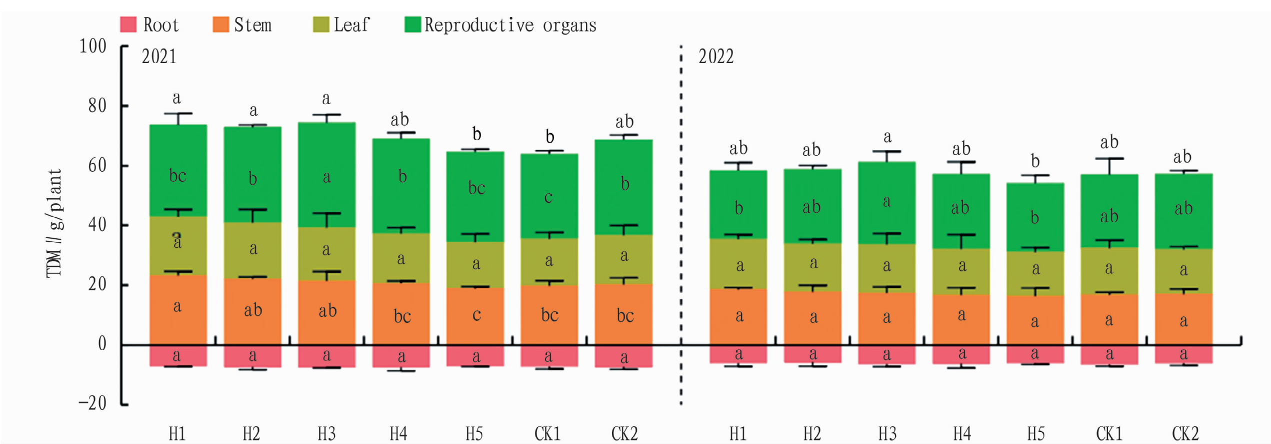



**Fig. 1 Variation in air temperature and precipitation during cotton growth season in Shihezi City in 2021 and 2022**

**3.2 Effect on total dry matter accumulation (TDM) per cotton plant** As illustrated in Fig. 2, in 2021, 20 d after topping, the TDM per plant in treatments H1, H2, and H3 did not differ significantly from that of CK2 but was significantly greater than that observed in CK1 and H5. In 2022, the TDM per plant was significantly higher only in the H3 treatment compared to H5, suggesting that the H3 treatment was more effective in enhancing TDM.

