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Original Research

Optimizing Seed Rate and Herbicide Doses With or Without Adjuvant for Weed Control and Its Influence on Yield of Winter Wheat

Mujahid Hussain[1, 2], Nadia Rafique[1], Rehana Kaousar[1], Syed Ijaz Ul Haq[1], Changfeng Shan[1], Guobin Wang[1], Wang Shizhou[1], Yubin Lan[1, 2, 3*]

[1]College of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo 255022, Shandong, PR China
[2]National Center for International Collaboration Research on Precision Agricultural Aviation Pesticides Spraying Technology (NPAAC), Ministry of Science and Technology, College of Electronics Engineering, South China Agricultural University, Guangzhou 510642, China
[3]Department of Biological and Agricultural Engineering, Texas A&M University, College Station, TX 77845, USA

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Abstract

A field trial was conducted to evaluate the interactive effect of seed rates and herbicides in combination with adjuvants on weed dynamics and wheat yield. This study was comprised of 3 seed rates; 100 kg h^{-1} (S1), 130 kg h^{-1} (S2), 160 kg h^{-1} (S3), and 3 herbicide dosages (100% recommended dose of Mesosulfuron-methyl + Iodosulfuron-methyl-sodium (H1), 75% of the dose (H2), and 75% dose + adjuvant (H3). The results revealed that average weed density, fresh weight, and dry weight were lower in seed rate 160 kg h^{-1} by 33.37%, 31.52%, and 28.78% compared to 100 kg h^{-1} before herbicide application, respectively. After 30 days of herbicide application, weed density, fresh weight, and dry weight were 42.16%, 34.74%, and 40.91% less in treatment with the combination of S3H3 compared with S1H2. Yield and yield parameters were significantly affected by the different seed rates and herbicide dosages. 1000-grain weight, spikelets, and grains/spike were greater in the lower seed rate (100 kg h^{-1}) with H3, while the grain yield, biological yield, and harvest index were 26.05%, 21.81%, and 5.39% higher in the treatment S3H3 as compared with S1H2. To achieve optimal grain yield, a seed rate of 160 kg h^{-1} is recommended, along with 75% of the recommended herbicide dose with adjuvant.

Keywords: weed management; herbicide dose; adjuvant; seed rate; wheat yield

*e-mail: ylan@sdut.edu.cn
Tel.: +86-0533-2782718

Introduction

Wheat (*Triticum aestivum*) is the most widely grown cereal crop and a major part of the diet, contributing to about 40% of the world's food sources [1]. Wheat serves as a carbohydrate and energy source for around 82 to 85% of the world's population [2]. Wheat-based foodstuffs are also high in protein, carbs, and dietary fiber [3]. It is the world's most exported and cultivated crop, with 216 million hectares grown, an average yield of 3.5 tons' ha^{-1} and a total global output of 765 million tons. In China, wheat is the second most important staple grain; its aggregate consumption was 96.4 million tons in 2019 [4, 5]. The most critical restraints to producing high wheat yields are weed infestation and inappropriate use of seed rates in industrialized and developing countries. On the other hand, weeds in the crop cause the greatest potential yield loss to crops, along with pathogens and animal pests such as insects and birds, which are all ignored [6]. As a result, boosting wheat output is necessary to maintain food security.

Cereals constitute the most important feed inputs, and wheat consumption is expected to rise by about 50% between 2005 and 2050 [7]. To obtain a greater yield, it is necessary to use an optimum seeding rate for wheat because plant population directly influences wheat grain output by affecting primary yield attributes [8, 9]. In crop production, the seeding rate plays an important role. Seed rate considerably influences inter and intra-plant competition for nutrients, space, light, and water [10]. The optimal seed rate is an essential factor that governs a crop's ability to absorb resources effectively and can enhance yield by 15% to 20% [11]. It was found in research that 100 kg h^{-1} of seed rate [12], 125 kg h^{-1} [13], and 150 kg h^{-1} [14] result in greater growth and lower production costs depending on the various sowing times. Khalid et al. [15] used wheat seed rates of 100, 140, 180, and 220 kg ha^{-1} and found that higher seed rates increased the number of tillers and the biological yield. Another study demonstrated that grain yield is unaffected by a wide range of plant populations and seed rates but cannot ensure grain quality. Lowering the seed rate to an optimum level and seed scattering can improve grain quality [16]. High seeding rates necessitate more water demand before the seedling stage, resulting in higher production costs and a reduction in grain yield and grain per spike, while lower seed rates lead to increased plant tiller and higher yield [17]. It was also revealed that the seeding rate had a significant influence on the number of grains. In contrast, increased planting rates of wheat improved plant vigor and grain yield [18].

Wheat production is limited by several management constraints, the most prominent of which are severe weed infestations. Most farmers in the country utilize seed rates that are less than optimal, resulting in poor stand establishment and weed development [19]. In contrast, higher seeding rates may exacerbate difficulties such as lodging, insect and disease infestation, and crop yield degradation [20]. Weed population and dry matter can be significantly decreased by increasing the seed rate to an optimum level. Kolb et al. [21] and Singh et al. [22] found that a larger seed rate gives the crop an advantage over competition against weeds, resulting in increased yield. Marwat et al. [23] suggest that weeds can be suppressed by raising the seed rate, but using a seed rate higher than the optimal level can reduce yield production. Wheat is the only crop capable of producing the greatest number of tillers when compared to others. Wheat plant densities ranging from 125 to 270 plants m^{-2} can provide adequate weed suppression, and a linear association was found between total weed species and individual weed species [24]. Ayana et al. [25] conducted a wheat experiment with different seed rates in the presence of 12 weed species and concluded that a seed rate of 150 kg ha^{-1} was the ideal seed rate to suppress weeds and produced the most productive tillers in terms of biological yield, grain yield, seed per spike, and thousand grain weight, whereas the weedy check produced the least. Another study revealed that seed rate is a reliable determinant, with increasing seed rate decreasing the degree of weed infestation, weed dry weight output, and allowing 120 kg ha^{-1} [26] and 130 kg ha^{-1} [27] seed rates to be sown for better grain yield.

