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Droplet Deposition and Efficacy of Real-Time Variable-Rate Application of Herbicides at Reduced Dose in Winter Wheat Fields

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Abstract: Using an intelligent plant protection machine for spraying herbicides at a real-time variable rate plays a key role in improving the utilization efficiency of herbicides and reducing environmental pollution. Spraying volume (SV) and nozzle size (NS) are key factors influencing droplet deposition and herbicide efficacy and safety. A three-way split-split plot design experiment was conducted in the winter wheat field, with SV 180 L·ha^{-1} and 150 L·ha^{-1} in the main plot, a turbo air induction nozzle TTI11004 and TTI11003 in the subplot, herbicide flucarbazone-Na 70% WG mixed with florasulam 50 g·L^{-1} SC as the recommended dose, and a 20% reduced dose in the sub-subplot. Droplet deposition and weed control efficacy treated by these three factors and their combination were evaluated. Results indicated that there was a significant influence of SV on droplet coverage and density, but no significant influence of NS and its interaction with SV. A droplet coverage and density of treatment at 180 L·ha^{-1} were both significantly higher than at 150 L·ha^{-1}. The influence of SV and its interaction with NS on weed control efficacy were significant. The efficacy of treatment TTI11004 at SV 180 L·ha^{-1} was the highest but decreased when NS was switched to TTI11003 and the SV was decreased to 150 L·ha^{-1}. There was no significant effect of all the treatments on winter wheat yield and its components, but the yield loss could be reduced by 2.36% when the herbicide input was reduced by 20%. We can conclude that herbicide input can be reduced by at least 20% using the intelligent machine while equipped with the right NS at the right SV, which would increase the safety of winter wheat production.

Keywords: real-time variable-rate spraying; spraying volume; nozzle; droplet deposition; herbicide efficacy

Citation: Zhang, J.; Xu, X.; Lv, Y.; Zhao, X.; Song, J.; Yu, P.; Wang, X.; Zhao, E. Droplet Deposition and Efficacy of Real-Time Variable-Rate Application of Herbicides at Reduced Dose in Winter Wheat Fields. *Agronomy* **2024**, *14*, 211. https://doi.org/10.3390/agronomy14010211

Academic Editor: Andrea Peruzzi

Received: 15 December 2023
Revised: 14 January 2024
Accepted: 16 January 2024
Published: 18 January 2024

1. Introduction

Weeds in wheat fields severely restrict the improvement of wheat yield and quality by competing for water, nutrients, and space with wheat plants, as well as spreading diseases and pests [1,2]. The use of reduced- and no-tillage techniques, along with the spread of weed seeds by agricultural machinery during field plowing, wheat seed sowing, and harvesting, has aggravated weed infestation in wheat fields. Furthermore, the prevailing belief that weed control is of lesser importance compared to pest and disease control has exacerbated the harmful effects of weeds, posing a severe threat to wheat production safety in China. Applying herbicides for weed control is a necessary operation in wheat cultivation management due to its advantages of simplicity, high efficiency, and low cost.

Pesticides, as well as the machinery and technology used for their application, are three crucial factors that significantly impact the efficiency of pesticide utilization and the efficacy of pest control [3]. Pesticide production and input to the cropland of China has reached an internationally leading position [4]. However, pest control has not reached a correspondingly high level but produced the most extensive land area subjected to high pesticide pollution risk [5]. The main reason for this contradiction is the inadequate level of pesticide application machinery and technology. Significant progress has been made in improving the utilization efficiency of pesticides in cereal crops in China, accompanied by the fast development of the modern plant protection machine, but this still falls behind the level of developed countries [6]. In recent years, there has been significant development in the combination of precision variable-rate (PVA) application machinery and efficient application technology, aiming to enhance the accuracy and efficiency of pesticide application [7–9]. This is accomplished using the PVA technology spraying pesticide in real-time as decided by the central brain of the machine, the operation speed, spraying pressure, and flow velocity-based complex processing system [10,11]. This plays an important role in reducing off-rate errors and off-target environmental pollution [12]. In the field of weed management, although precision chemical weed management strategies have been developing rapidly worldwide in recent years [13,14], ground-based plant protection machine spraying still remains the primary herbicide application strategy in China. Furthermore, there is currently a lack of research in this field in China, especially regarding the appropriate spraying components and equipment parameters that can maximize the working efficiency of sprayers and improve the utilization efficiency of herbicides.

Nozzle size or type [15–17] and spraying volume [18–21] have a key impact on the atomization performance of herbicide solution, determining the number of droplets deposited on target weeds and ultimately influencing the efficacy of herbicides [22–24]. In particular, the nozzle is an important component in intelligent spraying machines that ensure spraying quality. It has significant effects on droplet size, coverage on target plant surfaces, and droplet deposition characteristics [25–28]. Selecting the appropriate nozzle type or size and determining the right spraying volume are effective strategies to increase the number of droplets arriving at the target weeds and decrease the waste of herbicide solutions, thereby improving the utilization efficiency of herbicides and reducing pollution in agricultural environments.

A preliminary study has shown that the real-time variable-rate boom sprayer can achieve comparable or even superior weed control efficacy compared to traditional sprayers when applying herbicide at reduced doses in wheat fields [8]. In this study, we investigate the effects of nozzle size (NS) and spray volumes (SV) on droplet deposition and the efficacy of herbicide at reduced doses using this sprayer, aiming to provide technical references for the further application of this precision real-time variable-rate boom sprayer in reducing herbicide application and improving its utilization efficiency in wheat fields in China.

