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Parameter Optimization and Impacts on Oilseed Rape (*Brassica napus*) Seeds Aerial Seeding Based on Unmanned Agricultural Aerial System

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Abstract: Aerial seeding based on the unmanned agricultural aerial system (UAAS) improves the seeding efficiency of oilseed rape (OSR) seeds, and solves the problem of OSR planting in mountainous areas where it is inconvenient to use ground seeding machines. Therefore, the UAAS has been applied in aerial seeding to a certain degree in China. The effective broadcast seeding width (EBSW), broadcast seeding density (BSD) and broadcast seeding uniformity (BSU) are the important indexes that affect the aerial seeding efficiency and quality of OSR seeds. In order to investigate the effects of flight speed (FS) and flight height (FH) on EBSW, BSD and BSU, and to achieve the optimized parameter combinations of UAAS T30 on aerial seeding application, three levels of FS (4.0 m/s, 5.0 m/s and 6.0 m/s) and three levels of FH (2.0 m, 3.0 m and 4.0 m) experiments were carried out in the field with 6.0 kg seeds per ha. The results demonstrated that the EBSW was not constant as the FS and FH changed. In general, the EBSW showed a change trend of first increasing and then decreasing as the FH increased under the same FS, and showed a trend of decreasing as FS increased under the same FH. The EBSWs were over 3.0 m in the nine treatments, in which the maximum was 5.44 m (T1, 4.0 m/s, 2.0 m) while the minimum was 3.2 m (T9, 6.0 m/s, 4.0 m). The BSD showed a negative change correlation as the FS changed under the same FH, and the BSD decreased as the FH increased under 4.0 m/s FS, while it first increased and then decreased under the FS of 5.0 m/s and 6.0 m/s. The maximum BSD value was 140.12 seeds/m^2 (T1, 4.0 m/s, 2.0 m), while the minimum was 40.17 seeds/m^2 (T9, 6.0 m/s, 4.0 m). There was no obvious change in the trend of the BSU evaluated by the coefficients of variation (*CV*): the minimum *CV* was 13.01% (T6, 6.0 m/s, 3.0 m) and the maximum was 64.48% (T3, 6.0 m/s, 2.0 m). The statistical analyses showed that the FH had significant impacts on the EBSWs (0.01 < p-value < 0.05), the FS and the interaction between FH and FS both had extremely significant impacts on EBSWs (p-value < 0.01). The FH had extremely significant impacts on BSD (p-value < 0.01), the FS had no impacts on BSD (p-value > 0.05), and the interaction between FH and FS had significant impacts on BSD (0.01 < p-value < 0.05). There were no significant differences in the broadcast sowing uniformity (BSU) among the treatments. Taking the EBSW, BSD and BSU into consideration, the parameter combination of T5 (T9, 5.0 m/s, 3.0 m) was selected for aerial seeding. The OSR seed germination rate was over 36 plants/m^2 (33 days) on average, which satisfied the requirements of OSR planting agronomy. This study provided some technical support for UAAS application in aerial seeding.

Keywords: UAAS; aerial seeding; oilseed rape; parameter optimization

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1. Introduction

Oilseed rape (OSR, *Brassica napus*) is the third most important oil crop in the world and the most important oil crop in China [1]. It provides high-quality oil for humans, feed pellets for livestock species and resources for certain industrial products [2–5], as well as being planted as a tourist attraction [6]. Therefore, it is planted widely in China, and planting areas are expanding rapidly, including plains, hills and river valleys. Overall, the current mechanization level of OSR seeding in China is still not high, and remains far below grain crops such as wheat and rice [6]. Traditional OSR planting methods include direct seeding and transplanting on the ground by manual labor or ground machines [7]. Aerial seeding based on the unmanned agricultural aerial system (UAAS), which does not touch with the ground at a certain height, is a method to improve the mechanized seeding operation [8], which is also a beneficial method supplementary to ground planting, providing a solution for OSR planting in regions where ground machines cannot enter.