Effective weed management is critical for maintaining food grain output to feed an ever-increasing population and ensuring food security. Among the several known weed management strategies, chemical weed control is the most efficient and cost-efficient way to control weeds in wheat [28]. One of the most critical and significant aspects of wheat management is selecting the suitable herbicide and applying it at the right time and at the correct rate. It is a simple and cost-effective strategy to manage weeds in crops, resulting in increased crop vigor and yield [29, 30]. Herbicides have become widely used in the industrialized world for weed control. There is an immediate need to lessen the chemical load on agricultural crop output by lowering the chemical rate and spray volume. This may be achievable by optimizing the efficacy of herbicides at a lower rate by including an adjuvant [31]. An adjuvant is a chemical that reduces the amount of energy and time required to absorb active substances and can reduce herbicide use by 75% without reducing yield or overall benefits for environmentally friendly weed control [5, 32-34]. Adjuvants entirely change the chemical composition of herbicides or even blanket the plant surface by maintaining the herbicide in contact with plant tissue, increasing herbicide absorption and binding capacity to kill the target plant while causing no damage to the genuine crop [35]. Rizwan et al. [36] stated that incorporating sunflower oil with a pyroxsulam spray solution increased the management of field bindweed and tiny seed canary grass. Moreover, when pyroxsulam was used alone or combined with sulfosulfuron without a surfactant, weed control was substantially poor, particularly for *Phalaris minor* [37]. Palma-Bautista et al. [38] concluded that adding adjuvants to herbicides lowered the contact angle of the herbicide solution, resulting in smaller droplets with low energy, improving herbicide absorption, retention, and insertion through plant cuticles, and eventually enhancing weed death and density.

Numerous obstacles exist to decreasing crop productivity in farms under the agricultural ecology of China. Weed infestation is one of the critical restrictions limiting wheat's potential yield, producing 20-40% yield reductions. It is advisable to use multifunctional adjuvants to reduce the environmental pollution and cost of intensive herbicide application [31]. According to Ashrafi et al. [39], the impacts of isoproturon, triasulfuron, and MCPA + bromoxynil on grain yield attributes and herbicide treatment significantly increased wheat yield components as compared to weedy control. Javaid and Tanveer [40] discovered that herbicides at lower rates with alkyl ether sulfate sodium salt (adjuvant) increased wheat grain yield more than herbicides at recommended rates without adjuvants. Therefore, it is essential to use multifunctional adjuvants with herbicides to achieve high efficiency with reduced cost, reduced herbicide dose, and minimal environmental impact.

In this study, we used 3 levels of seed rates and various dosages of herbicides. The herbicide dosages were designed by reducing 25% of the recommended dose and adding an adjuvant. The aim of this research was to (a) assess the comparative effect of seed rates and herbicide with or without adjuvant on weed dynamics and yield-determining parameters of wheat; (b) test the efficacy of a reduced dose of herbicide alone and in combination with adjuvant to control weeds in wheat.

Materials and Methods

Experimental Details

A field trial was conducted in 2022-2023 in Linzi Research Farm (N 37°0′15″N, E 118°1′20″), belonging to Shandong University of Technology, Shandong, China, to evaluate the effect of seed rate and adjuvant on the efficacy of the herbicide applied at a reduced rate for wheat weed control management. The experiment was laid out in a randomized complete block design (RCBD) with a factorial design to randomize the treatments. Four replications were used to reduce the experimental error. Winter wheat Luyuan-502 (Institute of Application of Atomic Energy, Shandong Academy of Agricultural Sciences, Jinan, Shandong, China) was sown on October 15 and harvested at physiological maturity on June 10, 2023. A total of 9 treatments with one control were used; each plot contained 20 rows with 22.5 cm of spacing; the net plot size was 40.5 m^2 (9 m × 4.5 m). Before sowing wheat, ten soil samples were taken randomly from the experiment field at 0-20 and 20-40 cm depth. After aeration and grinding, the samples were sieved (2 mm) to investigate physicochemical parameters. The soil type at the research farm is sandy clay loam with a pH of 8.5. The data obtained for chemical characteristics was examined and is shown in Table 1.

At the time of sowing, nitrogen, P_2O_5, and K_2O (150 kg ha^{-1}, 40 kg ha^{-1}, and 50 kg ha^{-1}) were incorporated as basal fertilizers in the soil. A whole dose of P_2O_5 and K_2O was applied during sowing. Nitrogen was divided into three parts, with one-third applied at the time of planting, the second dose supplied at the time of first irrigation, and the final dose applied at the time of second irrigation. One irrigation of 100 mm was administered before sowing, followed by the first irrigation 28 days after sowing (DAS). Irrigation was applied at various intervals, depending on the crop's needs. The 2nd irrigation was done at the tillering stage and the 3rd during the booting stage, for a total of four irrigations. Meanwhile, the crop got a variety of rainfall during the maturity and grain-filling stages of wheat. Experimental land was under the cultivation of a maize-wheat crop rotation. The weather on the research farm was monsoon temperate. The average temperature (ºC) and rainfall during the experiment are shown in Fig. 1. Herbicides were applied by using a CO_2-pressurized knapsack sprayer (Taizhou Gufeng Sprayer Co., Ltd.) equipped with four DG 110.2 fan spray nozzles, calibrated to deliver an herbicide solution of 150 L h^{-1} with a height of 50 cm, a walking speed of 3.5 kilometers ha^{-1}, and a constant pressure of 0.21 Mpa. This experiment comprised two factors: three seed rates (100, 130, and 160 kg ha^{-1}) and various herbicide formulations. One recommended level of seed rate (160 kg ha^{-1}) was used, and the other levels were reduced by 20% each (130, 100 kg ha^{-1}) from the recommended level to check the interactive effects of herbicide formulations. Three herbicide formulations (100%, 75%, and 75% + adjuvant) were applied with a 100% recommended dose (H1) of Mesosulfuron-methyl + Iodosulfuron-methyl-sodium (Findus 36WG) with a concentration of 11.9 g a.i. ha^{-1}

Table 1. Chemical analysis of soil.