2. Materials and Methods

2.1. Experimental Site

The experimental site was located in Nanyaojiazhuang Village, Zhaozhou Town, Zhao County, Hebei Province, China (37°43.4192′ N, 114°48.0982′ E). The wheat variety used was "Shiluan 02-1", and the wheat plants were at regrowth stage in the spring during the herbicide application. The dominant weeds in the field were *Descurainia sophia* and *Bromus japonicus*. *Descurainia sophia* was at the rosette stage (8–12 leaves) with an estimated density of 32–96 plants/m^2, while *Bromus japonicus* was at the 3–5 tillering stage with an estimated density of 26–48 plants/m^2. With the exception of herbicide application using the real-time variable-rate sprayer one time the whole growth season, all other cultivation management practices (such as fertilizer, fungicide, and insecticide application as well as irrigation) were kept constant for all experimental plots of the winter wheat field.

2.2. Experimental Materials

The real-time variable-rate sprayer used in the experiment was an autonomous intelligent crop protection machinery with precision spraying control system developed by the National Engineering Research Center for Information Technology in Agricultural (NERCITA, Beijing, China). Its main components are depicted in Figure 1 (a prototype). This system consisted of a differential global positioning system, a monitoring panel, specifically developed software, and a device for applying the herbicide solution rates proportionally related to the machine's traveling speed, spraying pressure, and nozzle flow rate. As illustrated in the research of Li et al., regarding the operating principle [29], monitored by this system, the target spraying volume could be accurately achieved. The spraying boom had a width of 13 m and was equipped with 26 nozzles, spaced at 0.5 m intervals. The uneven terrain of the winter wheat field, along with sporadic obstacles, posed a challenge for the machine moving constantly. Hence, the speed was 5–8 km/h while spraying, and when the spraying volume was appropriately adjusted, the spraying pressure and nozzle flow rate were adjusted accordingly in real time. The theoretical settings among the spraying volume, the travel speed, the flow rate, and so on were presented in Table 1. Nozzles equipped were turbo air-induction type, with sizes of TTI11004 (red color) and TTI11003 (blue color), both produced by TeeJet® Technologies, and their detailed features are shown in "broadcast_nozzles.pdf" (teejet.com.cn, accessed on 14 December 2023). The sprayer was calibrated before herbicide application to ensure compliance with the precision spraying requirements. During the process of herbicide application, the wind speed was less than 2 m·s^{-1}, and the relative humidity was approximately 30%.

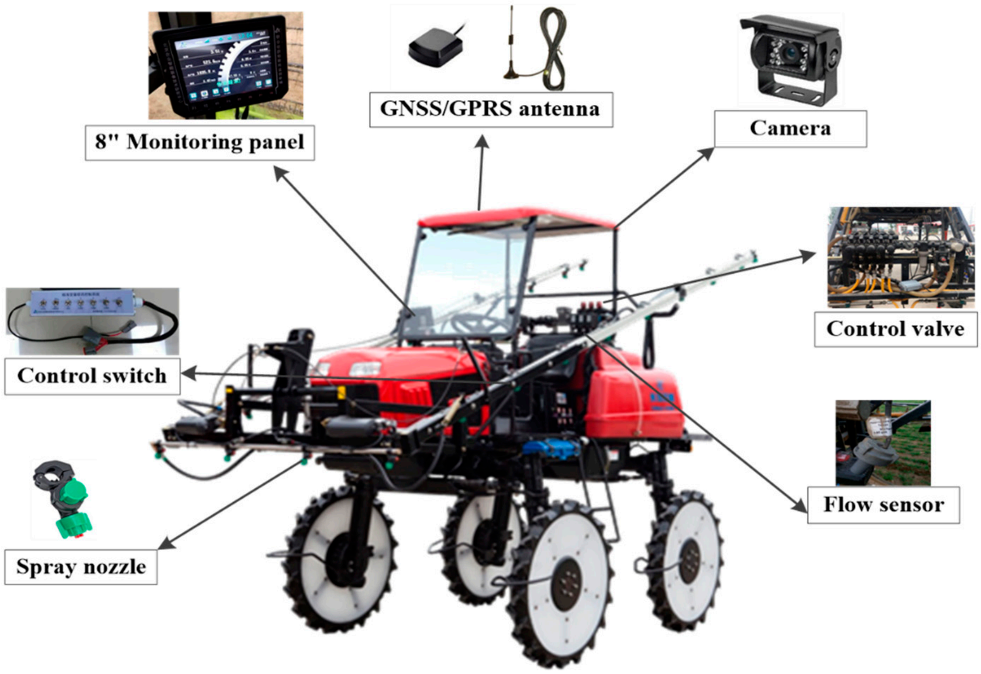

Figure 1. Autonomous intelligent crop protection machinery with precision spraying control system.

The herbicides used in the experiment were flucarbazone-Na 70% WG, produced by Shandong Changqing Pesticide Co., Ltd. (Jinan, China), and florasulam 50 g·L^{-1} SC, produced by Hebei Zhicheng Biochemical Co., Ltd. (Shijiazhuang, China) The droplet measuring cards were provided by the Institute of Plant Protection, Chinese Academy of Agricultural Sciences (Beijing, China).