As a new type of agricultural machinery, the UAAS has rapidly developed in China [9–12]. With different airborne mission equipment, the UAAS can execute aerial spraying [13,14], remote sensing [15–17], supplementary pollination [18,19], and aerial seeding [8,20]. With the advancement of technologies such as real-time kinematic high-precision positioning, automatic navigation, flight control and active obstacle avoidance, the safety and accuracy of UAAS have been significantly improved [21,22]. Some researchers have carried out relevant studies on aerial seeding based on UAAS. Chen et al. [23] designed a UAAS with a centrifugal swing tube for seeding; here, the seeds entered into the swing tube would be thrown out from the end of the tube by centrifugal force. Bao [24] developed an aerial seeding system by changing the size of the outlet to adjust the sowing rate. Huang et al. [25] designed an aerial strip seeding device based on an electric-driven centrifugal system, and realized the aerial rapeseed sowing in strips through a special seed-guiding device. Zhang et al. [26] developed a rapeseed sowing device matched with the UAAS P20 (Guang Zhou XAG Co., Ltd, China) including a seed box, a seed filling funnel and the corresponding control system. They determined the parameter combinations under which the rotor airflow affected the seeds slightly, and the optimized parameters were chosen for the field tests. The test results showed that the effective broadcast seeding width of the rapeseed was 2.0 m–2.5 m, and the coefficient of variation of the seed distribution uniformity was 32.05–34.78%, which could meet the requirements of rapeseed agronomic planting. Song et al. [20] introduced the air-assisted method to the aerial seeding, and designed a seeding device using the high-speed airflow to blow seeds out for rice.

Meanwhile, driven by the large-scale application requirements, some technology companies in China such as Yuren UAV (Zhuhai) Co., Ltd. [27], Shenzhen D.J. Co., Ltd. [28], Guangzhou XAG Co., Ltd. [29], Wuxi Hanhe Aviation Co., Ltd. [30], TopXGun robotics (Nanjing) Co., Ltd. [31] and Quanfeng Aviation Co., Ltd. [32] have developed aerial seeding devices and installed them onto their crop protection UASs (CPUAS) to expand the functions, making the UAAS more versatile and acceptable.

The OSR seeds are small in size with a diameter of about 1.9 mm, and are light in weight with a thousand-rapeseed weight of 5 g [8,19]. Therefore, compared with rice and wheat, the aerial seeding of OSR has higher requirements to achieve good aerial seeding quality. In this study, in order to investigate the UAAS operation parameter effects of EBSW, BSD and BSU, and to achieve the optimized parameter combinations on aerial seeding, experiments with different parameter combinations were designed and carried out with UAAS T30. The study conclusions would provide some technical support for UAAS application in aerial seeding.

2. Materials and Methods

2.1. Experimental Site, UAAS

The experiment site was located in Qiqiao Town (31.373390° N, 118.992170° E) in Nanjing City, Jiangsu Province, China. The trials were conducted on 18 October 2021, the mean wind speed was 0.75 m/s and the mean temperature was 27.68 °C. The six-rotor electric UAAS T30 (Shenzhen D.J. Co., Ltd., Shenzhen, China) was selected for the aerial seeding tests, as shown in Figure 1. It is a fully autonomous UAAS with real-time kinematic Global Positioning System (RTK-GPS), and the flight routes, FH, FS and aerial seeding rate can be planned and set by the mobile app. The main technical parameters of T30 are shown in Table 1.

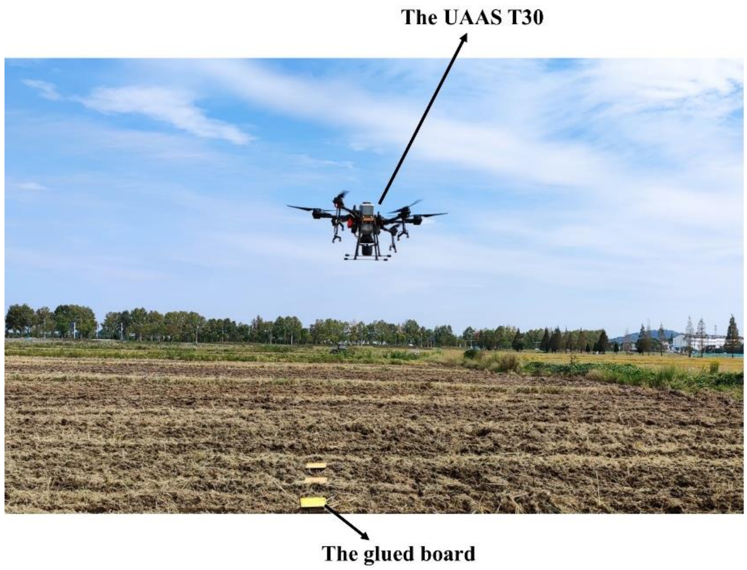

Figure 1. UAAS T30 flying in the test field.

