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Abstract: (1) Background: This study aims to analyze the defoliation and boll opening performance of 123 upland cotton germplasm resources after spraying defoliant, using multispectral data to select relevant vegetation indices and identify germplasm resources sensitive to defoliants, providing methods for cotton variety improvement and high-quality parental resources. (2) Methods: 123 historical upland cotton germplasm resources from Xinjiang were selected, and the defoliation and boll opening of cotton leaves were investigated at 0, 4, 8, 12, 16, and 20 days after defoliant application. Simultaneously, multispectral digital images were collected using drones to obtain 12 vegetation indices. Based on defoliation rate, the optimal vegetation index was selected, and defoliant-sensitive germplasm resources were identified. (3) Results: The most significant difference in defoliation rate of cotton germplasm resources occurred 16 days after application. Cluster analysis grouped the 123 breeding materials into three categories, with Class I showing the best defoliation effect. Among the 12 vegetation indices, the Plant Senescence Reflectance Index (PSRI) has the highest correlation coefficient with the defoliation rate; and when the PSRI value is higher, the defoliation effect of the material is better. Using drone multispectral technology, 15 defoliant-sensitive cotton materials were identified, with defoliation rates exceeding 85%, boll opening rates ranging from 76.67% to 98.04%, and PSRI values between 0.1607 and 0.1984.(4) Conclusions: The study found that vegetation indices with sensitive responses can serve as effective indicators for evaluating the sensitivity of cotton breeding materials to defoliants. The combined analysis of traditional survey methods and PSRI classification demonstrates that using drone multispectral technology as a substitute for manual methods in large-scale, rapid monitoring and selection of cotton breeding materials with excellent defoliation effects is feasible.

Keywords: cotton; UAV; multispectral; defoliation rate; vegetation index

1. Introduction

Cotton is an important global economic crop. Xinjiang is the largest cotton-producing area in China. In 2024, the national cotton output was 6.164 million tons. Among them, the cotton output in Xinjiang was 5.686 million tons, accounting for 92.2% of the national total cotton output [1].With rising costs and the development of agricultural mechanization, the area planted with machine-harvested cotton in Xinjiang has expanded, forming a new planting model that integrates equipment and technology. The mechanization rate of plowing, sowing, and harvesting has reached 97%, effectively ensuring a high cotton yield [2].During the cotton harvesting stage, there are issues such as increased labor costs, low harvesting efficiency, and extended harvesting time due to labor shortages [3]. With the development of mechanized cotton-picking technology, machine-picked cotton has greatly alleviated the labor pressure.The mature mechanized cotton-picking technology has promoted the rapid development of the whole-process mechanization and precision agriculture of cotton production in China. Popularizing machine-picked cotton has become the trend of the future development of the cotton industry, and chemical defoliation and ripening is one of the key technologies to ensure the smooth completion of machine-picked cotton[4].

In the early stages of cotton harvesting, defoliants are used to promote ripening and address the problem of late-maturing cotton with excessive green growth. Scientific and reasonable field management measures, along with the correct use of defoliants, are fundamental to achieving high yield and quality cotton [5]. During the mechanized cotton harvesting process, the application of defoliants for defoliation and ripening is an indispensable key step. The innovation of machine-harvested cotton germplasm resources and the breeding of new varieties are critical for the development of the industry. Defoliant sensitivity, as an important breeding index, has placed higher demands on breeding work. Currently, agricultural monitoring is gradually achieving an integrated approach that combines space, air, and ground, focusing on comprehensive monitoring of resources, environment, and crop growth status, aimed at providing strong support for the smart development of agriculture. Unmanned Aerial Vehicle (UAV) remote sensing, with its advantages of short cycle, simple operation, dynamic data acquisition and low cost [6], has become a new trend and research hotspot in agricultural monitoring. In recent years, remote sensing technology has been applied in the inversion research of physiological and biochemical parameters such as crop biomass [7], chlorophyll content [8], and water and nitrogen content [9].In terms of characterizing leaf changes, spectral reflectance and vegetation indices have their own characteristics. The spectral reflectance index based on the green and red wavelength regions can more precisely reveal the continuous changes in pigment composition and its quantity during the leaf senescence process[10].In the study of cotton defoliation and ripening, the evaluation of defoliation effect mainly relies on the traditional manual fixed-point investigation [11], which is time-consuming, inefficient and the results are accidental.In contrast, unmanned aerial vehicle remote sensing has the advantages of high resolution and real-time monitoring, and its application in agricultural monitoring is increasingly widespread [12], which provides new thinking and research directions for the monitoring of cotton defoliation rate and material screening.

At present, there are relatively few studies on using unmanned aerial vehicle (UAV) remote sensing technology to monitor the defoliation effect of cotton and screen materials. In this experiment, 123 upland cotton germplasm resources after spraying defoliant were screened for defoliation sensitivity, and combined with UAV multispectral data, the feasibility of UAV multispectral technology in monitoring and classifying and screening germplasm resources was evaluated. The study compared the two methods to select defoliation-sensitive cotton germplasm resources, filling the gap in the application of drone multispectral technology and vegetation indices for evaluating cotton defoliation sensitivity. This provides a theoretical basis and technical reference for screening cotton germplasm resources with sensitivity to defoliants suitable for mechanical harvesting.

2. Materials and Methods

2.1. Materials and Geographical Location

In this experiment, 123 cotton germplasm resources were selected, all of which were collected and provided by the Key Laboratory of Crop Breeding and Biotechnology of Xinjiang (Table 1). These materials include 48 from the Northwest Inland Cotton Area, 19 from the Yellow River Basin Cotton Area, 14 from the Yangtze River Basin Cotton Area, 8 from overseas, 20 from self-bred materials by Xinjiang regional seed companies, 11 from self-bred materials by the research team, and 3 other materials. The experiment was conducted in 2024 at the HuYangHe City Experimental Base of the Agricultural Science Research Institute of the Seventh Division of the Xinjiang Production and Construction Corps (Latitude 44°20'–47°04', Longitude 83°51'–85°51').