Table 1. Theoretical settings, including spraying volume, travel speed, flow rate, and other variables related to the real-time variable-rate sprayer.

Treatment	Spraying Volume (L/ha)	Width of Spraying Boom (m)	Travel Speed (km/h)	Total No. of Nozzles on the Spraying Boom	Theoretical Working Time per Hectare (min)	Theoretical Flow Rate per Nozzle (L/min)
1	150	13	5	26	9.23	0.63
2	150	13	6	26	7.69	0.75
3	150	13	7	26	6.59	0.88
4	150	13	8	26	5.77	1.00
5	180	13	5	26	9.23	0.75
6	180	13	6	26	7.69	0.90
7	180	13	7	26	6.59	1.05
8	180	13	8	26	5.77	1.20

2.3. Experimental Methods

2.3.1. Experimental Design

This experiment was conducted under field conditions with a split-split plot three-factor design. The main plot was the spraying volume, with two levels of 180 L·ha^{-1} and 150 L·ha^{-1}. The subplot was the nozzle type, with two levels of TTI11004 and TTI11003. The sub-subplot was the herbicide dose, with two levels of 60 g·ha^{-1} (formulation) of 70% flucarbazone-Na 70% WG mixed with 150 mL·ha^{-1} (formulation) of 50 g·L^{-1} florasulam 50 g·L^{-1} SC, and a 20% reduced rate of the abovementioned herbicide mixture. A total of 2 × 2 × 2 = 8 treatment combinations were conducted with three replications, and each experimental plot had an area of 75 m × 13 m = 975 m^2 (depicted in Figure 2). In each treatment plot, two 5 m × 5 m = 25 m^2 sample squares were selected randomly as the blank control (weedy) and manual weeding control (weed-free) treatment, respectively.

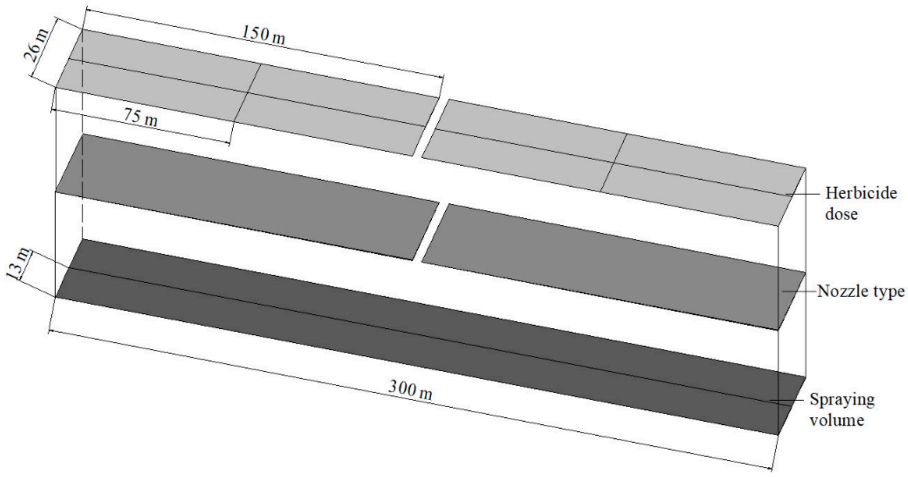

Figure 2. Schematic diagram of spraying volume, nozzle type, and herbicide dose three-factor split-split plot experimental design.

2.3.2. Measurement of Droplet Deposition

In each experimental plot, a rectangle area of 20 m × 13 m was selected along the running direction of the sprayer as the droplet deposition measurement zone (MZ). Within the MZ, 13 droplet measuring cards were placed parallel to the ground surface, with a height of approximately 10 cm (fixed on a device, shown in Figure 3), spacing around 1 m in a straight line perpendicular to the direction of the sprayer running. After herbicide solution was sprayed and the attached droplets were dried, the measuring cards were collected and brought back to the laboratory. The measuring cards with droplet traces were scanned, and the droplet deposition was analyzed using the iDASPro (Version 1.0) droplet deposition analysis software developed by the NERCITA [30]. The coverage rate of droplets and the density of droplets with a particle size (diameter of the droplet sphere) of 50–1000 µm are selected as the evaluation indicators for the deposition effect. The average coverage rate of droplets on the measuring cards was used to evaluate the effects of the SV and NS on droplet deposition. The average coefficient of variation ($CV_{\overline{X}}$) of the coverage rate on the measuring cards was used to assess the effects of different SV and NS on the spray consistency among nozzles from different locations on the spraying boom. The calculation formula for $CV_{\overline{X}}$ is shown in Equation (1).

$$Mean\ Coefficient\ of\ Variation(CV_{\overline{X}}\%) = \frac{Standard\ Error\ of\ the\ Mean\ Coverage\ Rate(S)}{Mean\ Coverage\ Rate(\overline{X})} \times 100 \quad (1)$$