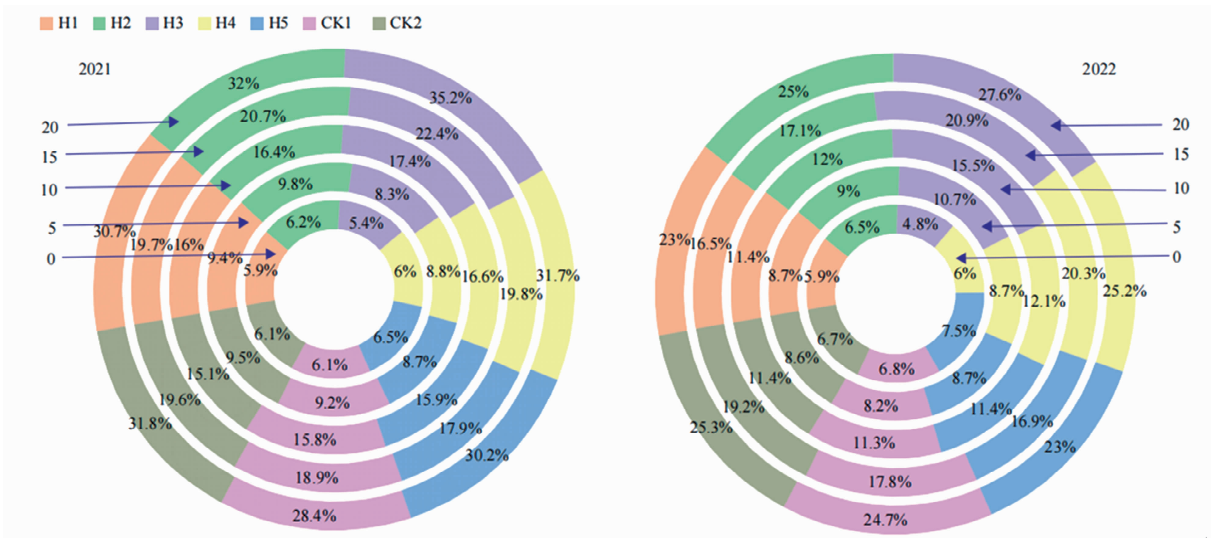



**NOTE** H1, H2, H3, H4, and H5 denote UAV spraying treatments with topping agent concentrations of 0.300, 0.525, 0.750, 0.975, and 1.200 L/hm$^2$, respectively. CK1 and CK2 represent manual and tractor spraying treatments, respectively, both applied at the same concentration of 0.750 L/hm$^2$ and serving as controls. Different lowercase letters positioned on or above the bars denote statistically significant differences among treatments in the same part ($P<0.05$).

**Fig. 2 TDM in various parts of cotton plants following 20 d of topping treatments**

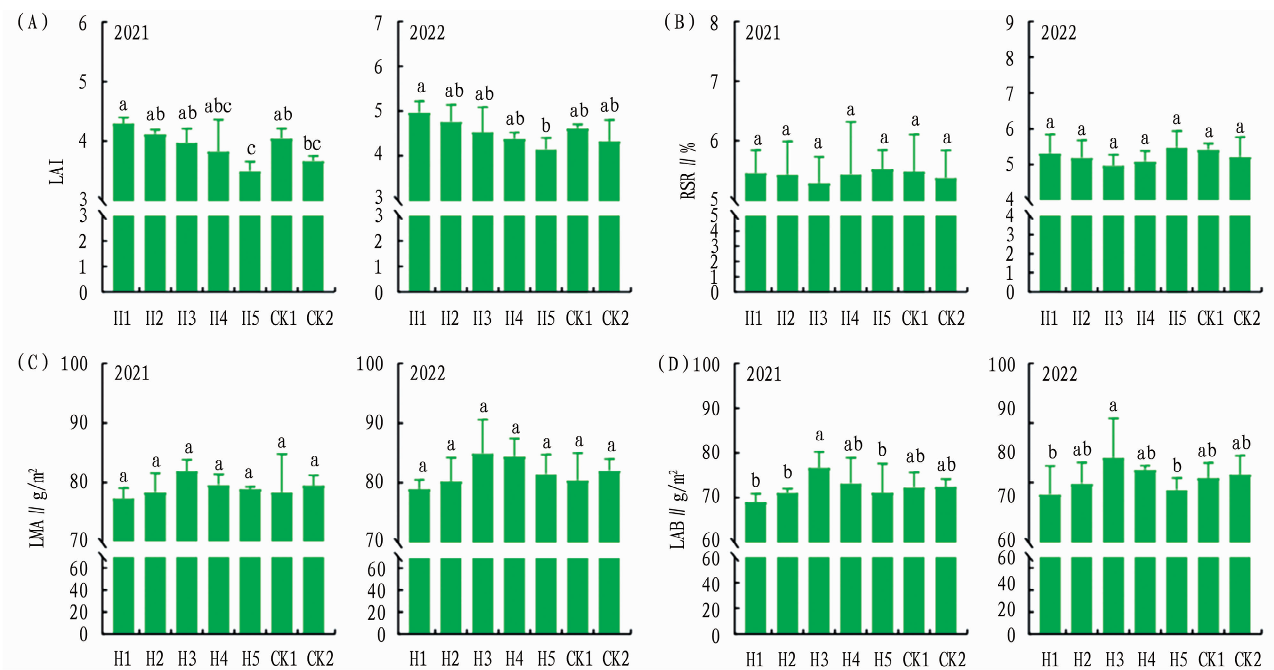
As illustrated in Fig. 3, the variation pattern of the reproductive organ dry matter ratio (RRDM) in all treated cotton samples remained consistent over the two-year period. In the UAV topping treatments, treatments H1 to H5 exhibited an initial increase followed by a decrease in RRDM as the concentration of the topping agent increased. Compared to CK1, CK2 demonstrated an increase ranging from 2.46% to 4.98%. Under the UAV-based topping agent treatment, the RRDM value of the H3 treatment surpassed those of other treatments starting 15 d after application. After 20 d, the RRDM for the H3 treatment reached 35.2% in 2021 and 27.6% in 2022, representing the highest values among all treatments. These values were 2.4% – 5.0% greater than those observed in other UAV treatments and 2.3% and 6.8% higher than CK1 and CK2, respectively. The results demonstrate that the topping treatment influences the RRDM of cotton. The concentration in the H3 treatment is relatively optimal for spraying, as it effectively regulates the growth of both reproductive and vegetative organs, thereby increasing RRDM. Furthermore, at the same dosage, UVA treatment yields superior effects compared to manual and tractor spraying.