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Table 1. Names of 123 cotton breeding materials for the test.

No.	Material Name	No.	Material Name	No.	Material Name	No.	Material Name	No.	Material Name
YT 001	Liaomian 25	YT 028	Xinluzao 74	YT 053	Ari971	YT 078	Simian 2	YT 103	Source Cotton 8
YT 002	Liaomian 35	YT 029	Xinluzao 75	YT 054	BP52	YT 079	Simian 3	YT 104	J206-5
YT 003	Shengmian 6	YT 030	Xinluzao 76	YT 055	Si-1470	YT 080	Xinluzao 42	YT 105	Guanmian 678
YT 004	Xinmian 3	YT 031	Xinluzao 78	YT 056	J02-247	YT 081	Xinluzao 33	YT 106	Baijin 3045
YT 005	Xinshi K18	YT 032	Xinluzao 79	YT 057	Z37less	YT 082	Xinluzao 23	YT 107	Guanmian 614
YT 006	Xinshi K24	YT 033	Xinluzao 84	YT 058	Bamian 1	YT 083	Xinluzao 10	YT 108	Kang 41
YT 007	Chuangmian 512	YT 034	Xinluzhong 38	YT 059	Changkangmian	YT 084	Xinluzao 8	YT 109	Feng Haimian
YT 008	Longmian 10	YT 035	Xinluzhong 50	YT 060	Chuan 169-6	YT 085	Tu 83 - 161	YT 110	Fengze 7
YT 009	Jinken 1441	YT 036	Mutant1	YT 061	Jingzhou Degenerated Cotton	YT 086	Xinluzao 47	YT 111	Huimin 52
YT 010	Jinken 1565	YT 037	Mutant2	YT 062	Jing 55173	YT 087	Xinluzao 48	YT 112	Huimin 4
YT 011	Jinken 1643	YT 038	Mutant3	YT 063	Jinmian 36	YT 088	Xinluzao 49	YT 113	Guanmian V5
YT 012	Jiumian NE01	YT 039	Mutant4	YT 064	Jinzimian King	YT 089	Xinluzao 52	YT 114	Genesis 8
YT 013	W8225	YT 040	Mutant5	YT 065	Jiangsu Cotton 1	YT 090	Xinluzao 61	YT 115	Hexin Seed Industry 14
YT 014	Xinniumian 206	YT 041	Mutant6	YT 066	Jimian 8	YT 091	Xinluzhong 6	YT 116	Guanmian 648
YT 015	Zhongmiansuo 115	YT 042	Mutant7	YT 067	Jijiaohongye Mian	YT 092	Xinluzhong 14	YT 117	Genesis 5
YT 016	Xinluzao 27	YT 043	Mutant8	YT 068	Han 241	YT 093	Xinluzhong 36	YT 118	Zhongya Huijin 6
YT 017	Xinluzao 50	YT 044	Mutant9	YT 069	Ganmian 12	YT 094	Xinluzhong 41	YT 119	Fengdekang 4
YT 018	Xinluzao 51	YT 045	Mutant10	YT 070	Ferganskaya 175	YT 095	Xinluzhong 54	YT 120	Genesis 7
YT 019	Xinluzao 54	YT 046	R22—46	YT 071	Miaohua in Judian Township, Lijiang County, Yunnan	YT 096	Zhongmiansuo 17	YT 121	Genesis 8
YT 020	Xinluzao 55	YT 047	Xinluzao 11	YT 072	Daihongdai	YT 097	Zhongmiansuo 12	YT 122	Genesis 3

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YT 021	Xinluzao 57	YT 048	Zhongmian Institute 43	YT 073	Kuche 96515	YT 098	Zhong 203016	YT 123	Xiangsui Seed Industry 2
YT 022	Xinluzao 60	YT 049	70-1437	YT 074	Liaomian 9	YT 099	Yuan 247 - 31	YT 124	Jike Huayu 1
YT 024	Xinluzao 64	YT 050	73-184	YT 075	Zhongmiansuo 23	YT 100	Yumian 1	YT 125	Xinluzao 73
YT 025	Xinluzao 68	YT 051	AC321	YT 076	Shaan 416	YT 101	Xinluzhong 68		
YT 026	Xinluzao 69	YT 052	Ari3697	YT 077	Shen 547	YT 102	Xinluzhong 75		

2.2. Experimental Design and Treatments

The experiment was designed with two treatments: one with defoliant spraying (DT) and one without defoliant spraying (CK), each with two replicates. Protective rows were also set up. The plot length was 2 meters, with 30 membranes per zone, and each membrane covering three rows. Mechanical mulching with hole punching and manual seeding were applied. One membrane was planted with one cotton material. Drip irrigation was applied beneath the film, and other field management was the same as in the field. The defoliant was a 540 g/L thiabendazole · diuron suspension (containing 180 g/L diuron and 360 g/L thiabendazole) and a special additive (produced by Bayer CropScience, Germany).On September 5, the defoliant treatment was carried out. When the treatment group (DT) unmanned aerial vehicle sprayed the defoliant for the first time, 13 - 15 ml of 540 g/L thidiazuron + diuron suspension concentrate was used per mu, with an additive added at a ratio of 1:4. The dosage of ethephon was 70 - 100 ml per mu, and it was sprayed with 30 - 40 L of water. On September 13, the defoliant was sprayed for the second time, and 10 - 12 ml of 540 g/L thidiazuron + diuron suspension concentrate was used per mu, with an additive added at a ratio of 1:4. The control group (CK) did not spray the defoliant but sprayed the same amount of clear water.