Table 1. Main technical parameters of T30.

Items	Parameters
UAAS size	2858 mm × 2685 mm × 790 mm
Rotor diameter × Pitch	38 × 20 inch
Battery capacity	29000 mAh–51.8 V
FS	1.0 –7.0 m/s
FH	0.5–6.0 m
Seed box volume	40 L
Aerial seeding rate	16.67 kg/min (MAX)

2.2. Experimental Materials

A glued board with an effective sticky area of 27 cm × 18 cm and a glue layer about 3.0 mm thick was used for sampling the OSR seeds on the field. The *Brassica napus*-type hybrid OSR seeds Ning R101 (Anhui Hongqi Seed Science & Technology Ltd., Hefei, China) were the seeds used for the experiments. The field was well tilled before the tests to ensure the accuracy of the results.

2.3. Experimental Treatments

2.3.1. Experiment Design

According to the practical application, the FH was set to three levels: 2.0 m, 3.0 m and 4.0 m. The FS was set to three levels: 4.0 m/s, 5.0 m/s and 6.0 m/s. To ensure the seed germination rate, the aerial seeding dosage of the OSR seeds per ha was set as 6 kg/ha; this seeding dosage is greater than the dosage used in traditional planting. A total of nine treatments are shown in Table 2 along with the treatment parameters. The T30 flew from the acceleration area to the flight stopping area along the center line of the sampling area in autonomous mode [14].

Table 2. Aerial seeding experiment treatment designs.

Treatments	FH/m	FS (m/s)	Aerial Seeding Dosage (kg/ha)
T1	2.0	4.0	6.0
T2	2.0	5.0	6.0
T3	2.0	6.0	6.0
T4	3.0	4.0	6.0
T5	3.0	5.0	6.0
T6	3.0	6.0	6.0
T7	4.0	4.0	6.0
T8	4.0	5.0	6.0
T9	4.0	6.0	6.0

2.3.2. Sampling Arrangements

Figure 2 shows the field experimental sampling layout. The whole experimental area was divided into the flight acceleration area, aerial seeding sampling area and flight stopping area. The flight acceleration area and the flight stopping area were both 50 m long in order to ensure that the UAAS could accelerate to a predetermined speed and stop in timely manner. The glued boards were arranged along the vertical direction of the UAAS flight route symmetrically in three repeating lines with a 5.0 m interval. A total of fifteen sampling points were arranged symmetrically on both sides of the flight route of each repetition line. The sampling points, labeled S1 to S15, were distributed from left to right on both sides of the flight route. Based on the experiences, the EBSW would be between 3.0 m to 6.0 m, so the interval distances among S1 to S5 were set as 0.25 m for the accurate boundary of the EBSW. The interval distances among S5 to S7 were set as 0.5 m, and the distance between S7 and S8 was set as 1.0 m, to improve the test efficiency. The right-side sampling points were arranged in the same way as the left-side ones. The sampling points were labeled S1 to S15 from left to right (top view), as shown in Figure 2.