Physiochemical properties	Units	Analytical value
Electrical conductivity	Dsm^{-1}	1.34
Soil pH	-	7.70
Organic matter	%	0.94
Available P	ppm	9.80
Available K	ppm	190
Available N	ppm	0.09
Texture	-	Sandy clay loam
Sodium adsorption ratio	-	7.0
Saturation	%	40.8
Exchangeable sodium percentage	-	6.0
Available Mo	ppm	0.07

Table 2. Herbicide composition and dosage applied in the field experiment.

Abbreviation	Composition	Dosage (ha^{-1})	Seed rate kg ha^{-1} (SR)
H1	100% recommended dose of Mesosulfuron-methyl + Iodosulfuron-methyl-sodium (Findus 36WG)	11.90 a.i. + 2.37 a.i. (395.2 g)	100
			130
			160
H2	75% recommended dose of Mesosulfuron-methyl + Iodosulfuron-methyl-sodium (Findus 36WG)	8.925 a.i. + 1.78 a.i. (296.4 g)	100
			130
			160
H3	75% recommended dose of Mesosulfuron-methyl + Iodosulfuron-methyl-sodium (Findus 36WG) + Alkyl ether sulfate salt (adjuvant)	8.925 a.i. + 1.78 a.i. (296.4 g) + Alkyl ether sulfate salt 395.2 ml	100
			130
			160

+ 2.37 g a.i. ha^{-1} (395.2 g ha^{-1}); the 2nd formulation (H2) was decreased by 25% from the recommended dosage with a concentration of 8.925 g a.i. ha^{-1} + 1.78 g a.i. ha^{-1} (296.4 g ha^{-1}); and 3rd formulation (H3) was 75% of the recommended herbicide dosage with the addition of adjuvant with a concentration of 8.925 g a.i. ha^{-1} + 1.78 g ha^{-1} (296.4 g ha^{-1}) + alkyl ether sulfate salt 395.2 mL ha^{-1}. The herbicides were formulated according to the company that owns the molecules and sprayed with a knapsack sprayer on 30-day-old plants (Table 2).

Weed Dynamics

Weed density was measured every 15 days (45 days after sowing) with a square meter, according to treatments. Weeds were observed and measured in meter squares randomly distributed across the experimental units. After a 15-day interval, data on the total fresh weight of the weeds was collected from each trial by randomly arranging a square meter in the experimental sample and harvesting all the fresh biomass of the weeds.

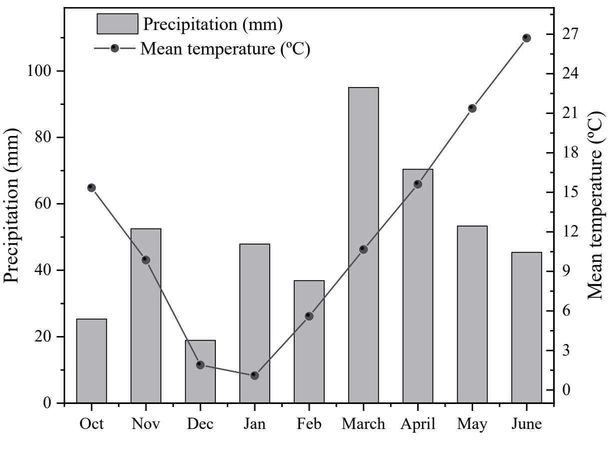

Fig. 1. Average temperature and precipitation during the experiment 2022-2023. Sample Collection and Measurements.

Following the fresh weight of weeds, the complete weeds were sun-dried for three days before being placed in an electric oven at 71ºC to 73ºC for 72 hours. The total dry weight of the weeds was then calculated and recorded using an electric weight scale.

Crop Parameters

The 1-m^2 area was marked and visited after a one-day interval to count the sprouted seeds. The field was visited on a regular basis until the constant emergence and number of seeds emerged. The marked area was counted. Plant height was measured using a meter rod from the soil surface to the tip of the wheat head by selecting five random plants from each treatment. The height was measured from the soil's surface to the spike's tip using a meter rod, and the mean plant height was determined. When the crop was fully grown, a meter square was placed in each treatment randomly to count the number of spike-bearing and non-spike-bearing tillers.

Grain Yield

Six sections of one m^{-2} from each treatment were harvested to determine the grain yield. Wheat heads were removed from the selected sections and packed in well-aerated bags. Before threshing, spikelet numbers per spike were counted by selecting fifteen spikes randomly from each treatment; these spikes were threshed manually to count the grains per spike. Five random samples from each treatment were selected to record a 1000-grain weight using an electric scale. After determining the yield component data, the grains were put back in the tagged bags. Harvested samples were sun-dried for three days and then threshed using a mini-thresher. After threshing, the obtained yield and biological yield of each plot were measured and converted into tons h^{-1}. The harvest index was calculated using the following formula:

Harvest index (%) = Grain yield / Biological yield × 100 (1)

Statistical Analysis

All statistical analysis was conducted using SPSS 16.0 (SPSS, Chicago, IL, USA). The factorial ANOVA was used to determine the mean comparison and significant differences between all the treatments at $p<0.05$, followed by LSD. Linear regression fitting and all other equations were fitted using Origin 2019 software (OriginLab Co., Northampton, MA, USA).