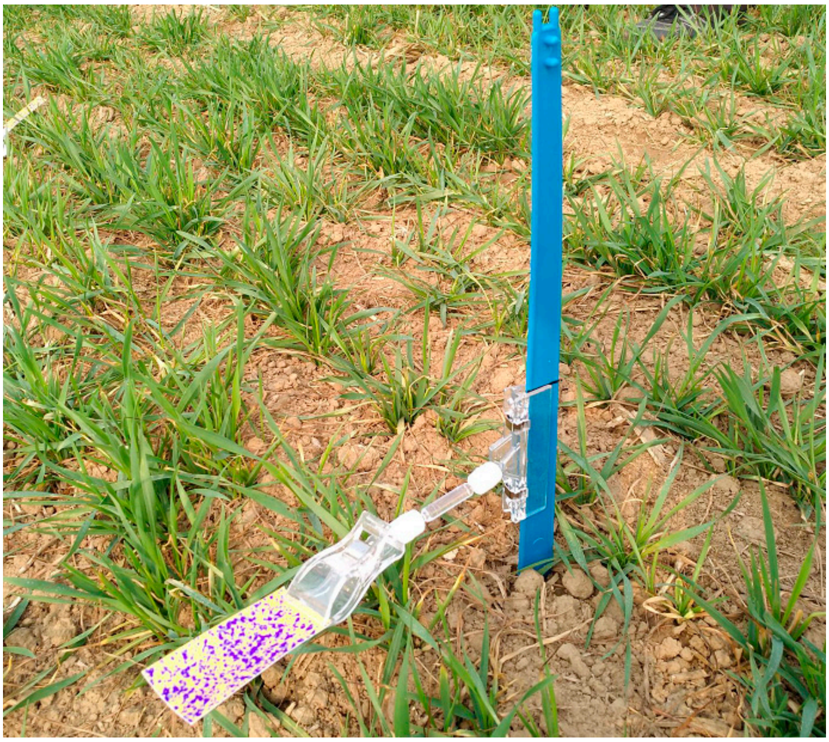

Figure 3. A device used for fixing the droplet measuring cards in the field. (The photograph was captured shortly after the spraying process).

2.3.3. Evaluation of Weed Control Efficacy

At 38 days after herbicide application (DAT), the efficacy of different herbicide treatment combinations using the precise variable-rate boom sprayer on weed control was assessed. Firstly, each herbicide treatment plot was divided into three equal sections along the longer side. Within each section and the weedy control plot, four 0.5 m × 0.5 m = 0.25 m^2 quadrats were randomly selected. The above-ground portion of the weeds in each quadrat was harvested and weighed. The percentage reduction in the fresh weight of weeds compared to the blank control treatment was used as the evaluation indicator for weed control efficacy. The calculation formula was detailed in Equation (2).

$$Fresh\ Biomass\ Efficacy(\%) = \frac{FW_{CK} - FW_T}{FW_{CK}} \times 100 \quad (2)$$

In the equation, FW_{CK} refers to the above-ground fresh biomass weight of weeds in the blank control treatment, while FW_T refers to the fresh biomass weight of weeds in different herbicide treatments.

2.3.4. Evaluation of Wheat Safety

At 38 DAT, each herbicide treatment plot was divided into three equal sections along the longer side. Within each section and the weedy and weed-free plot, 15 wheat plants were randomly selected as samples, and the plant height was measured and recorded. During the wheat harvesting period, four 0.5 m $\times$ 0.5 m = 0.25 m^2 quadrats were randomly selected from each section and the weedy and weed-free plot. All wheat ears within each quadrat were harvested, and the number of ears was counted. Additionally, the number of grains in each ear of ten randomly selected ears was counted. The harvested wheat ears were allowed to air dry naturally (with a moisture content of approximately 14%) and then threshed. After threshing, the grain weight of each sample was measured, and 1000 wheat grains were counted randomly for weight measurement. Wheat yield was estimated based on indicators such as ear number per square meter, grain number per ear, and thousand grain weight (TGW).

2.4. Data Analysis

The SPSS 25.0 software was used to perform univariate process of the General Linear Model on the precise variable-rate boom sprayer spraying with different SV and NS to compare the deposition effect of droplets. One-way three-factor ANOVA was performed to analyze the effects of different SV, NS, and application rates of herbicides on weed control efficacy, wheat yield, and its constituent factors using the above-mentioned sprayer. Differences in yield between different treatment combinations and the blank control and manual weeding were compared using one-way ANOVA. To ensure the normality of the data, square root arcsine transformation was employed to percentage data, and the least significant difference (LSD) method was used for multiple comparisons, with a significance level of $\alpha = 0.05$.

3. Results

3.1. Effect on Droplet Deposition

The results of two-way ANOVA indicate that only the SV had a significant effect on droplet density and coverage ($p < 0.05$). However, the NS and its interaction with SV had no significant effect on the two above-mentioned indicators and the mean coefficient of variation ($p > 0.05$, Table 2). The spraying volume of 180 L·ha^{-1} showed significantly higher droplet density and coverage compared to 150 L·ha^{-1} ($p < 0.05$) (Figure 4). This demonstrated that under the condition of both nozzle sizes, spraying with a volume of 180 L·ha^{-1} could achieve better droplet deposition quality, while spraying with a volume of 150 L·ha^{-1} results in relatively poor droplet deposition.

Table 2. Two-way ANOVA of nozzle size and spraying volume on the influence of droplets deposition.