2.3. Investigation Contents and Measurement Methods

2.3.1. Field Data Acquisition in Datian

Select 5 consecutive and uniformly growing cotton plants in each plot for tagging. According to "Descriptors and Data Standard for Cotton Germplasm Resources" edited by Du Xiongming[13] et al., investigate the agronomic traits. Before and after the spraying of defoliant, investigate the number of cotton plant leaves and boll opening numbers of the CK and DT groups at the fixed points and plants on the 0th day of spraying defoliant and 4 days, 8 days, 12 days, 16 days, and 20 days after spraying defoliant. When conducting the investigation of the ground defoliation rate, cotton leaves smaller than 2 cm^2 are not calculated. When conducting the last field data investigation, investigate the number of effective bolls.

2.3.2. UAV Multispectral Data Acquisition

The DJI Phantom 4 quadcopter multispectral unmanned aerial vehicle is used for the acquisition of digital images. Before and after spraying the defoliant, conduct a manual investigation, and simultaneously carry out image acquisition work. The shooting time period is between 12:30 and 14:00. The flight altitude of the unmanned aerial vehicle is set at 20 m. The DJI GO software is used to plan the fixed-point flight route for the target cotton field, and the flight speed is set at 1 m/s, with an image overlap rate of 80%. Before the flight, a multispectral sensor is used to shoot the radiation calibration plate to facilitate the subsequent radiation calibration of the images. Digital image data were collected at the same intervals as the manual investigation, with UAV data acquisition performed at 0d, 4d, 8d, 12d, 16d, and 20d after the first spraying of defoliant.

2.4. Data Processing

The data were statistically analyzed using EXCEL 2010, IBM SPSS Statistics 20 software, GraphPsd Prism software, and R 4.3.1 software; Pix4D software was used for UAV digital image stitching and preprocessing, and the ArcGIS software platform was used for extracting multispectral image data.

2.4.1. Calculation of Defoliation Rate and Boll Opening Rate

The defoliation rate (RD) was calculated using the following formula:

$$RD(\%) = (N_0 - N_1) / N_0 \times 100\%, \quad (1)$$

In the equation, N_0 is the number of leaves before the defoliant treatment, and N_1 is the number of leaves after the defoliant treatment.

The boll shedding rate (RB) was calculated using the formula:

$$RB(\%) = B_1 / B_0 \times 100\%, \quad (1)$$

In the equation, B_1 is the number of bolls that are opening, and B_0 is the number of effective bolls.

2.4.2. Unmanned Aerial Vehicle Data Processing

The processing of UAV high-definition digital images is carried out using Pix4D software. The UAV digital images containing location information (including latitude and longitude coordinates and altitude information) are imported into Pix4D to complete image stitching. The output result is to generate a multispectral image. Set to automatically perform image stitching. After the stitching is successful, the reflectance image of the test site is obtained through the index calculator, and 5 TIFF format files of different bands and a digital orthophoto image (Figure 1) are obtained. The ArcGIS software platform is used for analysis. The image is imported into ArcMAP 10.2 software to create a layer to extract the average reflectance of each cotton material research area as the reflectance of the sample in this band. Finally, the vegetation index is calculated (Figure 2).

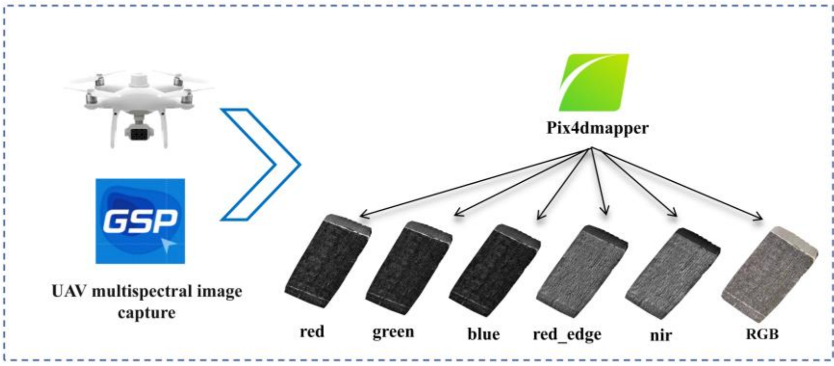

Figure 1. Flowchart of UAV Multispectral image acquisition.

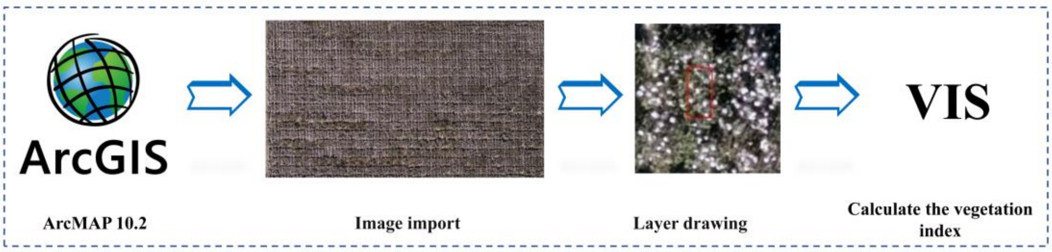

Figure 2. Flowchart for extracting UAV Multispectral image data.

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2.4.3. Vegetation Index

Vegetation index is a key parameter for evaluating the growth status of crops. Through in-depth discussion and analysis of the existing literature, this study screened out 12 vegetation indices closely related to the leaf abscission characteristics (Table 2). These vegetation indices cover multiple aspects from chlorophyll content to vegetation water status, and can reflect the growth status of cotton and its leaf abscission characteristics, thereby providing a scientific basis for the subsequent material screening and variety improvement.

Table 2. Summary of Vegetation Indices.