Results

Weed Density Before and After Herbicide Application

Data for weed density before herbicide application showed that seed rate had a highly significant effect on weed density, and the interaction between two factors was not significant (Table 3). A maximum number of weeds (343.27 m^{-2}) was noted in the plots where a 100 kg h^{-1} seed rate was used. The minimum number of weeds (228.75 m^{-2}) was found in the plots where a seed rate of 160 kg h^{-1} was used (Fig. 2a). This means that the seeding rate has a significant impact on weed density. A lower seed rate means fewer plants and more room for weeds to grow and flourish. A higher weed population may affect grain yield and plant height. A higher seed rate equals more plants, which gives weeds less space, soil, and environmental resources, resulting in low weed density. Fifteen days after the application of herbicide (DAA), the data revealed that seed rate and herbicide treatments had a significant effect on weed density. The interactive effect between seed rate and herbicide was found to be non-significant in the weed density of wheat (Table 3). A large number of weeds (219.36 m^{-2}) were counted at a 100 kg h^{-1} seed rate, while the fewest weeds (170.41 m^{-2}) were seen where 160 kg h^{-1} of seed was used. Treatments with herbicides significantly affected the weed density as well. In the treatment of 75% herbicides, the highest number of weeds (237.55 m^{-2}) were recorded, while the least number of weeds (150.70 m^{-2}) were found in these plots, which were treated with the combination of 75% weedicide and adjuvant (Fig. 2b). On 30 DAA, the impact of seed rate and herbicide on weed density was highly significant. In these plots with a 100 kg h^{-1} seed rate, the most weeds (44.015 m^{-2}) were found, while the plots with 160 kg h^{-1} had the fewest weeds (35.937 m^{-2}) on record. Application of 75% of the recommended herbicide showed the highest number of weeds (48.634 m^{-2}), while 75% of the herbicide combined with adjuvant showed the lowest number of weeds (33.63 m^{-2}) (Fig. 2c). The interaction between seed rate and herbicide application had no significant impact on weed density (Table 3).

Weed Fresh Weight Before and After Herbicide Application

Seed rates have a highly significant effect on the fresh weight of weeds before herbicide application. In contrast, the interactive effect was noted as non-significant on the fresh weight of weeds (Table 3). In the plots where 100 kg h^{-1} of seed was used, the maximum fresh weight of weeds (302.75 g m^{-2}) was observed before herbicide application. The plots containing 160 kg h^{-1} seed rate showed the lowest fresh weight of weeds (207.34 g m^{-2}) before the application of herbicide treatment. Meanwhile, at a 100 kg h^{-1} seed rate, the maximum fresh weight of weeds (304.67 g m^{-2}) was observed with the combination of a 75% herbicide dosage. In the plots with a 160 kg h^{-1} seed rate, the minimum fresh weight of weeds (133.67 g m^{-2}) was noted with a 75% herbicide dosage with adjuvant

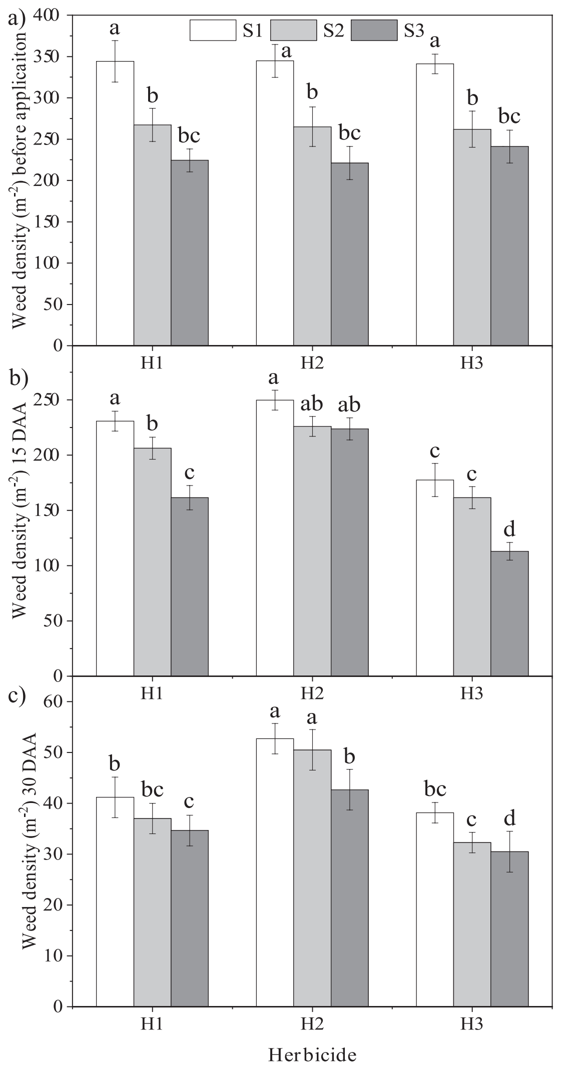

Fig. 2. Effects of herbicide dosage and seed rate on weed density: a) before herbicide application; b) 15 days after herbicide application (15 DAA); c) 30 days after herbicide application (30 DAA). Different letters above the bars show significant differences between the values of treatments at $p<0.05$.

(Fig. 3a). The fresh weight of weeds after 15 DAA indicated a significant relationship between seed rate and herbicide applications at the 5% probability level. After applying herbicide, the interaction between seed rate and herbicide was found to have no significant influence on the fresh weight of weeds (Table 3). In plots with 100 kg h^{-1} seed rates, the highest fresh weight of weeds (381.56 g m^{-2}) was discovered. In plots using a 160 kg h^{-1} seed rate, the lowest fresh-weight weeds (296.22 g m^{-2}) were noted. Treatments with herbicides significantly affect the number of weeds growing. The highest fresh weight of weeds (408.11 g m^{-2}) was observed. 75% percent of the recommended dose of herbicide was used, and weeds were kept to a minimum (270.22 g m^{-2}) in those plots where 75% of the recommended dose and adjuvant mixture were used. In the interaction, the plots with 100 kg h^{-1} of seed