As depicted in Fig. 4, 20 d after topping, treatment H5 exhibited the lowest LAI, followed by CK2. No significant differences were detected in the RSR and LMA among the treatments. However, variations in LAB were observed across treatments. Specifically, treatments H3, H4, CK1, and CK2 showed relatively high LAB values, with H3 being significantly greater than both H1 and H5. These results indicate that both the concentration of the topping agent and the application method affect LAB in cotton. Under an optimal concentration of the topping agent, application via UVA spraying produces the most favorable outcomes.




**NOTE** H1, H2, H3, H4, and H5 denote UAV spraying treatments with topping agent concentrations of 0.300, 0.525, 0.750, 0.975, and 1.200 L/hm$^2$, respectively. CK1 and CK2 represent manual and tractor spraying treatments, respectively, both applied at the same concentration of 0.750 L/hm$^2$ and serving as controls.

**Fig. 3 Proportion of cotton bolls in the total dry matter of cotton plants subjected to various topping treatments**




**NOTE** H1, H2, H3, H4, and H5 denote UAV spraying treatments with topping agent concentrations of 0.300, 0.525, 0.750, 0.975, and 1.200 L/hm$^2$, respectively. CK1 and CK2 represent manual and tractor spraying treatments, respectively, both applied at the same concentration of 0.750 L/hm$^2$ and serving as controls. Different lowercase letters above the bars denote statistically significant differences among treatments in the same year.

**Fig. 4 Leaf area index (LAI), root-to-shoot ratio (RSR), leaf mass area (LMA) and leaf area bell load (LAB) in cotton plants 20 d following topping treatments**

**3.3 Effect on cotton yield and its components** Further analysis of cotton yield and its components (Table 3) indicated that both the year and treatment significantly influenced the number of plants per unit area and the weight of single bolls ($P < 0.05$). However, these factors did not have a significant effect on the number of bolls per plant, seed cotton yield, lint cotton yield, lint percentage, or harvest index. Compared to CK1, treatments CK2, H1, H2, and H3 resulted in a reduction in the number of single bolls in 2021. In 2022, the lowest single boll weight was observed in treatments H1 and H5, whereas H3 exhibited the highest weight. No significant differences were detected among treatments regarding lint percentage, seed cotton yield, or lint cotton yield. Additionally, except for H1, the harvest index did not differ significantly across treatments. In summary, under the same concentration of the topping agent as the two controls, the UAV treatment demonstrated a tendency to increase the weight of single bolls.