No.	Vegetation index	Abbreviation	Formula	Source
1	Normalized Difference Vegetation Index	NDVI	$(nir - red)/(nir - red)$	[14]
2	Normalized Green Difference Vegetation Index	GNDVI	$(nir - green)/nir + green$	[15]
3	Transformed Vegetation Index	TVI	$\sqrt{(NDVI + 0.5)}$	[14]
4	Ratio Vegetation Index	RVI	nir/red	[16]
5	Soil adjusted vegetation index	SAVI	$(nir-red)\times(1+L)/(nir+red+L)$ $(nir - red) \times (1 + L)/(nir + red + L)$	[17]
6	Enhanced Vegetation Index	EVI	$2.5 \times (nir - red)$	[18]
7	Excess Green Minus Red	EXGR	$2 \times green - 2.4 \times red$	[19]
8	Modified Chlorophyll Absorption Reflectance Index	MCARI	$[(red\_edge - red) - 0.2 \times (red\_edge - green)] \times (red\_edge/red)$	[20]
9	Modified second ratio index	MSRI	$(nir/red - 1)/\sqrt{nir/red + 1}$	[21]
10	Moisture Vegetation Index	MVI	$\sqrt{(nir - red)/(nir + red) + 0.5}$	[22]
11	Structure Independent Pigment Index	SIPI	$(nir - blue)/(nir + biue)$	[23]
12	Plant Senescence Reflectance Index	PSRI	$(red - blue)/nir$	[24]

3. Results and Analysis

3.1. Descriptive Statistical Analysis of Phenotypic Traits of 123 Upland Cotton Germplasm Resources

The agronomic traits of 123 upland cotton germplasm resources were statistically analyzed. The results showed that the plant height of the germplasm materials was 59.20 - 120.80 cm, the height of the first fruiting branch was 5.80 - 38.00 cm, the number of fruiting branches was 5.80 - 13.75, the number of effective fruiting branches was 3.60 - 12.00, and the number of bolls per plant was 4.80 - 14.20. The coefficient of variation of each trait exceeded 10% (Table 3). The coefficient of variation and extreme values of the agronomic traits of cotton germplasm materials indicated that there were significant differences in each trait among different materials, revealing the rich genetic variation in the 123 upland cotton germplasm resources, which provided a basis for the comparison and screening of planting materials.

Table 3. Descriptive statistics of agronomic traits of germplasm resources.

Traits	Average	Standard deviation	Min	Max	Coefficient of variation(%)
Plant height (cm)	87.30	9.64	59.20	120.80	11.04
Height of the first fruiting branch (cm)	20.41	4.70	5.80	38.00	23.00
Number of fruiting branches	10.17	1.19	5.80	13.75	11.66
Number of effective fruiting branches	6.58	1.15	3.60	12.00	17.47
Number of bolls per plant	8.19	1.65	4.80	14.20	20.16

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3.2. *The Effect of Defoliants on the Defoliation Rate and Boll Opening Rate of Cotton Germplasm Resources*

To study the defoliation effect of cotton after the application of defoliants, the defoliation rate after the application of defoliants was statistically analyzed (Figure 3-a), and a significant t-test was conducted on the defoliation rate at the corresponding time points (Figure 3-b). The results show that the defoliation rate continues to rise with the increase of days after application, indicating that the defoliant effectively promotes the defoliation process of cotton. Extreme value analysis shows that the defoliation effects of 123 germplasm resources are significantly different, and the defoliation rate change in the treatment group at the T_4 period (16 d) is the most significant, providing a basis for the in-depth analysis of subsequent defoliation-sensitive materials. In addition, the analysis of the change in the boll opening rate of cotton after spraying defoliants (Figure 3-c) and the significant t-test of the boll opening rate at different investigation times (Figure 3-d) found that the boll opening rate shows an increasing trend over time, and the boll opening rate in the experimental area where defoliants are sprayed increases more rapidly. Compared with the control CK group, the boll opening rate in the experimental area treated with defoliants increased significantly, indicating that spraying defoliants has a significant promoting effect on the boll opening of upland cotton germplasm resources.