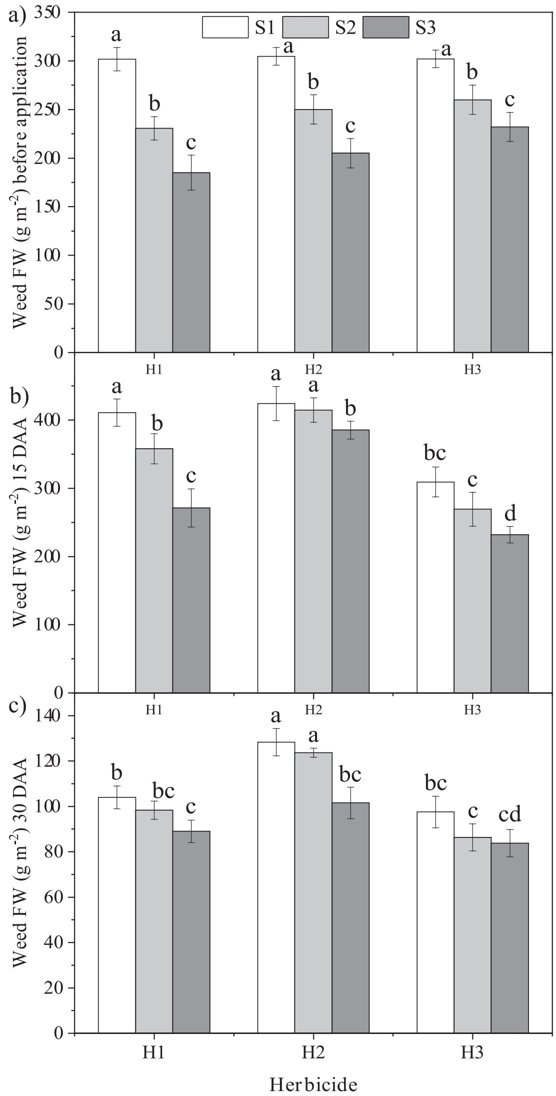

Fig. 3. Effects of herbicide dosage and seed rate on weeds fresh weight: a) before herbicide application; a) 15 days after herbicide application (15 DAA); c) 30 days after herbicide application (30 DAA). Different letters above the bars show significant differences between the values of treatments at $p<0.05$.

and 75% of the recommended herbicide dose found the highest fresh weight of weeds (424.00 g m^{-2}). With a seed rate of 160 kg h^{-1} and 75 percent of the recommended dose of herbicide with adjuvant, the lowest fresh weight (232.00 g m^{-2}) was observed. Compared to herbicide application without an adjuvant, herbicide application at a reduced rate with the chemical adjuvant significantly reduced the fresh weight of the weeds (Fig. 3b). The fresh weight of weeds on 30 DAA indicated that herbicide application and seed rate had a statically significant influence on the fresh weight of weeds. Moreover, herbicide and seed rate interactions had no discernible effect at the 5% probability level. Data pertaining to the fresh weight of weeds after herbicide application with or without adjuvant showed a significant effect of seed rate on the fresh weight of weeds. The plots with the highest fresh weed weight (109.89 g m^{-2}) had a seeding rate of 100 kg h^{-1}, whereas the plots with the lowest fresh weed weight (91.44 g m^{-2}) had a seeding rate of 160 kg h^{-1}. The fresh weight of weeds is significantly affected by herbicide treatments as well. The treatment where 75% of the recommended dose of herbicide was used showed the highest fresh weight of weeds (117.85 g m^{-2}), while it was the minimum (89.20 g m^{-2}) when 75% of the herbicide dose was applied with adjuvant. For the interaction, the plots with 100 kg h^{-1} seed rates and 75% of the recommended herbicide dose showed the maximum fresh weight of weeds (128.33 g m^{-2}). The plots with a 160 kg ha^{-1} seed rate and a 75% herbicide dosage with adjuvant had the minimum weed fresh weight (83.75 g m^{-2}) overall (Fig. 3c).

Weed Dry Weight Before and After Herbicide Application

Weed dry weight depends on the fresh weight of weeds. The data revealed that weed dry weight was significantly affected by seed rate at the 5% probability level. Weeds dry weight was maximum (59.78 g m^{-2}) in the treatments where a seeding rate of 100 kg h^{-1} was used, while the lowest dry weight of weeds was (42.57 g m^{-2}) in plots where a 125 kg ha^{-1} seed rate was used (Fig. 4a). On 15 DAA, seed rate and herbicide treatments had a statistically significant impact on the dry weight of weeds. While the interactive effect between the two factors was found to be non-significant. Weeds dry weight was maximum (64.62 g m^{-2}) on 15 DAA at 100 kg h^{-1} of seed rate, while it was minimum (53.78 g m^{-2}) at 160 kg h^{-1} of seed rate. Herbicides of various dosages also had a significant impact on the dry weight of the weeds. The maximum average dry weight (70.54 g m^{-2}) was recorded in the treatment where 75% of the recommended herbicide dosage was used. In comparison, the minimum average dry weight (50.38 g m^{-2}) was noted in 75% of the recommended dosage and adjuvant combination. The interactive effect between seed rate and herbicide treatment had a non-significant effect on the dry weight of weeds