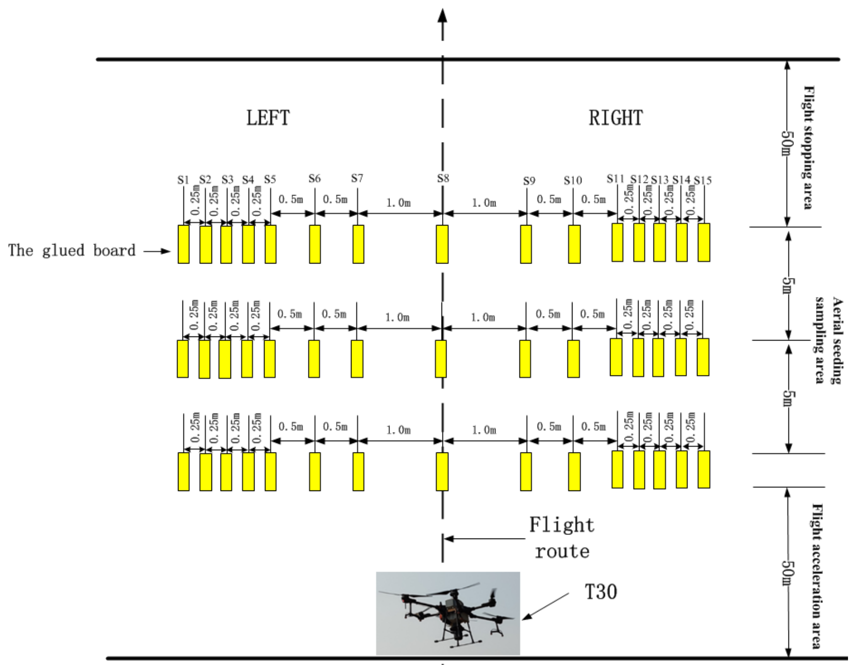

Figure 2. Field experimental sampling layout (top view).

2.4. Evaluation Methods of EBSW, BSD and BSU

EBSW: The quantity of OSR seeds collected on each glued board of the sampling points was counted. According to the standard Technical Specification of Quality Evaluation Aerial Broadcast Seeder by Remote Control (NY/T 3881-2021) [32], if the OSR seed quantity could satisfy the OSR planting agronomic needs, that is, about three to five seeds on the glued board, the sampling point would be considered as being within the effective seeding range. The effective seeding boundary of each repetition line was calculated statistically, and the average value was considered as the EBSW.

BSD: The aerial seeding dosage is 6.0 kg/ha. The OSR seed quantity per square meter should theoretically be about 120 (n_1) with 5 g thousand-rapeseed weight, according to Formula (1), and 5.83 (n_2) OSR seeds should be collected on each glued board assuming that the OSR seeds were spread evenly on the field surface, according to Formula (2).

$$n_1 = \frac{m_1}{C \cdot m_2} \times 1000 \tag{1}$$

$$n_2 = n_1 \times S_{gb} \tag{2}$$

where n_1 is the theoretical seed quantity per square meter, seeds/m^2; m_1 is the seeding dosage per ha, 6 kg; m_2 is weight of one OSR seed, 5×10^{-3} kg; C is the conversion factor from one ha to one square meter, C =10,000; n_2 is the theoretical seed quantity on each glued board, seeds/m^2; and S_{gb} is the glued board area, 0.0486 m^2.

The actual quantity of rapeseeds collected on each glued board in each treatment was counted, and the average value of the rapeseed quantities on each sampling point of three repetitions in each treatment was taken as the BSD of the treatment.

BSU: BSU was evaluated by the coefficients of variation (CV). The CV calculation formula is as follows:

$$CV = \frac{S}{\overline{\overline{X}}} \times 100\% \tag{3}$$

$$S = \sqrt{\sum_{i=1}^{n} \frac{\left(X_i - \overline{X}\right)^2}{n-1}} \tag{4}$$

where S represents the standard deviation of the OSR seed quantity on the glued boards of each repetition; X_i is the OSR seed quantity of each glued board in the repetition; and $\overline{X}$ is the average of X_i.

2.5. Evaluation Method of OSR Seed Germination Rate

According to Formula (1), there should be about 120 seeds per square meter in the field, and the germination rate should be the ratio of the quantity of plants germinated per unit area to the quantity of seeds per unit area. However, this method of evaluating the germination rate is only suitable for a greenhouse or laboratory with controlled environmental conditions. In the actual field, the germination rate is affected by the individual seed quality, soil moisture, temperature and other factors. Therefore, in this study, the authors adopt the method commonly used in agronomy, that is, in the area where the OSR plants grow uniformly, select three repeated areas of one square meter, and count the OSR plant, and the calculated average quantity of OSR plants is used as the germination rate.