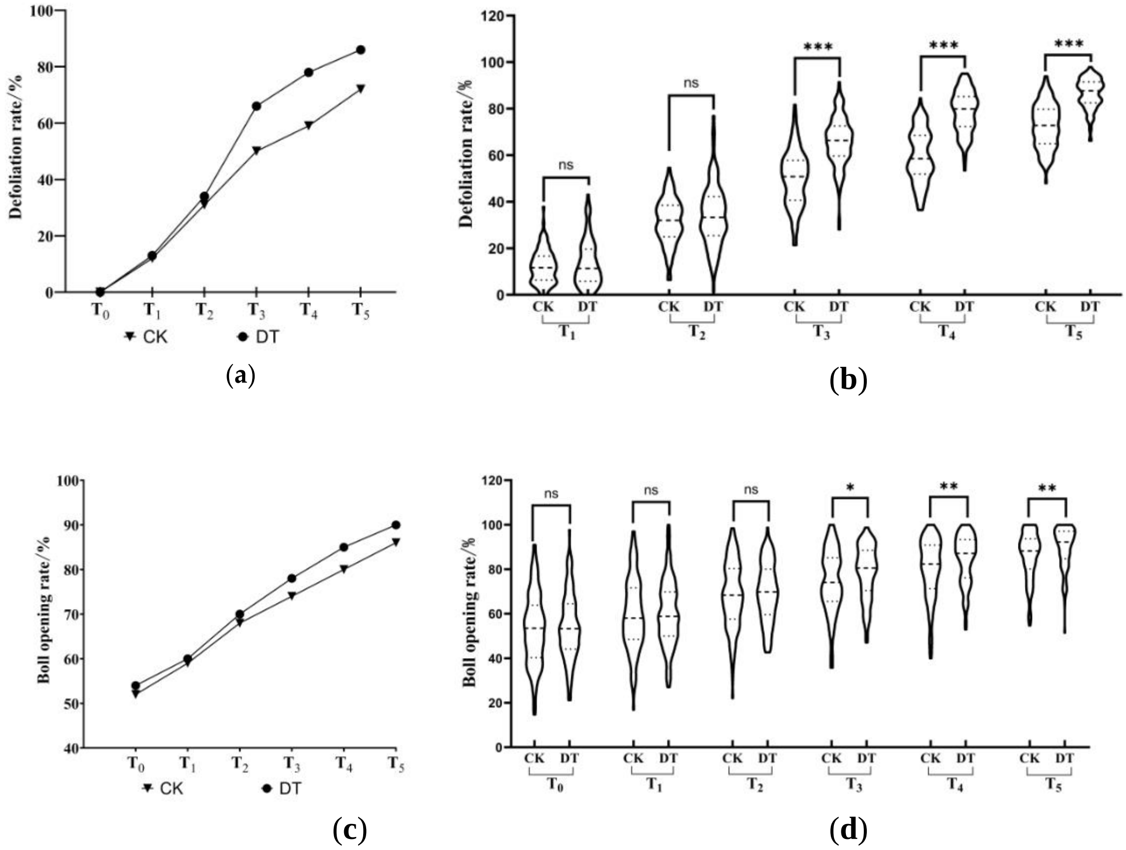

Figure 3. Changes in defoliation rate and boll opening rate of cotton materials. T_0, T_1, T_2, T_3, T_4, T_5 respectively indicate 0 days, 4 days, 8 days, 12 days, 16 days, and 20 days after spraying the defoliant; ns indicates not significant, * represents $P < 0.05$; ** represents $P < 0.01$; *** represents $P < 0.001$; The significance test method is the two-tailed t-test. (**a**): Changes in the average defoliation rate in different time periods; (**b**): Analysis of the difference in the defoliation rate in different time periods; (**c**): Changes in the average boll opening rate in different time periods; (**d**): Analysis of the difference in the boll opening rate in different time periods.

3.3. *Screening of Defoliation-Sensitive Varieties Based on Defoliation Rate*

The change trend of the defoliation rate of cotton materials after spraying defoliant shows (Figure 3) that a significant difference in the defoliation rate occurs in the T4 period, which is convenient for screening materials with good defoliation effects. Therefore, a cluster analysis of the defoliation rate in the T4 period (Figure 4) is conducted, and 123 germplasm resources are divided into three categories. Among them, category I belongs to the defoliation-sensitive germplasm resources, with 37 copies (Table 4), accounting for approximately 30%, and the defoliation rate is between 84.76% and 95.12%; category II belongs to the moderately defoliation-sensitive intermediate materials, with 53 copies, accounting for approximately 48%, and the defoliation rate is between 72.22% and 84.10%; category III belongs to the defoliation-insensitive germplasm resources, with 27 copies, accounting for approximately 22%, and the defoliation rate is between 53.50% and 71.34%.

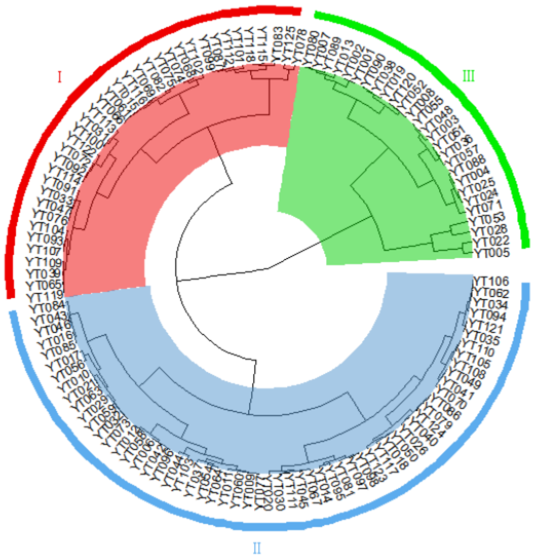

Figure 4. Clustering diagram of defoliation rate. Category I refers to defoliation-sensitive germplasm resources, Category II refers to moderately defoliation-sensitive germplasm resources, and Category III refers to defoliation-insensitive germplasm resources.

Table 4. Defoliant-sensitive germplasm resources.

No.	Material Name	Defoliation Rate（%）	Lint Percentage（%）	No.	Material Name	Defoliation Rate（%）	Lint Percentage（%）
YT078	Simian 2	95.12	82.72	YT119	Fengdekang 4	88.11	100.00
YT125	Xinluzao 73	94.23	98.04	YT065	Jiangsu Cotton 1	88.10	75.29
YT083	Xinluzao 10	93.43	93.24	YT039	Mutant 4	88.03	78.48
YT115	Hexin Seed Industry 14	93.08	93.42	YT109	Fenghaimian	87.91	86.25
YT118	Zhongya Huijin 6	93.05	97.89	YT091	Xinluzhong 6	87.57	89.81
YT112	Huimin 4	92.82	96.59	YT076	Shan 416	87.43	76.67
YT087	Xinluzao 48	92.67	81.91	YT047	Xinluzao 11	87.41	91.43
YT099	Yuan 247-31	92.57	94.20	YT033	Xinluzao 84	87.35	88.24
YT101	Xinluzhong 68	92.15	87.04	YT102	Xinluzhong 75	86.52	88.00
YT113	Guamian V5	90.97	88.06	YT074	Xinluzhong 75	85.95	97.08
YT031	Xinluzao 78	90.59	86.60	YT068	Han 241	85.81	86.32

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YT100	Yumian 1	90.48	84.88	YT082	Xinluzao 23	85.28	91.57
YT122	Genesis 3	89.73	90.65	YT075	Zhongmiansuo 23	85.16	80.85
YT114	Genesis 8	89.47	96.15	YT116	Guanmian 648	84.95	95.51
YT092	Xinluzhong 14	89.36	61.84	YT069	Ganmian 12	84.92	81.36
YT072	Daihongdai	89.17	77.17	YT066	Jimian 8	84.82	95.35
YT104	J206-5	88.56	91.86	YT061	Jingzhou Degenerated Cotton	84.80	90.00
YT093	Xinluzhong 36	88.32	88.31	YT015	Zhongmiansuo 115	84.76	89.29
YT107	Guomian 614	88.31	94.20				