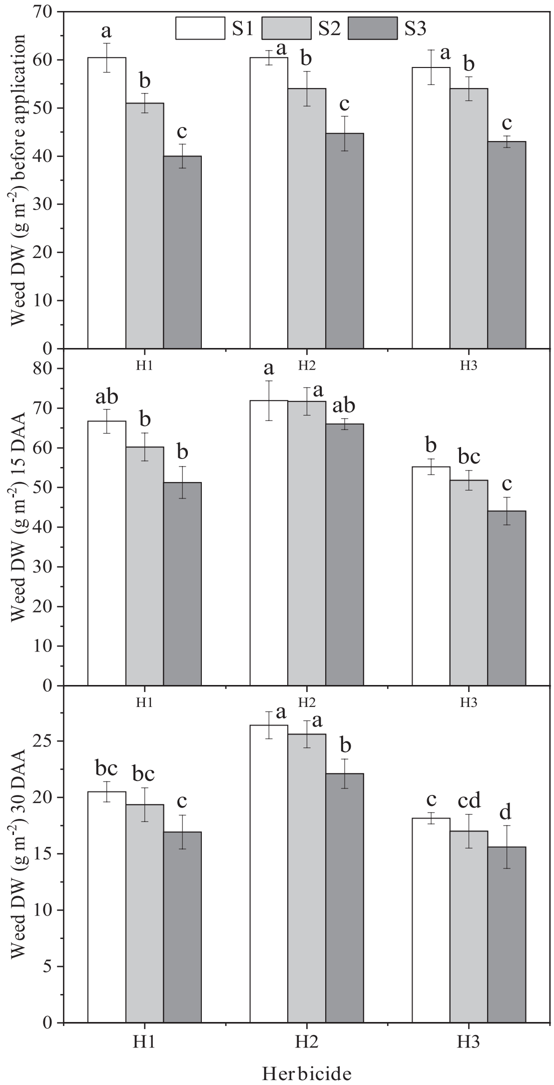

Fig. 4. Effects of herbicide dosages and seed rate on weed dry weight: a) before herbicide application; b) 15 days after herbicide application (15 DAA); c) 30 days after herbicide application (30 DAA). Different letters above the bars show significant differences between the values of treatments at $p \leq 0.05$.

after herbicide application of 15 DAA. In interaction, maximum dry weight (71.91 g m^{-2}) was noted in the 100 kg h^{-1} seed rate and 75% of the recommended dose of herbicide. Meanwhile, it was minimum (44.06 g m^{-2}) at 160 kg h^{-1} of seed rate, and the combination of 75% of the prescribed herbicide with adjuvant (Fig. 4b) on 30 DAA, seed rate and herbicide application had a significant effect on weed dry weight. Moreover, the interaction between seed rate and herbicide had a non-significant influence at the 5% probability level (Table 3). Seed rate had a statistically significant impact on the dry weight of weeds following herbicide application with or without an adjuvant. Weed dry weight was maximum (21.68 g m^{-2}) at 100 kg h^{-1}, while it was minimum (18.23 g m^{-2}) at 160 kg h^{-1} of seed rate. Treatments with herbicides also have a sizable impact on the dry weight of weeds. In the herbicide treatments, 75 percent of the recommended dose had the highest dry weight of weeds (24.74g m^{-2}), and the minimum dry weight of weeds (16.92 g m^{-2}) were recorded in 75% of the herbicide with the combination of adjuvant. For interaction, the maximum dry weight of weeds (26.400g m^{-2}) was observed at a 100 kg h^{-1} seed rate with 75% of the recommended herbicide dosage. In comparison, the minimum dry weight (15.60 g m^{-2}) was noted in the 160 kg h^{-1} seed rate with 75% of the recommended herbicide dosage and adjuvant mixture (Fig. 4c).

The seed rates and herbicide treatments have a statistically non-significant effect on emergence. The interactive effect between seed rate and herbicide was also non-significant on the emergence of wheat plants at $P \leq 0.05$. In interaction, maximum emergence (84.59 m^{-2}) was recorded in these plots, which contained 100 kg h^{-1} seed rate. The minimal emergence (83.35 m^{-2}) was recorded in these plots, which contained a seed rate of 160 kg h^{-1}. Plant height can be altered by changes in genetic makeup and by modifying agronomic factors such as soil fertility and seed rates. Seed rates and herbicides significantly affected plant height, and the interaction between the two factors was also significant. The highest plant height (109.04 cm) was recorded with 160 kg h^{-1} seed rates and herbicide at 75% with adjuvant, while 130 kg h^{-1} seed rate with 75% of herbicide had the shortest plant height (83.13 cm). Productive tillering is one of the most essential traits strongly linked to wheat crop output. Seed rate and herbicide treatment showed a significant difference in productive tillers and non-spike bearing tillers, spikelet per spike, grains per spike,

Table 3. ANOVA of data showing the differences in values of seed rates, weed density, and fresh and dry biomass before and after herbicide application.

Treatments	Before application	Density15 DAA	Density30 DAA	FW before application (g m^{-2})	FW 15 DAA (g m^{-2})	FW 30 DAA (g m^{-2})	DW before application (g m^{-2})	DW 15 DAA (g m^{-2})	DW 30 DAA (g m^{-2})
ANOVA									
Seed rate (S)	*	*	**	*	**	**	*	**	**
Herbicide (H)	NS	**	**	NS	**	***	NS	**	**
H*S	NS	NS	NS	NS	NS	NS	*	NS	NS

*, **, and *** show significant differences at 0.05, 0.01, and 0.001 probability levels, respectively. NS: not significant

and 1000 grain weight, while the interaction between the two factors was insignificant at P≤0.05. Maximum productive tillers (373.71 m^{-2}) were counted when 75% of the recommended herbicide rate with adjuvant was applied. In comparison, the lowest productive tillers (354.75 m^{-2}) were recorded where the herbicide was used at 75% of the recommended dose without adjuvant. Maximum non-productive tillers (34.22 m^{-2}) were counted in the 130 kg h^{-1} seed rate, while it was minimum (31.11 m^{-2}) in 100 kg h^{-1}. The highest number of spikelets (16.84) and grain numbers per spike (45.42) were recorded in the treatment with a seed rate of 100 kg h^{-1}, while these were the minimum (15.60 and 36.31) in the 160 kg h^{-1} seed rate. Maximum spikelet per spike (17.267 m^{-2}) and grain numbers (42.34) were counted under the 75% dose of recommended herbicide with adjuvant, while these were minimum (15.32 and 38.29) under the 75% herbicide dosage. Grain weight is a crucial yield-contributing characteristic; the greater the grain weight, the greater the grain yield, and vice versa. Seed rate and herbicide treatments showed a statistically significant effect on 1000-grain weight, while the interaction between two factors was insignificant. The highest 1000-grain weight (43.87 g) was measured at a seed rate of 130 kg h^{-1}, while it was at the minimum (41 g) at a 100 kg h^{-1} seed rate. A 1000-grain weight of 43.11 grams was recorded at 75% of the recommended dosage with the adjuvant combination, while it was 42.11 grams when 75% of the recommended herbicide dosage was applied alone (Table 4).