Indexes	***p*-Value (n = 52)**		
	Spraying Volume	**Nozzle Size**	**Spraying Volume × Nozzle Size**
Droplet density	0.000	0.551	0.131
Droplet coverage	0.000	0.130	0.233
Mean coefficient of variation	0.577	0.138	0.267

All the effects of SV, NS, and their interaction on the mean coefficient of variation in the horizontal direction of the spray boom are not significant ($p > 0.05$, Table 1). Neither the SV (180 L·ha^{-1} or 150 L·ha^{-1}) nor the NS (TTI11004 or TTI11003) has a significant effect on this parameter (the left bar chart of Figure 5). However, while using the TTI11004 nozzle matched the spraying volume of 180 L·ha^{-1}, the coefficient of variation was significantly lower than the other treatments (the right bar chart of Figure 5), indicating better spraying uniformity could be achieved. This demonstrated that a certain spraying volume should be matched with the right nozzle size for much more spraying uniformity and stability.

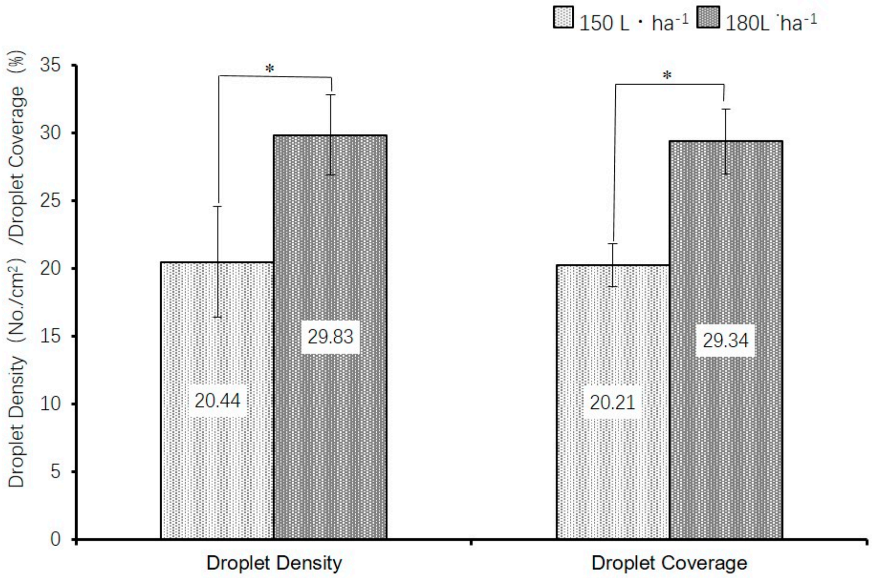

Figure 4. Effect of spraying volume on the droplet density and droplet coverage (with sample size n = 52; * means difference was significant at $p = 0.05$).

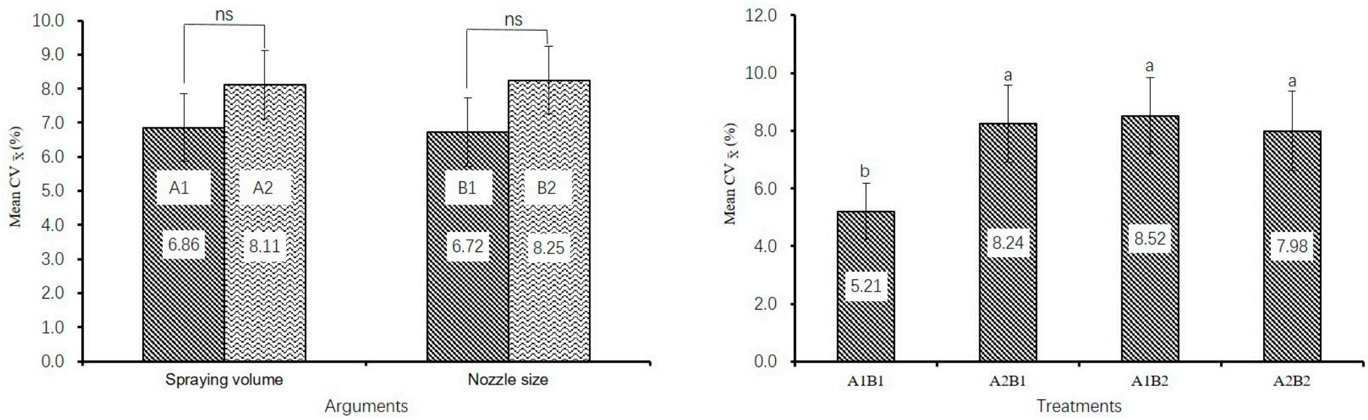

Figure 5. Droplet deposition coefficient of variation in the horizontal direction of the spray boom influenced by different nozzle sizes and spraying volumes. (A1: with spraying volume of 180 L·ha^{-1}; A2: with spraying volume of 150 L·ha^{-1}; B1: with nozzle size of TTI11004; B2: with nozzle size of TTI11003; ns means difference was not significant at $p = 0.05$; means in different columns followed by the same letter were not significantly different at $p = 0.05$).

3.2. *Efficacy of Weed Control*

Results of three-way ANOVA showed that the SV and its interaction with NS had a significant effect on weed control efficacy ($p < 0.05$). However, the effects of NS ($p = 0.140$), herbicide dose ($p = 0.186$), their interaction ($p = 0.949$), interaction between SV and herbicide dose ($p = 0.848$), and interaction among the three factors ($p = 0.654$) were not significant ($p > 0.05$, Table 3).