3.4. Screening of Defoliation-Sensitive Materials of Cotton Based on Multispectral

3.4.1. Changes in Multispectral Reflectance Values

Through the stitching and processing of unmanned aerial vehicle (UAV) multispectral images, the values of five bands were extracted, and their variation is shown in Figure 5. It is found that the values of the red, green, and blue bands show an upward trend with the shedding of cotton leaves, while the values of the near-infrared (nir) and red-edge (red_edge) bands show a downward trend with the shedding of cotton leaves. Through the investigation of field experiment data, it is found that there is a significant difference in the defoliation situation at 16 days (T_4) after the application of the defoliant. Therefore, the multispectral values at 16 days (T_4) after the application of the pesticide are selected for the subsequent study.

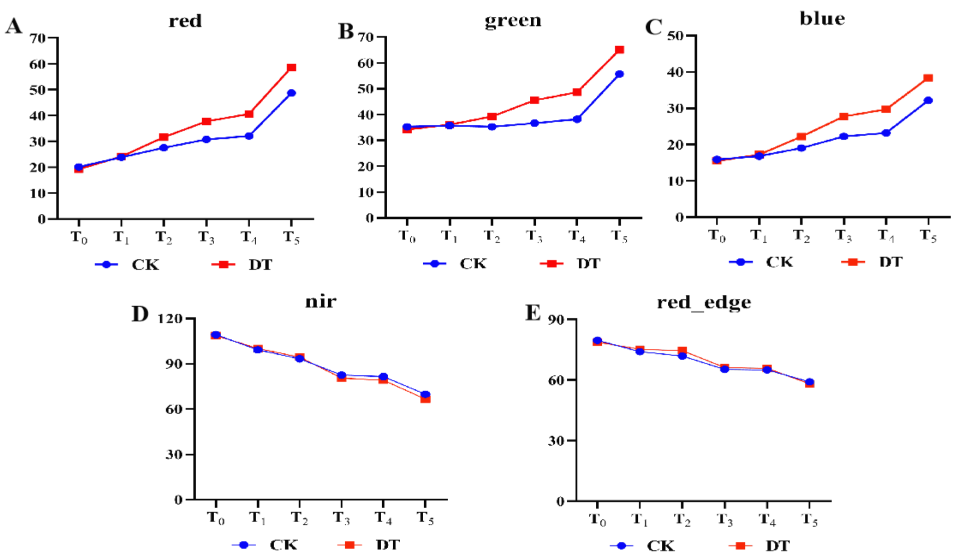

Figure 5. Changes in multispectral of defoliant treatment and control in different time periods.

3.4.2. Analysis of the Correlation between Multi-Spectral Bands and Vegetation Indexes and Defoliation Rate

A correlation analysis was conducted on the defoliation rate, multispectral bands, and vegetation indices on the 16th day after pesticide application (Figure 6). PSRI shows a significant

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positive correlation with the defoliation rate, and the highest correlation coefficient reaches 0.52; an increase in the PSRI value indicates an increase in canopy pressure, the beginning of vegetation senescence, and the maturity of plant fruits. This index is commonly used to monitor vegetation health, vegetation physiological stress, and crop yield analysis. SIPI has a significant positive correlation with the defoliation rate, reaching 0.51; SIPI can monitor vegetation health, detect plant physiological stress, and analyze crop yield. Among them, MSRI, RVI, NDVI, SAVI, TVI, MVI, MCARI, EVI, and GNDVI show a significant negative correlation with the defoliation rate, and the correlation coefficient reaches more than -0.40. These several vegetation indices have a significant correlation with the defoliation rate and can be used as relevant indicators to evaluate the defoliation of cotton.

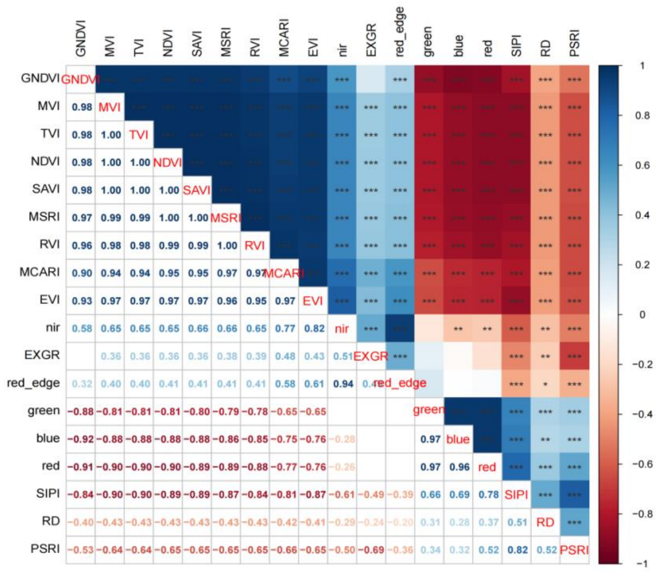

Figure 6. Correlation analysis between defoliation rate and multispectral bands/vegetation indices at 16 days after defoliant application. RD denotes defoliation rate; * indicates $P<0.05$; ** indicates $P<0.01$; *** indicates $P<0.001$.

3.4.3. PSRI Clustering Screening for Defoliation-Sensitive Upland Cotton Germplasm Resources

Relevance analysis found that the correlation between PSRI and defoliation rate is the highest. Therefore, 123 germplasm resources are divided into three categories using the PSRI value (Figure 7). Among them, 24 germplasm resources with excellent defoliation effect are classified as Type I (Table 5), accounting for approximately 19.5%, with PSRI values ranging from 0.1607 to 0.1984; 43 germplasm resources with a general defoliation effect are classified as Type II, accounting for approximately 35.0%, with PSRI values ranging from 0.1358 to 0.1588; 56 germplasm resources with a poor defoliation effect are classified as Type III, accounting for approximately 45.5%, with PSRI values ranging from 0.0763 to 0.1350.