The results showed that seed rate and herbicide treatments revealed a significant influence on grain yield and biological yield. The interactive effect between two factors was also significant at P≤0.05. The grain yield (6.37 tons h^{-1}) and biological yield (15.76 tons h^{-1}) were maximum in the treatments where a seed rate of 160 kg h^{-1} and 75% of the dose of herbicide with adjuvant were applied, while these were minimum (4.71 and 12.32 tons h^{-1}) at a 100 kg h^{-1} seed rate and 75% of the herbicide dosage alone. Herbicide dosage and seed rates had a significant effect on the harvest index. Harvest index was at its maximum (40.41%) with a 160 kg h^{-1} seed rate and a combination of adjuvant and 75% herbicide dosage. In comparison, it was recorded as minimum when only 75% of the recommended herbicide dose was used with a seed rate of 130 and 160 kg h^{-1} (Table 4).

Discussion

Wheat is the best-known cereal crop for use as a staple food. Weeds, particularly grasses with comparable morphological traits, reduce yield and spoil the grain quality. Herbicides have been used to manage weeds since 1940, when synthetic pesticides became available. Weed resistance develops when the same herbicide group or type is used repeatedly. Hamouda et al. [41] determined that adjuvants help to increase the performance of specific herbicides by reducing interfacial strength and increasing chemical dispersion, which results in more effective weed control with lower doses. This research was designed to evaluate the impact of herbicides with adjuvants on crop growth, development, and yield using different seed rates.

Table 4. Effect of herbicide in various dosages under different seed rates on wheat biomass, yield, and yield components.

Treatments	Emergence (m^{-2})	Plant height (cm)	Productive tillers (m^{-2})	Non-productive tillers (m^{-2})	Spikelet per spike	Grains per spike	1000-Grain weight	Grain yield (t ha^{-1})	Biological yield (t ha^{-1})	HI (%)
H1S1	83.43 a	91.44 a	361.65 b	31.33 b	16.93 a	45.53 a	41.0 bc	5.03 cd	13.87 bc	36.25 bc
H1S2	84.39 a	86.53 b	362.37 b	34.33 a	16.13 ab	40.13 c	44.2 a	5.12 d	13.63 cd	37.56 ab
H1S3	84.41 a	86.77 ab	370.41 a	33.0 ab	15.73 b	36.26 cd	41.2 bc	6.15 a	15.91 a	38.67 a
H2S1	83.59 a	89.07 ab	353.43 c	34.0 a	15.66 bc	43.40 ab	39.36 c	4.71 d	12.32 d	38.23 a
H2S2	83.47 a	83.13 c	354.72 c	36.0 a	15.53 bc	37.53 cd	43.5 ab	5.47 bc	16.05 a	34.08 c
H2S3	83.79 a	84.83 b	356.09 bc	34.33 a	14.73 c	33.93 d	39.46 c	5.73 ab	16.59 a	34.53 c
H3S1	84.59 a	95.26 a	369.99 a	28.0 c	17.93 a	47.33 a	42.63 b	5.33 cd	14.74 ab	36.16 b
H3S2	84.31 a	92.81 ab	372.82 a	32.33 ab	17.53 a	40.93 bc	43.90 ab	5.53 b	14.73 ab	37.54 ab
H3S3	83.35 a	109.04 a	378.31 a	30.0 b	16.33 ab	38.73 c	42.76 b	6.37 a	15.76 a	40.41 a
ANOVA										
S	NS	**	*	*	**	**	**	***	**	NS
H	NS	**	**	**	**	**	*	***	*	**
H*S	NS	**	NS	NS	NS	NS	NS	**	*	*

*, **, and *** show significant differences at 0.05, 0.01, and 0.001 probability levels, respectively. NS: not significant

Weed infestation, numerous agronomic variables, growth, and yield components were observed. Results showed that the seed rate and herbicide treatments significantly affected weed density and fresh and dry weight (Figs. 2, 3, and 4). Before herbicide application, higher weed density (343.27 m^{-2}), fresh (302.78 g m^{-2}) and dry weight (8.78 g m^{-2}) were observed in the treatments where 100 kg h^{-1} seed rate (S1) was used, which was 22.86% and 33.36%, 18.46% and 31.52%, 6.51% and 16.84% higher than in seed rates of 130 kg h^{-1} (S2) and 160 kg h^{-1} (S3), respectively. Higher seeding rates had a competitive advantage over weed suppression compared to lower seeding rates. As a result, it was discovered that a higher seeding rate reduces the weed density, hence increasing the final yield. Our results were similar to those of [42, 43], who concluded that weed density decreased when higher seed rates were used, possibly due to competition between weeds and crops for space, light moisture, and nutrients. In contrast, weed density increased when low seed rates were used. On 15 days after application of herbicide, weed density was 36.56% and 24.45%, fresh weight was 33.78% and 22.07%, and dry weight was 28.59% and 15.19% lower when 75% of the recommended dose of herbicide with a combination of adjuvants (H3) was sprayed, as compared to 75% of the recommended dose of herbicide (H2) and 100% of the recommended dose of herbicide (H1), respectively. Similarly, on 30 DAA weed density, fresh and dry weight were 30.86% and 10.56%, 33.78% and 22.07%, 24.31% and 8.13% less than in the treatment of 75% of the recommended dose of herbicide (H2) and 100% of the recommended dose of herbicide (H1), respectively. The decreasing intensity in density and fresh and dry weight of weeds was much higher compared to 15 DAA because of the slow effect of herbicides on the weeds. After the herbicide application, it was noticed that the decrease in fresh and dry weight in weed density was less between H3 and H1 compared with the H2 herbicide dose. The reason for this difference is the addition of an adjuvant with 75% of the recommended dose of herbicide. The research concluded that herbicides applied at the recommended dose without adjuvant resulted in lower weed density. Adjuvant mixed with herbicide efficiently can minimize the amount of sprayed herbicide while significantly lowering total weed control expenses. The addition of adjuvant improved the efficiency of herbicides and resulted in a 98% reduction of weed biomass, while 87% of biomass was reduced by applying herbicide alone [38, 44-46].