Results of multiple comparisons under the interaction of NS and SV indicate that the highest weed control efficacy was achieved with a spraying volume of 180 L·ha^{-1} using the TTI11004 nozzle. The efficacy was significantly reduced ($p < 0.05$) when using the TTI11003 nozzle under the same spraying volume. Additionally, when the spraying volume was decreased to 150 L·ha^{-1}, the efficacy of both nozzle sizes was also significantly reduced ($p < 0.05$), but there was no significant difference between these two NS treatments ($p > 0.05$, Figure 6).

Table 3. Three-way ANOVA of nozzle size, spraying volume, and herbicide dose on weed control efficacy.

Source of Variation	*p*-Value (n = 12)
Spraying volume	0.000
Nozzle size	0.140
Herbicide dose	0.186
Spraying volume × Nozzle size	0.043
Spraying volume × Herbicide dose	0.848
Nozzle size × Herbicide dose	0.949
Spraying volume × Nozzle size × Herbicide dose	0.654

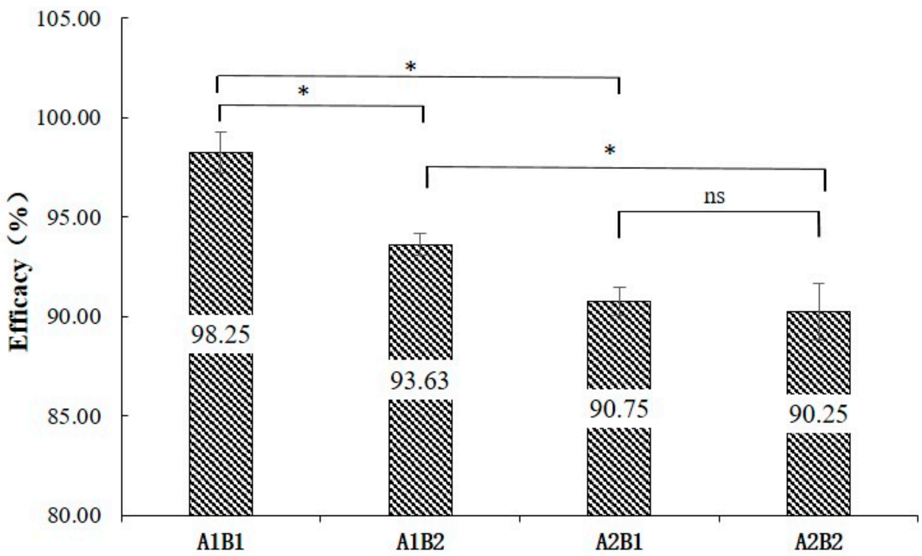

Figure 6. Efficacy of weed control under interaction effect of spraying volume and nozzle sizes. (A1: with spraying volume of 180 L·ha^{-1}; A2: with spraying volume of 150 L·ha^{-1}; B1: with nozzle size of TTI11004; B2: with nozzle size of TTI11003; with sample size n = 24; * means difference was significant at $p = 0.05$ and ns means difference was not significant at $p = 0.05$).

3.3. Effect on Wheat Growth

The results of the three-way ANOVA indicated that only the factor herbicide dose had a significant effect on wheat height at 38 days after herbicide application ($p < 0.05$). The plant height of winter wheat treated with herbicides (both with the recommended dose and at a 20% reduction among the various spraying volumes and nozzle types) was significantly lower than the weedy and weed-free treatment ($p < 0.05$). Additionally, the plant height of winter wheat treated by herbicides at a 20% dose reduction was significantly higher than that of the recommended dose treatment ($p < 0.05$, Figure 7).

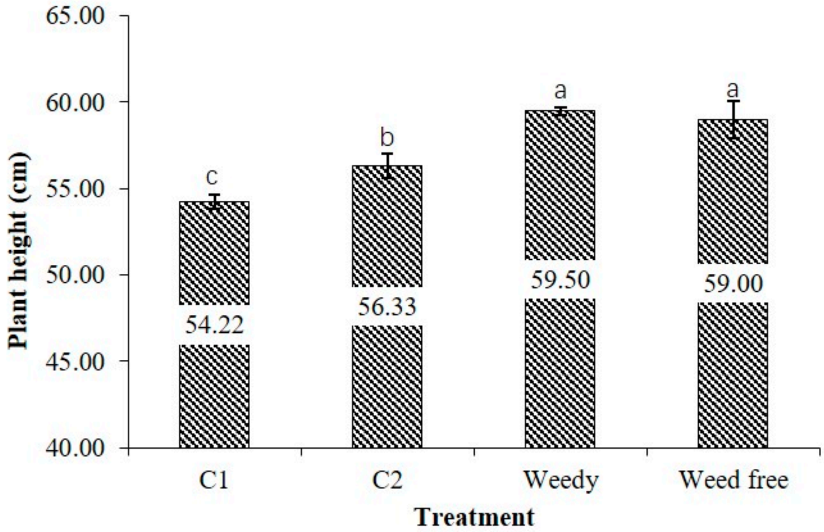

Figure 7. Effect on wheat growth under recommended and 20% reduced dose of herbicides applied using the real-time variable-rate sprayer. (C1: herbicides applied at the recommended dose; C2: herbicides applied at the 20% reduced dose; with sample size n = 180 for C1 and C2, and sample size n = 120 for weedy and weed-free control; means in different columns followed by the same letter were not significantly different at $p = 0.05$).