3. Results

3.1. Test Data Statistics

The OSR seeds were collected from the glued boards during the experiments shown in Figure 3. According to the methods described in Section 2.4, the maximum broadcast seeding width, average broadcast seeding width, BSD and BSU (coefficient of variation (CV), %) of each treatment were calculated and are shown in Table 3. The average broadcast seeding width of each treatment was as the EBSW.

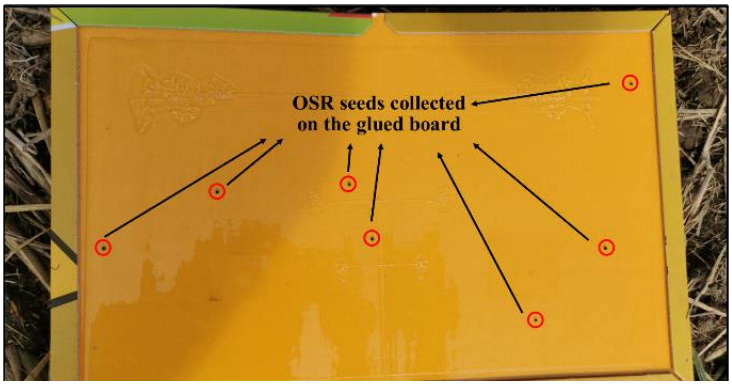

Figure 3. OSR seeds collected on the glued board.

Table 3. Test result data of broadcast seeding widths, BSD and BSU.

Treatments	Maximum Broadcast Seeding Width/m	EBSW/m	BSD (Seeds/m^2)	CV/%
T1	5.35	5.30	140.12	29.12
T2	4.98	4.25	87.92	45.36
T3	3.85	3.85	59.28	64.48
T4	5.44	5.05	106.93	32.22
T5	5.25	5.25	107.03	48.22
T6	5.20	5.20	79.22	13.01
T7	5.37	5.30	101.90	25.09
T8	4.80	4.80	52.42	29.91
T9	3.50	3.20	40.17	55.92

Note: the average broadcast seeding width is taken as the EBSW.

From Table 3, it can be seen that the EBSWs were not constant, ranging from 3.20 m (T7, T9) to 5.35 m (T1), which did not reach 6.0 m as expected. The maximum broadcast seeding width of each treatment was more than 3.5 m, of which the maximum was 5.44 m (T4). In terms of the BSU, the maximum *CV* exceeded 60%, while the minimum was 13.01% (T6), which meant the BSU fluctuated greatly within the EBSWs. In terms of the BSD, the maximum reached 140.12 seeds/m^2 (T1) and the minimum was only 40.17 seeds/m^2 (T9).

3.2. EBSW Analysis

3.2.1. EBSW Changes

Figures 4 and 5 show the EBSW changes under different FHs and FSs. The EBSW decreased as the FS increased under the FHs of 2.0 m and 4.0 m, while the EBSW increased first and then decreased as the FS increased under the FH of 3.0 m. The EBSW increased first and then decreased as the FH increased under the FSs of 5.0 m/s and 6.0 m/s, while the EBSW decreased first and then increased as the FH increased under the FS of 4.0 m/s. Obviously, there was no monotonic change trend on the EBSW as the FH and FS changed. Therefore, it could be considered that the FH and the FS affected the ESWs.

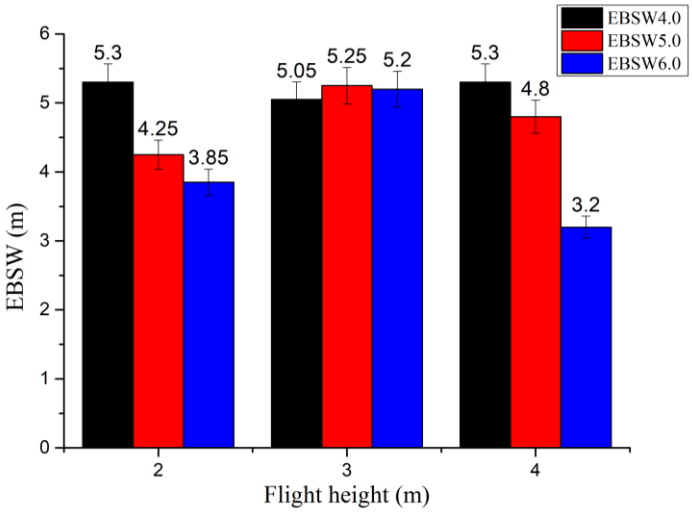

Figure 4. EBSW changes under different heights. Note: EBSW4.0, EBSW5.0 and EBSW6.0 represent the EBSW when the FSs were 4.0 m/s, 5.0 m/s and 6.0 m/s, respectively.