Productive tillering is one of the most important traits strongly linked to wheat crop output. By modifying agronomic procedures such as seed rate, we can improve the productivity of tillers, lowering output costs and increasing final yield. Seed rate and herbicide application significantly affected productive and non-productive tillers. The highest number of productive tillers (378.31 m^{-2}) were counted in the treatment with a seed rate of 100 kg h^{-1} with 75% of the recommended dose mixed with adjuvant, while non-productive tillers were counted (30 m^{-2}) lower. The lowest productive tillers (353.43 m^{-2}) were counted in the treatment with a 100 kg h^{-1} seed rate with 75% of the recommended dose alone. This shows that the treatment of a reduced dosage of herbicide with adjuvant showed a higher number of productive tillers than the herbicide applied alone. At the same time, there was an increase in non-productive tillers in treatment, where 75% of herbicide dosage alone was due to the increased weed density. Although the seed rate was optimal in this treatment to ensure the plant population, the presence of weeds created crucial plant competition and increased non-productive tillers. Javaid and Tanveer [40] findings testified that controlling wheat weeds by application of herbicide at high dosages or reduced doses mixed with alkyl ether sulfate salt resulted in minimum non-productive tillers. These results are also similar to the findings of [47, 48]. The spikelet number per spike, grain number, and 1000-grain weight are the key characteristics of wheat crops that affect production. The higher number of spikelets, grain number per spike, and 1000 grain weight were recorded at lower seed rates by spraying herbicide mixed with adjuvant. Treatments of 100 kg h^{-1} had a low plant population and more chances to get light, air, nutrients, and other plant resources, but a lower seed rate also made them more vulnerable to weeds. Applying herbicide mixed with adjuvant significantly controlled weed growth, provided frequent availability of growth resources to the wheat plants, and resulted in increased spike length and other yield components. Although plant growth was well established in this treatment, the yield production was not satisfactory due to a lower seed rate and a smaller plant population. The same results were reported by [13, 49, 50], in which it was concluded that the rate and length of grain filling are critical factors in the development of each grain weight and size. Grain filling heavily relies on photosynthetic substrates and the availability of nutrients. In this case, lower seed rates and a smaller plant population give a free space for weed growth and reproduction; applying an optimum herbicide concentration can decrease crop competition with weeds for limited resources such as light for photosynthesis, irrigation, and other nutrients in the soil and environmental conditions. Features such as productive tillers, spikelets per spike, and grains per spike all impact grain yield. These qualities can be improved to maximize grain yield. Grain yield can be increased by using the optimum seed rate and weeding at the right time. The maximum grain yield (6.37 tons h^{-1}) was attained in these treatments, where a seed rate of 160 kg h^{-1} and 75% of the standard dose of herbicide were implemented. A minimum grain yield (4.71 tons h^{-1}) was recorded in these plots, where the seed rate was 100 kg h^{-1} and 75% of the suggested dose of herbicide was used. Although the yield components, such as grains per spike or spikelets per spike and 1000 grain weight, were lower in the treatments where the higher seed rate (160 kg h^{-1})

was used. However, due to the optimum plant population, the final crop yield was higher in this treatment than in the treatments with lower seed rates. These results were consistent with those of [51], who found that the higher the seed rate, the higher the plant population and increased grain yield. Biological yield also had significant importance for the farming population. The biological yield was maximum at the 160 kg h^{-1} seed rate, which was 7.95% and 15.17% higher than at the 130 kg h^{-1} and 100 kg h^{-1}, respectively. Biological yield is the product of the total plant population and productive tillers; the greater the number of tillers, the larger the biological yield [52]. The harvest index is defined as the ratio of grain yield to biological yield. Herbicides had significantly affected the harvest index. The highest harvest index was calculated in the treatments where the higher seed rate of 160 kg h^{-1} and 75% of the recommended dose of herbicide with adjuvant were applied, which was 6.37% and 1.41% higher than the treatments where the seed rate of 130 kg h^{-1} and 100 kg h^{-1} were used. These findings are consistent with those made by [53], who noted a significant herbicide impact on the wheat harvest index. Hence, it is concluded that due to the strong competitive ability of weeds with wheat crops, the management of these weeds needs to be addressed by applying optimum herbicide dosages and selecting the optimum seed rates to avoid grain yield losses.

Conclusion

Field research was conducted to evaluate the influence of different seed rates and herbicide dosages with adjuvants on weed control and wheat yield. The treatments comprised a possible combination of seed rates (100, 130, and 160 kg h^{-1}) and 3 herbicide combinations (100% of the recommended dose of Mesosulfuron-methyl + Iodosulfuron-methyl-sodium (Findus), 75% of the recommended dose, and 75% of the recommended dose + alkyl ether sulfate salt adjuvant). Increasing seed rates from 100 to 160 kg h^{-1} significantly decreased the weed density and fresh and dry biomass. Thirty days after the application of herbicides, weed density, and fresh and dry biomass were significantly decreased in the treatments where a seed rate of 160 kg h^{-1} and 75% of the recommended dose of herbicide with adjuvant were practiced, as compared to the combination of a 100 kg h^{-1} seed rate and 75% of the recommended dose of herbicide alone. The reduced weed biomass resulted in increased productive tillers, spikelets, grains per spike, 1000 grain weight, wheat final yield, biological yield, and harvest index. A higher seed rate of 160 kg h^{-1} and a 75% recommended dose of herbicide mixed with adjuvant significantly increased the wheat yield, biological yield, and harvest index by 26.05%, 21.82%, and 5.39%, respectively, compared with a lower seed rate (100 kg h^{-1}) and 75% of the recommended dose alone. Thus, it can be concluded that the seed rate of 160 kg h^{-1} with post-emergence application of the 75% recommended dose of Mesosulfuron-methyl + Iodosulfuron-methyl-sodium (Findus) + alkyl ether sulfate salt adjuvant at 30 DAS is the most efficient weed management practice for achieving high yields in wheat.

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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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