3.4. Effect on Wheat Yield

The results of the three-way ANOVA indicated that there was no significant effect of SV, NS, herbicide dose, and their interactions on wheat yield and its components ($p > 0.05$, Table 4). The wheat yield under different treatment combinations showed that all eight different herbicide treatment combinations resulted in significantly higher wheat yield compared to the weedy control ($p < 0.05$), but differences among each of the two treatments were not significant ($p > 0.05$).

In addition, compared with the weed-free treatment, the average loss in wheat yield of the recommended dose treatment was 9.13%, while the loss in wheat yield under the 20% reduced dose treatment was 6.77%. Therefore, reducing the herbicide input using the real-time variable-rate sprayer can reduce wheat yield loss by 2.36% (9.13% minus 6.77%, Table 5).

Table 4. Three-way ANOVA of nozzle size, spraying volume, and herbicide dose on winter wheat yield and its component parameters.

Source of Variation	*p*-Value (n = 12)			
	No. of Ears/m^2	No. of Kernels/Ear	Thousand Kernels Weight	Yield
Spraying volume	0.327	0.378	0.275	0.727
Nozzle size	0.642	0.238	0.847	0.742
Herbicide dose	0.660	0.543	0.709	0.741
Spraying volume × Nozzle size	0.843	0.425	0.506	0.581
Spraying volume × Herbicide dose	0.660	0.246	0.464	0.929
Nozzle size × Herbicide dose	0.707	0.815	0.167	0.098
Spraying volume × Nozzle size × Herbicide dose	0.745	0.947	0.256	0.891

Table 5. Influence of nozzle size, spraying volume, and herbicide dose on winter wheat yield and its component parameters.

Treatment			Parameters (n = 12)				Parameters (n = 48)	
Spraying Volume	Nozzle Size	Dose	No. of Ears/m^2	No. of Kernels/Ear	Thousand Kernels Weight (g)	Yield (t·ha^{-1})	Average of Yield (t·ha^{-1})	Yield Loss * (%)
180 L·ha^{-1}	TTI11004	Recommended	733.60 ± 11.19	24.80 ± 0.78	28.02 ± 0.83	6.35 ± 0.06	6.17 ± 0.06	9.13
180 L·ha^{-1}	TTI11003	Recommended	756.80 ± 12.97	25.17 ± 0.59	26.03 ± 0.94	6.18 ± 0.09		
150 L·ha^{-1}	TTI11004	Recommended	728.00 ± 37.51	23.65 ± 0.35	26.92 ± 0.74	6.10 ± 0.44		
150 L·ha^{-1}	TTI11003	Recommended	765.60 ± 44.27	24.43 ± 1.10	27.48 ± 0.36	6.06 ± 0.07		
180 L·ha^{-1}	TTI11004	20% Reduced	734.40 ± 50.47	24.58 ± 0.85	28.90 ± 0.66	6.48 ± 0.32	6.33 ± 0.08	6.77
180 L·ha^{-1}	TTI11003	20% Reduced	888.80 ± 25.21	22.64 ± 0.51	25.65 ± 0.41	6.45 ± 0.24		
150 L·ha^{-1}	TTI11004	20% Reduced	663.20 ± 29.63	26.16 ± 0.52	27.43 ± 0.75	6.14 ± 0.18		
150 L·ha^{-1}	TTI11003	20% Reduced	685.60 ± 13.85	25.91 ± 0.79	29.27 ± 0.72	6.26 ± 0.17		
Weedy (n = 32)			742.40 ± 56.45	23.71 ± 1.06	26.11 ± 0.86	4.86 ± 0.19	--	--
Weed-free (n = 32)			630.40 ± 11.16	25.85 ± 1.04	28.62 ± 0.81	6.79 ± 0.17	--	--

* The yield loss was calculated as the yield-reduced percentage of herbicide applied at recommended or 20% reduced dose compared with the weed-free treatment.

4. Discussion

According to the findings of Luck et al. [31], only 25% to 36% of the area in their research fields received application rates within the desired target rate of ±10%. Off-rate errors may arise from changes in ground speed or variations in velocity across the spray boom during turning movements with conventional pesticide application machines. The over-application of herbicides was observed to inhibit plant growth for crops [32,33]. Conversely, applying herbicides at rates below the desired level can lead to yield losses due to ineffective weed control [34,35]. Consequently, by being equipped with intelligent control systems, real-time variable-rate pesticide spray applications can significantly reduce off-rate errors and off-target environmental pollution, so it has gained significant attention in recent years.