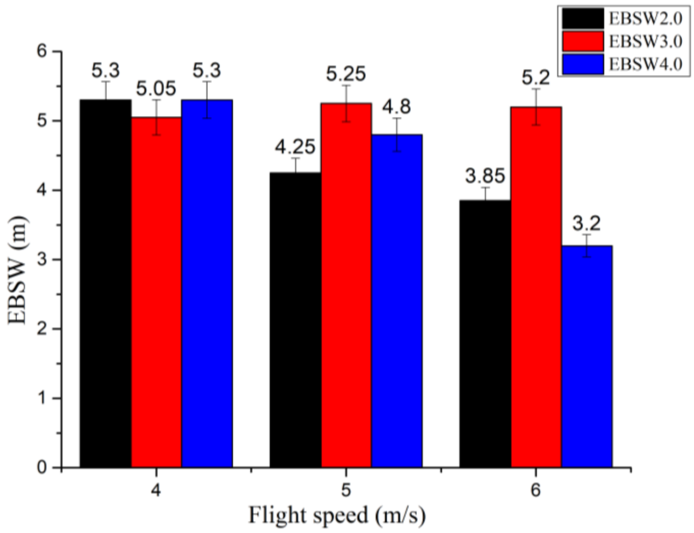

Figure 5. EBSW changes under different speeds. Note: EBSW2.0, EBSW3.0 and EBSW4.0 represent the ESW when the FHs were 2.0 m, 3.0 m and 4.0m, respectively.

3.2.2. Effects of FS and FH on EBSWs

A two-way analysis of variance (ANOVA) was conducted to verify the significance effect of FS and FH on ESBW at the significance level of $p = 0.05$, and the results are shown in Table 4. The FH had significant impacts on ESBW ($0.01 < p\text{-value} = 0.023 < 0.05$), the FS and the interaction between FH and FS had extremely significant impacts on EBSWS (p-value < 0.01).

Table 4. Two-way analysis of variance for ESBWs.

Source of Variance	df	F	*p*-Value	Significance
FH	2	19.43	0.023	*
FS	2	43.78	1.22×10^{-7}	**
FS×FH	4	12.15	5.84×10^{-5}	**

Note: *p*-value means the significance level of the factor affecting the result, 0.01 < *p*-value < 0.05 (* represents factors that have a significant impact on the test result), *p*-value < 0.01 (** represents factors that have an extremely significant impact on the test result).

3.3. BSD Analysis

3.3.1. BSD Changes

Figures 6 and 7 show the BSD changes under different FHs and FSs. It can be seen that the BSD showed the same change trends that first increased and then decreased under the FHs of 3.0 m and 4.0 m, while the BSD showed a monotonous decreasing trend as the FS increased under the FH of 2.0 m, which was 140.12 seeds/m^2 to 101.9 seeds/m^2. Under the FS, the BSD showed a decreasing trend, as the figures show. The maximum BSD value was more than 100 seeds/m^2 to the minimum BSD, so this indicated that the quantity of the OSR seeds per square meter varied greatly with different aerial seed parameter combinations.