**Table 3 Effects of different topping treatments on cotton yield and its components**

| Year | Treatment | Plant number $\times 10^4$/hm$^2$ | Boll number per plant | Single boll weight//g | Lint percentage//% | Seed cotton yield//kg/hm$^2$ | Lint cotton yield//kg/hm$^2$ | Harvest index |
|---|---|---|---|---|---|---|---|---|
| 2021 | H1 | 24.78 a | 6.04 b | 4.43 d | 39.95 a | 6 637.04 a | 2 654.71 a | 0.33 b |
| | H2 | 18.59 b | 6.08 b | 5.91 a | 39.38 a | 6 675.93 a | 2 618.36 a | 0.45 ab |
| | H3 | 18.98 b | 6.16 b | 6.11 a | 39.77 a | 7 142.87 a | 2 813.59 a | 0.46 ab |
| | H4 | 20.17 b | 6.39 a | 5.50 b | 39.92 a | 7 018.24 a | 2 830.50 a | 0.46 ab |
| | H5 | 24.33 a | 6.24 b | 4.59 d | 40.38 a | 6 965.33 a | 2 813.01 a | 0.40 ab |
| | CK1 | 18.59 b | 7.22 a | 5.01 c | 40.80 a | 6 717.60 a | 2 760.63 a | 0.49 a |
| | CK2 | 23.83 a | 6.29 b | 4.65 cd | 40.47 a | 6 973.81 a | 2 924.88 a | 0.39 ab |
| 2022 | H1 | 24.60 ab | 6.19 a | 4.44 b | 39.62 a | 6 758.76 a | 2 677.80 a | 0.43 a |
| | H2 | 25.40 a | 6.04 ab | 4.48 b | 39.69 a | 6 861.47 a | 2 723.19 a | 0.43 a |
| | H3 | 24.48 ab | 5.77 b | 5.04 a | 39.43 a | 7 120.99 a | 2 807.71 a | 0.43 a |
| | H4 | 24.59 ab | 5.96 ab | 4.80 ab | 41.77 a | 7 025.47 a | 2 934.59 a | 0.44 a |
| | H5 | 24.21 ab | 6.23 a | 4.62 ab | 43.04 a | 6 973.43 a | 3 001.59 a | 0.44 a |
| | CK1 | 25.20 ab | 6.18 a | 4.46 b | 43.73 a | 6 947.70 a | 3 038.08 a | 0.43 a |
| | CK2 | 23.66 b | 6.33 a | 4.67 ab | 41.47 a | 6 985.87 a | 2 897.28 a | 0.47 a |
| Source of variation | *Y* | * * | NS | * * | NS | NS | NS | NS |
| | *T* | * * | NS | * * | NS | NS | NS | NS |
| | *Y*×*T* | * * | NS | * * | NS | NS | NS | NS |

**NOTE** H1, H2, H3, H4, and H5 denote UAV spraying treatments with topping agent concentrations of 0.300, 0.525, 0.750, 0.975, and 1.200 L/hm$^2$, respectively. CK1 and CK2 represent manual and tractor spraying treatments, respectively, both applied at the same concentration of 0.750 L/hm$^2$ and serving as controls. Different lowercase letters in the same column denote significant differences among treatments in the same year ($P<0.05$). * and * * indicate significance at the 0.05 and 0.01 levels, respectively. NS denotes no significant effect. The same below.

**3.4 Effect on the quality of cotton fibers** As presented in Table 4, the year significantly influenced fiber length uniformity ($P<0.05$) and specific strength ($P<0.01$) of cotton. In contrast, the topping treatment significantly affected MIC ($P<0.05$), specific strength ($P<0.01$), and fiber maturity ($P<0.01$), but had no significant impact on fiber length, elongation rate, or short fiber index. Compared to CK1, CK2 increased fiber maturity in 2022 ($P<0.05$), whereas CK2 decreased specific strength in 2021. With the increase of spraying concentrations, the UAV topping treatment exhibited a pattern in which fiber length uniformity, MIC, specific strength, and fiber maturity initially increased and subsequently decreased; conversely, fiber elongation rate first decreased and then increased. In 2021, treatments H1 and H5 demonstrated significantly lower specific strength than H3 and H4. Notably, cotton fibers from H3 exhibited relatively high average length uniformity and specific strength. These findings suggest that the application of an appropriate concentration of topping agent via UAVs can significantly enhance cotton fiber quality.

**Table 4 Effects of topping treatments on cotton fiber quality**

| Year | Treatment | Fiber length//mm | Fiber length uniformity//% | MIC | Specific strength//cN/Tex | Fiber elongation rate//% | Fiber maturity | Short fiber index//% |
|---|---|---|---|---|---|---|---|---|
| 2021 | H1 | 31.66 a | 83.77 b | 3.15 a | 29.96 b | 6.93 a | 0.80 b | 6.93 a |
| | H2 | 31.84 a | 85.07 ab | 3.59 a | 35.00 a | 6.87 a | 0.82 ab | 6.60 a |
| | H3 | 31.19 a | 85.97 a | 3.82 a | 35.10 a | 6.97 a | 0.84 a | 6.63 a |
| | H4 | 31.68 a | 84.03 b | 3.68 a | 34.10 a | 7.03 a | 0.82 ab | 6.87 a |
| | H5 | 31.75 a | 84.43 ab | 3.19 a | 31.01 b | 6.92 a | 0.80 b | 6.66 a |
| | CK1 | 31.13 a | 84.57 ab | 3.35 a | 33.37 a | 6.90 a | 0.81 ab | 6.87 a |
| | CK2 | 31.20 a | 84.17 b | 3.85 a | 31.33 b | 6.90 a | 0.82 ab | 6.80 a |
| 2022 | H1 | 31.62 a | 83.73 ab | 3.12 b | 29.90 a | 6.94 a | 0.79 b | 6.90 a |
| | H2 | 31.08 a | 82.50 b | 3.37 ab | 29.73 a | 6.83 a | 0.80 b | 7.27 a |
| | H3 | 31.11 a | 84.20 a | 3.74 ab | 30.67 a | 6.90 a | 0.81 ab | 6.93 a |
| | H4 | 30.75 a | 84.00 ab | 3.80 ab | 29.90 a | 6.90 a | 0.82 ab | 7.13 a |
| | H5 | 31.52 a | 84.30 a | 3.31 ab | 30.97 a | 6.93 a | 0.80 b | 6.77 a |
| | CK1 | 31.42 a | 84.83 a | 3.52 ab | 31.40 a | 6.83 a | 0.81 b | 6.73 a |
| | CK2 | 31.24 a | 84.12 a | 3.84 a | 31.32 a | 6.90 a | 0.84 a | 6.85 a |
| Source of variation | *Y* | NS | * | NS | * * | NS | NS | NS |
| | *T* | NS | NS | * | * * | NS | * * | NS |
| | *Y*×*T* | NS | NS | NS | * * | NS | NS | NS |