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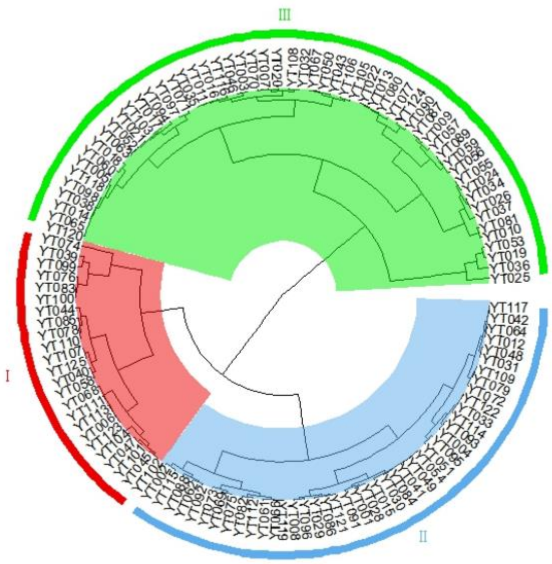

Figure 7. PSRI clustering diagram. Type I is the germplasm resource with excellent defoliation conditions, Type II is the germplasm resource with average defoliation conditions, and Type III is the germplasm resource with poor defoliation conditions.

Table 5. PSRI screening of germplasm resources sensitive to defoliants.

No.	Material Name	Defoliation Rate（%）	Lint Percentage（%）	PSRI	No.	Material Name	Defoliation Rate（%）	Lint Percentage（%）	PSRI
YT006	New Stone K24	75.34	84.54	0.1696	YT085	Tu 83 - 161	72.49	92.31	0.1640
YT039	Mutant4	88.03	78.48	0.1795	YT099	Yuan 247 - 31	92.57	94.20	0.1819
YT040	Mutant5	83.23	73.42	0.1628	YT100	Yumian 1	90.48	84.88	0.1852
YT044	Mutant9	78.34	70.83	0.1662	YT101	Xinluzhong 68	92.15	87.04	0.1723
YT045	Mutant10	79.51	58.46	0.1738	YT102	Xinluzhong 75	86.52	88.00	0.1733
YT047	Xinluzao 11	87.41	91.43	0.1720	YT104	J206-5	88.56	91.86	0.1756
YT058	Bamian 1	75.76	95.10	0.1632	YT107	Guanmian 614	88.31	94.20	0.1607
YT068	Han 241	85.81	86.32	0.1690	YT110	Fengze 7	82.46	96.15	0.1650
YT074	Liaomian 9	85.95	97.08	0.1984	YT111	Huimin 52	79.37	98.57	0.1700
YT076	Shan 416	87.43	76.67	0.1859	YT113	Guanmian V5	90.97	88.06	0.1694
YT078	Simian 2	95.12	82.72	0.1649	YT123	Xiangsui Seed Industry 2	83.62	95.89	0.1697
YT083	Xinluzao 10	93.43	93.24	0.1852	YT125	Xinluzao 73	94.23	98.04	0.1609

3.5. Defoliation Rate Classification and PSRI Classification Screening Materials Consistency Evaluation

During the field investigation of the cotton defoliation rate, due to human factors such as the movement and touching of the investigators, the leaves often fall unnaturally, thereby affecting the accuracy of the investigation data. To solve this problem, this study adopted two methods: artificial investigation and vegetation index PSRI classification to screen out cotton materials that are sensitive to defoliation reactions. Through comparative analysis, 15 defoliation-sensitive materials (Table 6) were screened out, accounting for 62.50% of the 24 materials in PSRI classification type I. Their defoliation rates range from 85.81% to 95.12%, their boll opening rates range from 76.67% to 98.04%, and their PSRI values range from 0.1607 to 0.1984. Among these 15 materials, 7 showed good

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defoliation effects (>85%) and high boll opening rates (>90%), specifically including Liaomian 9, Xinluzao 10, Yuan 247-31, J206-5, Xinluzao 11, Guomian 614, and Xinluzao 73, which can be used for the subsequent genetic improvement and breeding of cotton varieties.It is demonstrated that using unmanned aerial vehicle multispectral technology for large-scale screening of cotton breeding materials with excellent defoliation effects is feasible.

Table 6. The defoliation-sensitive materials jointly screened by the defoliation rate and PSRI.

No.	Material Name	Defoliation Rate（%）	Lint Percentage（%）	PSRI	No.	Material Name	Defoliation Rate（%）	Lint Percentage（%）	PSRI
YT074	Liaomian 9	85.95	97.08	0.1984	YT101	Xinluzhong 68	92.15	87.04	0.1723
YT076	Shaan 416	87.43	76.67	0.1859	YT047	Xinluzao 11	87.41	91.43	0.1720
YT083	Xinluzao 10	93.43	93.24	0.1852	YT113	Guanmian V5	90.97	88.06	0.1694
YT100	Yumian 1	90.48	84.88	0.1852	YT068	Han 241	85.81	86.32	0.1690
YT099	Yuan 247 - 31	92.57	94.20	0.1819	YT078	Simian 2	95.12	82.72	0.1649
YT039	Mutant4	88.03	78.48	0.1795	YT107	Guanmian 614	88.31	94.20	0.1607
YT104	J206-5	88.56	91.86	0.1756	YT125	Xinluzao 73	94.23	98.04	0.1609
YT102	Xinluzhong 75	86.52	88.00	0.1733					

4. Discussion

The main cotton-producing areas in Xinjiang generally adopt mechanized harvesting, but the residue of leaves will increase the impurity rate of seed cotton and reduce the fiber quality. Cotton varieties sensitive to defoliants have a good defoliation effect, with rapid leaf shedding, promoting boll opening, reducing mechanical harvesting impurities. The defoliation effect is crucial to the mechanical harvesting efficiency and cotton quality. Therefore, it is necessary to screen breeding materials sensitive to defoliants. In this study, different cotton germplasm resources were treated with defoliants and control experiments. The results showed that defoliants can effectively promote cotton leaf shedding and boll opening, significantly improving the defoliation and boll opening speed of cotton. This indicates that defoliants can effectively promote cotton leaf shedding and boll opening, which is consistent with the research results of Chen Beibei et al. [25] and Gao Lili et al. [26].