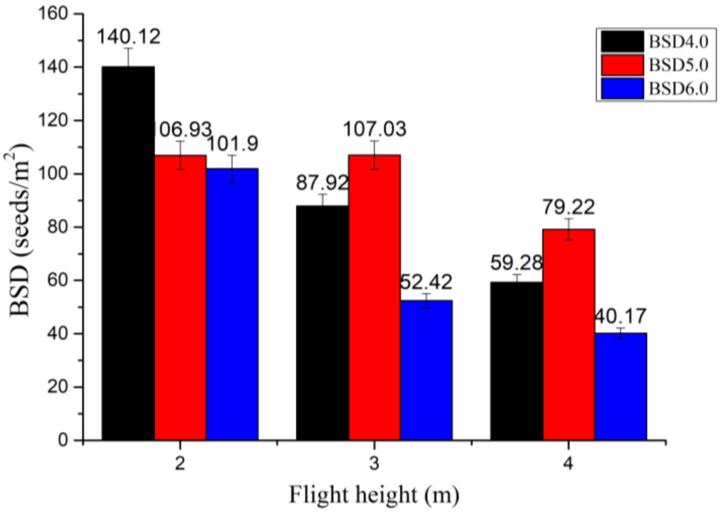

Figure 6. BSD changes under different heights. Note: BSD4.0, BSD5.0 and BSD6.0 represent the BSD when the FHs were 4.0 m/s, 5.0 m/s and 6.0 m/s, respectively.

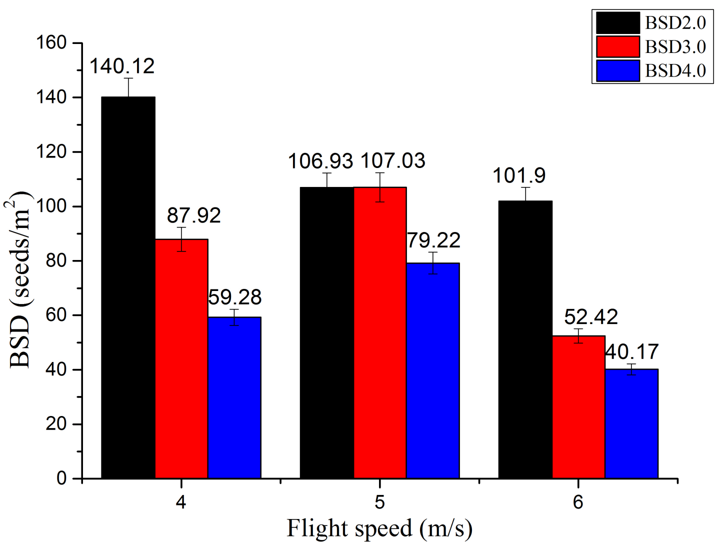

Figure 7. BSD changes under different speeds. Note: BSD2.0, BSD3.0 and BSD4.0 represent the BSD when the FSs were 2.0 m, 3.0 m and 4.0m, respectively.

3.3.2. Effects of FS and FH on BSDs

The two-way ANOVA results (Table 5) showed that the FH had extremely significant impacts on BSD (p-value < 0.01), the FS had no impacts on BSD (p-value > 0.05) and the interaction between FH and FS had significant impacts on EBSWs (p-value < 0.01).

Table 5. Two-way analysis of variance for BSDs.

Source of Variance	df	F	*p*-Value	Significance
FH	2	122.21	3.36×10^{-11}	**
FS	2	290.22	0.67	NS
FS × FH	4	33.78	0.036	*

Note: *p*-value means the significance level of the factor affecting the result, 0.01 < *p*-value < 0.05 (* represents factors that have a significant impact on the test result), *p*-value < 0.01 (** represents factors that have an extremely significant impact on the test result), *p*-value > 0.05 (NS represents factors with no significant impact on test result).

3.4. BSU Analyses

The broadcast seeding uniformity (BSU) was an important indicator to evaluate the aerial seeding quality. The average CV of the aerial seeding was 38.15% for the nine treatments, which satisfied the standard requirements [33]. The maximum was 64.48% (T3) and the minimum was 13.01% (T6). Figure 8 shows the broadcast seeding uniformity of each treatment by CVs. The two-way ANOVA results indicated that the FH, FS and the interaction between FH and FS all had no significant impacts on the BSU.