## 4 Discussion

**4.1 Effect on primary agronomic traits of cotton** Cotton is a plant characterized by continuous growth. Consequently, the application of the topping technique is essential to regulate vegetative growth within the constrained growth period, thereby maximizing reproductive development and enhancing yield and efficiency. Wu Xueqin *et al.* [27] reported that plant height following chemical topping was significantly greater than that of the control group ($P < 0.05$), whereas no significant difference was observed in the number of fruit branches ($P > 0.05$). This study demonstrated that the plant height, number of fruit branches, and leaf age in treatments H1 to H5 were generally greater than those observed in CK1. The findings also indicated that the concentration of the UAV-applied topping agent significantly influenced the primary agronomic traits of cotton. Specifically, at the H1 concentration, the topping agent exhibited a relatively mild inhibitory effect on the vegetative growth of cotton plants, resulting in increased plant height and leaf area, accompanied by pronounced longitudinal growth. In contrast, concentrations at H3 and H4 were moderate, producing an inhibitory effect on excessive longitudinal growth of plant height and leaf age comparable to that of manual topping, with only slight increases observed. These results suggest that high-concentration applications of the topping agent via UAVs can effectively suppress the growth of key agronomic traits in cotton to a certain extent. Therefore, during the chemical topping process, the concentration of the UAV-based topping agent should be appropriately selected according to the growth vigor of the cotton's vegetative organs to achieve a balanced development of the primary agronomic traits.

**4.2 Effect on the accumulation and distribution of dry mass in cotton** Scientific chemical topping methods can effectively regulate the excessive growth of cotton plants, maintain a balance between nutritional and reproductive development, and enhance the accumulation of dry matter[28]. Hu Yukai *et al.* [29] demonstrated that with increasing concentrations of chemical topping agents, the total dry matter accumulation in cotton reproductive organs gradually declined. Moreover, both the total amount and the accumulation rate of dry matter decreased under treatments with high concentrations of chemical topping agents. Comparable findings were observed in the present study. LAB directly reflects the "source-reservoir" relationship and significantly influences the final cotton yield[30]. Chen Dehua *et al.* [31] demonstrated that an elevated LAB level can enhance photosynthesis in the vegetative organs, specifically cotton leaves, thereby increasing the translocation of assimilates from the "source" (cotton leaves) to the "reservoir" (cotton bolls). This process provides a material foundation for achieving high cotton yields. In this study, the differences in LAB values between H2 to H5 and CK1 were not statistically significant, suggesting that, at appropriate concentrations of chemical topping agents, vegetative growth was suppressed without substantially affecting the photosynthetic products necessary for cotton boll development. LMA in cotton is a critical parameter for regulating the photosynthetic activity of cotton leaves. Its magnitude not only indicates the accumulation of photosynthetic products per unit leaf area but also reflects the efficiency with which cotton leaves utilize light and thermal resources, as well as their adaptability to various environmental conditions within the cotton field[32-33]. This study demonstrated that as the concentration of the topping agent applied via UAVs increased, the LMA of treatments H1 to H5 initially increased and subsequently decreased, exhibiting a trend consistent with the yield of seed cotton. Previous research has indicated that LMA levels can directly influence dry matter accumulation and the net photosynthetic rate of leaves[34]. Consequently, the authors hypothesize that the observed overproduction in cotton fields subjected to chemical topping treatment may be associated with alterations in the LMA of cotton. Nevertheless, the precise cause remains unclear, and the underlying mechanisms require further investigation and validation.