On the traditional investigation method, the evaluation of cotton defoliation effect relies on manual investigation, including counting the number of cotton plant leaves and bolls before and after pesticide application. This method is time-consuming and error-prone. Moreover, when evaluating large cotton fields, due to vision limitations and subjective factors, it is difficult to accurately assess. The combination of high spatial resolution remote sensing and intelligent agricultural machinery provides a strong technical support for the acquisition of precise cultivated land information [27]. The method of using unmanned aerial vehicle (UAV) remote sensing as a data acquisition platform for crop monitoring can combine other auxiliary information. Previous studies have used UAV-related technologies to obtain relevant information such as crop water content [28], crop nitrogen content [29], radiation use efficiency [30], crop height information, and crop chlorophyll content.

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Currently, the monitoring research related to green leaves based on UAV is mainly focused on aspects such as leaf area index, biomass, and vegetation coverage. This study integrates UAV multispectral technology and vegetation index to evaluate the defoliation sensitivity of cotton, effectively overcoming the shortcomings of the traditional screening method, and providing a reference for the application of UAV multispectral technology in the field of cotton defoliation effect evaluation research.

Vegetation index is calculated through the reflectance of specific bands. It helps to reduce the interference of external factors such as soil and climate, thereby improving the accuracy and sensitivity of the target parameters. The shedding of cotton leaves is usually closely related to indicators such as chlorophyll content, leaf water status, and leaf area index (LAI); during the process of leaf shedding, chlorophyll degrades, and the photosynthetic capacity weakens, resulting in a decrease in the reflectance of the near-infrared band and an increase in the reflectance of the red light band. The shedding of cotton leaves leads to a reduction in the number of green leaves in the canopy. Researchers such as Yi Qiuxiang [31] used remote sensing technology to monitor this change. For example, Li Yabing [32] diagnosed the premature senescence degree of cotton through different color spaces and eigenvalues, and achieved a good fitting effect. Yan Chunyu [33] and the team used a quad-rotor unmanned aerial vehicle to collect multispectral images of cotton before and after spraying, combined with the maximum entropy and vegetation index threshold method to extract cotton leaf information, used the support vector machine to classify the cotton after spraying, and constructed a model through the comparison of field data to verify the application potential of unmanned aerial vehicle remote sensing technology in monitoring cotton defoliation. Previous studies have also confirmed the accuracy of the vegetation index as an indicator for monitoring changes in the cotton canopy. This study found that there is a significant positive correlation between PSRI and SIPI in the vegetation index and the defoliation rate, with the correlation coefficients exceeding 0.50; while MSRI, RVI, NDVI, SAVI, TVI, MVI, MCARI, EVI, and GNDVI show a significant negative correlation with the defoliation rate; indicating that the vegetation index can indicate the situation of cotton defoliation by reflecting the changes in the vegetation canopy.

Looking forward to the future, with the continuous progress of unmanned aerial vehicle (UAV) remote sensing technology, data analysis methods, and artificial intelligence algorithms, the application of UAV technology in the field of precision agriculture is expected to provide more efficient solutions and promote agricultural production towards refined and intelligent management. Compared with the traditional manual observation and sampling methods, UAV remote sensing technology can achieve large-scale, real-time, and non-contact monitoring of the growth status of cotton plants. Traditional methods may be limited by the insufficient representativeness of samples and human errors, while UAV multispectral data provides a high spatial resolution and high-frequency data acquisition capability. Using this technology can effectively make up for the deficiencies of traditional investigation methods. UAV-related technologies provide a powerful technical support for screening sensitive materials suitable for cotton defoliation. To verify the stability and reliability of these screened sensitive materials, multi-point field experiments should be conducted in future studies to further evaluate their defoliation effect and boll opening rate performance. At the same time, continue to explore more vegetation indices and remote sensing technologies to improve a more accurate and efficient screening method for cotton defoliation-sensitive materials; this not only helps to promote the progress of cotton genetic improvement and breeding work, but also provides a strong technical support for the sustainable development of cotton production.

5. Conclusions

The test results show that the defoliant can significantly increase the defoliation rate and boll opening rate of cotton. After spraying the defoliant, there are significant differences in the leaf spectral characteristics of different cotton varieties. Through the comparison and screening of two methods, artificial investigation and the vegetation index PSRI, 15 cotton materials sensitive to

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defoliation were determined. The defoliation rate and boll opening rate are between 85.81% - 95.12% and 76.67% - 98.04% respectively, and the PSRI value is within the range of 0.1607 - 0.1984, which verifies the effectiveness of the unmanned aerial vehicle multispectral technology in screening cotton breeding materials sensitive to defoliation. The vegetation index related to the defoliation rate is screened out, which can be used as an effective indicator to evaluate the defoliation effect of cotton. Through the correlation analysis between the traditional investigation method and the classification of PSRI (Plant Senescence Reflectance Index), it is further indicated that it is feasible to use the unmanned aerial vehicle multispectral technology to replace manual rapid monitoring and screening of cotton breeding materials with excellent defoliation effect. Among these materials, the defoliation rate of 7 materials exceeds 85.00%, and the boll opening rate exceeds 90%, including Liaomian 9, Xinluzao 10, etc., showing good defoliation and boll opening characteristics, and are suitable as the preferred materials for germplasm resource improvement.

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