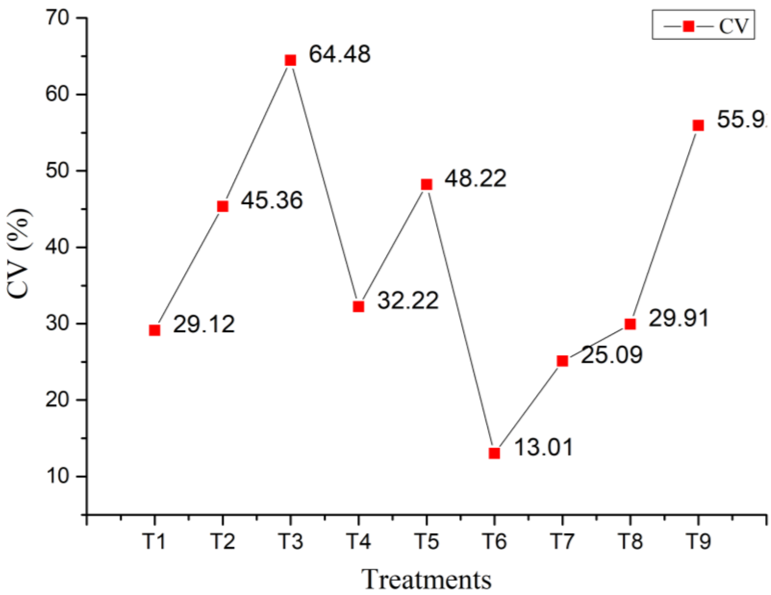

Figure 8. Broadcast seeding uniformity of each treatment by CVs.

3.5. OSR Seed Germination Rate

Taking the operation efficiency (EBSW), BSD and BSU into consideration comprehensively, the parameter combination of T5 (FH > 3.0 m, FS = 5.0 m/s, EBSW = 5.25 m, BSD = 107.03 seeds/m^2, CV = 48.22%) was chosen to carry out the OSR seed aerial seeding experiment. The OSR seed germination rate was over 36 plants/m^2 (33 days) on average, which satisfied the requirements of OSR planting agronomy. Figure 9 showed the OSR plants growth in the test field 33 days after aerial seeding.

Figure 9. OSR plants in the field 33 days after aerial seeding experiment.

4. Conclusions and Discussion

In this study, the authors designed nine sets of parameter combinations to test the performances of UAAS T30 on the aerial seeding of OSR seeds. The results verified that the application of UAAS for the aerial seeding of OSR seeds was feasible, thus providing a new method for OSR planting. The maximum EBSW was 5.30 m when the FH was 2.0 m and the FS was 4.0 m/s, while the minimum was only 3.20 m when the FH was 4.0 m and the FS was 6.0 m/s. The difference between the maximum and minimum EBSW reached 2.10 m. The maximum BSD was 140.12 seeds/m^2 and the minimum was only 40.17 seeds/m^2; the BSD value difference was close to 100 seeds/m^2. The above results demonstrated that aerial seeding based on UAAS would be very different under different operation parameters. If the appropriate operation parameters were not selected, then the aerial seeding quality would not satisfy the agronomic requirements of OSR planting. Taking the FH and FS as the independent variables, the FH and FS had effects on the EBSW and BSD to different degrees, according to the ANOVA test results. The FH had significant impacts on the EBSWs, the FS and the interaction between FH and FS both had extremely significant impacts on the EBSWs. The FH had extremely significant impacts on the BSD, and the interaction between FH and FS had significant impacts on the BSD. Therefore, lowering the FH and FS of the UAAS could obtain larger EBSW and BSD generally, but meanwhile, there is a contradiction with the aerial seeding efficiency. The BSU was also an important index that reflected the aerial seeding quality because a good BSU guarantees the uniform growth of OSR plants in the field. From the statistical data presented in Table 3, the best BSU was under T6 where the CV was only 13.01%. Although the CV was 13.01%, the BSD was not large, and did not reach 80 seeds/m^2. The T5 parameter combination with a larger EBSW, a larger BSD and a better BSU was chosen to conduct the aerial seeding of the OSR seeds, and the field survey found that over 36 plants/m^2 germinated 33 days after the aerial seeding.

Through the above research, it is concluded that the EBSW, BSD and BSU are not constant with the changes of operation parameters for UAAS T30. Thus, for different types of UAAS used in aerial seeding, it is necessary to undergo rigorous tests to ensure that optimized operation parameters could be obtained for the aerial seeding quality, so that they can be truly applicative in agricultural production.

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