**4.3 Effect on the LAI of cotton** The magnitude of LAI can indirectly influence photosynthetic productivity[35]. This study demonstrated that, under treatment with topping agents sprayed via UAVs, the LAI values from treatments H1 to H5 progressively decreased as the concentration of the topping agent increased. This trend may be attributed to the insufficient concentration of the topping agent in the H1 treatment, which was inadequate to effectively suppress the vegetative growth of cotton, thereby resulting in excessive vegetative development, an overabundance of cotton leaves, and consequently a relatively high LAI. Conversely, the concentrations of the topping agents in treatments H3 and H4 were moderate, promoting a balanced allocation between vegetative and reproductive growth. Additionally, under the CK topping treatment, vigorous vegetative growth was observed in CK1, accompanied by inhibited reproductive growth, leading to a higher LAI in CK1 compared to CK2. This observation corresponded with the lower yield recorded for CK1 relative to CK2.

**4.4 Effect on cotton yield and its components** Crop yield is primarily influenced by photosynthesis and the accumulation of dry matter[36]. Chemical topping can sustain high biomass production by modifying the canopy structure of cotton, which mitigates shading of the middle and lower leaves and improves the efficiency of light energy utilization, thereby contributing to stable and elevated yields[37-39]. This study demonstrated that the seed cotton yield and single boll weight of treatments H1 to H5, which were subjected to UAV-based chemical topping, exhibited a trend of initially increasing followed by decreasing as the concentration of the topping agent increased. A plausible explanation is that both low (H1) and high (H5) concentrations of the UAV-based topping agent may induce excessive growth or inhibit key agronomic traits of cotton. Such effects can disrupt the coordinated development between nutrient allocation and reproductive organs, as well as alter the proportion of dry matter in reproductive organs, ultimately impacting cotton yield. The agronomic traits of cotton treated with a high-concentration topping agent (H3) applied via UAVs were favorable, exhibiting a moderate LAI and coordinated growth of nutritional and reproductive organs, which contributed to increased seed cotton yield and single boll weight. Additionally, it was observed that higher concentrations of the topping agent applied via UAVs corresponded with an increased cotton lint percentage, leading to greater lint cotton yields in treatments H4 and H5. This effect may be attributed to the suboptimal development of cotton bolls under high-concentration topping agent application via UAVs. However, the precise underlying mechanisms require further investigation and validation.

**4.5 Effect on the quality of cotton fibers** This study demonstrated that various topping treatments exerted a relatively minor overall effect on the quality of cotton fibers. The fiber quality parameters of CK1 and CK2 were largely comparable. Under the treatments involving UAV spraying with a topping agent and CK topping, several fiber quality attributes including fiber length uniformity, MIC, specific strength, and maturity of samples from treatment H1 to H5 differed significantly from those of CK ($P < 0.05$). Notably, most quality indicators of cotton subjected to medium-concentration UAV-based topping agents (H3, H4) were superior, whereas those treated with low-concentration UAV-based topping agents (H1) exhibited relatively poorer quality. This outcome may be attributed to the insufficient concentration of the topping agent, which failed to effectively inhibit the unrestricted growth of cotton plants. Consequently, the vegetative organs exhibited vigorous growth, leading to increased consumption of assimilates and a reduced allocation of photosynthetic products to reproductive bolls. This imbalance adversely affected the internal development of certain cotton bolls.

## 5 Conclusions

The concentration of the topping agent is a critical factor influencing the chemical topping efficacy of UAVs. At optimal spraying concentrations, UAV application more effectively regulates vegetative growth, promotes the accumulation and distribution of dry matter in cotton bolls, increases the weight of single bolls, and enhances the MIC, specific strength, and elongation rate of cotton fibers compared to manual and mechanical spraying methods. Therefore, it is recommended to utilize UAVs for the application of chemical topping agents, with a suggested dosage range of 0.750 to 0.975 $L/hm^2$.

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