Spraying volume (SV) could be reduced up to 55% but still assure excellent coverage by adjusting parameters such as boom height, nozzle spacing and inclination, pump pressure, and machine traveling speed [6]. The real-time variable-rate sprayer used in our experiment has accomplished the application of herbicides proportionally according to the machine's forward speed, pump pressure, and nozzle flow rate. The spraying volume still had a significant effect on droplet coverage, and its interaction with nozzle size had a significant effect on weed control efficacy. Additionally, while using the TTI11004 nozzle with a spraying volume of 180 L·ha^{-1}, the mean coefficient of variation was significantly reduced, indicating better spraying uniformity and deposition quality could be achieved. According to the research of Meyer et al. [22], nozzle selection and spray volume play critical roles in maximizing the efficacy of post-emergence herbicides. Their study showed that using a low spray volume could actually reduce the efficacy of the herbicides. Our findings align with these results. When the spraying volume was decreased from 180 L·ha^{-1} to 150 L·ha^{-1}, a significant reduction in droplet density, coverage, and, ultimately, weed control efficacy was observed. The findings of this study provide strong evidence that achieving adequate target coverage is crucial for achieving desired herbicide efficacy. Furthermore, it is important to clarify that caution must be exercised when using an SV of 150 L·ha^{-1} with either the TTI11004 or TTI11003 nozzle at a moving speed of 5 to 8 km/h. This is due to the low pressure at this SV level and speed range, which may result in an inconsistent spray.

The type or size of the nozzle largely affects the droplet size and deposition of the sprayers [25,36], but its impact on herbicide efficacy is not significant in most cases [37]. The SV usually influences herbicide efficacy greatly; sometimes, a relatively low level is favorable [20,38], but sometimes, a relatively higher level is necessary for some weed species [19,39]. In certain situations, these two factors jointly influence droplet size, deposition, and the efficacy of herbicides [23,40,41]. Since the nozzles used in our experiment were both of the turbo air-induction type, and the difference in their flow rate was relatively small, there was no significant effect on droplet deposition (density and coverage) and herbicide efficacy. However, the interaction between nozzle size and spray volume (SV) was found to have a considerable impact on weed control efficacy in our study, aligning with the findings of the aforementioned references. Therefore, selecting the appropriate nozzles and determining the optimal spraying volume are crucial components that serve as a reliable foundation for intelligent pesticide application machines.

As indicated in the National Planting Development Plan for the 14th Five-Year Plan [42], China will continue to emphasize the policy of reducing the application dose of chemical pesticides in the future. Incorporating intelligent plant protection machines with precision application technologies, such as the real-time variable-rate sprayer equipped with the right nozzle size and spraying volume in our study, is a crucial strategy for reducing herbicide dose and improving its use efficiency. In addition to mitigating the risks to human health and the ecological environment caused by herbicide application, this approach will also significantly enhance the safety of the desired crop plants. The results of our study suggest that reducing herbicide input by 20% may lead to a decrease in its inhibitory effect on winter wheat plants. Consequently, the treatments with a 20% reduction in herbicide dose exhibited higher plant height and yield compared to the recommended dose treatments. Based on our findings, an investigation into the further reduction of herbicide input is warranted. Additionally, exploring the use of more advanced nozzle types or sizes with optimized spraying volumes for real-time variable-rate sprayers holds promise for future research.

5. Conclusions

Using ground-based real-time variable-rate intelligent plant protection machine spraying is still the main herbicide application strategy in winter fields in China. In this study, we focused on the effects of spraying volume (SV) and nozzle size (NS) on droplet deposition and weed control efficacy, and these two factors, combined with herbicide, reduced application rates on wheat production safety. The results indicated that the SV had a significant effect on droplet density and coverage, and its interaction with NS significantly influenced weed control efficacy. Higher droplet deposition and quality and weed control efficacy were achieved when using a spraying volume of 180 L·ha^{-1} with the TTI11004 nozzle. As for wheat yield, the three treatment factors (SV, NS, and herbicide dose) had no significant effect on yield and its components. However, all of the herbicide treatment combinations resulted in significantly higher wheat yields compared with the weedy control. Meanwhile, reducing the herbicide dose by 20% can help mitigate the wheat yield loss, resulting in a reduction of 2.36%. We can conclude that the interaction between spraying volume and nozzle size plays a crucial role in using the real-time variable-rate sprayer to apply herbicide for weed control. Additionally, reducing the herbicide input can probably mitigate the yield loss by reducing the herbicide recessive phytotoxicity in wheat production. Real-time variable-rate spraying through autonomous agricultural vehicles equipped with intelligent implements will represent an important step forward for optimizing weed control applications in sustainable cereal crop production systems in the future. Our findings will provide valuable insights for optimizing equipment parameters for using the real-time variable-rate sprayer to apply herbicide in a high-efficiency way for weed control in wheat production in China.

Author Contributions: J.Z.: literature search, figures, data analysis, and writing and revising, final approval of the version to be published and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; X.X.: data acquisition, revising the draft critically for important intellectual content, final approval of the version to be published and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; Y.L.: data acquisition, revising the draft critically for important intellectual content, final approval of the version to be published and agreement to be

accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; X.Z.: data analysis, revising the draft critically for important intellectual content, final approval of the version to be published and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; J.S.: data analysis, revising the draft critically for important intellectual content, final approval of the version to be published and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; P.Y.: data analysis, revising the draft critically for important intellectual content, final approval of the version to be published and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; X.W.: conception or design of the study, interpretation of data, final approval of the version to be published and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; E.Z.: study design and data interpretation, final approval of the version to be published and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Research and Application of Key Technologies for Intelligent Farming Decision Platform, An Open Competition Project of Heilongjiang Province, China (No. 2021ZXJ05A03).

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

Acknowledgments: We thank the Institute of Plant Protection of the Chinese Academy of Agricultural Sciences for their donations in kind of the droplet measuring cards and technical support.

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

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