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RESEARCH ARTICLE

Optimizing nitrogen splitting and herbicide use for weed suppression and yield enhancement in wheat (*Triticum aestivum* L.)

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Abstract

Weeds are one of the most important biological threats in crop production and cause severe irrecoverable losses in crop yields. Therefore, minimizing weed severity is crucial for sustaining and boosting crop productivity. With this aim, a field experiment was conducted during the rabi seasons of 2018-19 and 2019-20 on clay loam soil at the Research Farm of Mata Gujri College, Fatehgarh Sahib (Punjab). Three nitrogen schedules as main plots and five weed management treatments as subplots were arranged in a split-plot design with three replications. Nitrogen scheduling treatments included N_1 (½ Basal + ¼ at 4WAS + ¼ at 8 WAS), N_2 (⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS), N_3 (¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS). Weed management treatments comprised of W_0 (weedy check), W_1 (weed free), W_2 (clodinafop at 60 g ha^{-1}), W_3 (sulfosulfuron at 25 g ha^{-1}) and W_4 (carfentrazone at 20 g ha^{-1}). A significant reduction in weed density, biomass, weed index and NPK uptake by weeds was observed in N_3 (¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS) and W_3 (sulfosulfuron at 25 g ha^{-1}) at 60 DAS and harvest stage. The highest weed control efficiency, yield attributes, crop yield, Net return and B: C ratio were recorded with N_3 (¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS) and W_3 (sulfosulfuron at 25 g ha^{-1}). The increase in grain yield by treatment N_3 (¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS) was 21.2 % over N_1.

Keywords: nitrogen; nutrient depletion; weed management; wheat; yield

Introduction

Wheat (*Triticum aestivum* L.) is one of the important cereal crops as well as a staple food in various continents of the world, including Asia. India has reliably ranked second in global wheat production during the last decade. Worldwide, wheat is grown on an area of 220.60 million hectares with production of 789.50 million tonnes and productivity of 3.58 tonnes ha^{-1} (1). Countries leading in wheat production are China, followed by India, the USA, Russia, France and Australia. In India, wheat crop is cultivated on an areaof about 30.47 million hectares with production and productivity of about 106.84 million tonnes and 3507 kg ha^{-1}, respectively (2). In North-Western India, weeds are a major threat to wheat crop production and cause severe irrecoverable yield losses. Therefore, minimizing weed severity is crucial for sustaining and boosting wheat productivity. The shifting weed flora within wheat fields is rapidly altering, leading to significant challenges for cultivation. The aggressive growth and intense competition of weeds for nutrients, water, light and space severely hamper crop growth and yield potential (3). Therefore, controlling the weed flora to achieve its maximum yield potential is crucial. Wheat crop is sown at narrow row spacing, making mechanical weed control difficult, as it escalates the cost of production. Hence, weed control through herbicides is the best solution for the farmer community. In the mid-1970s, broad-spectrum herbicides like isoproturon, chlortoluron and methabenzthiazuron were recommended for weed control in wheat. But isoproturon quickly gained popularity among farmers in the early years of its recommendation due to its flexible application method and wide application window (4). It became the preferred choice for weed control throughout the 1980s and 1990s (5). The continuous use of isoproturon in the rice-wheat rotations contributed to the resistance of *Phalaris minor* in Haryana, which was also the first case of weed resistance to isoproturon globally (6). Therefore, alternate herbicides such as clodinafop, sulfosulfuron and carfentrazone were introduced to manage resistance in weeds. Thus, the combined use of herbicides with effective N-scheduling was found to lower the load on the environment and provide adequate weed control without any adverse effect on the wheat crop. Nitrogen plays a crucial role in crop production and is required by plants throughout their growth. Wheat, among the major cereal crops, utilizes 1 kg of nitrogen to yield 44 kg of grain. However, plants typically assimilate less than 50 % of the applied nitrogen. In wheat, nitrogen availability has a direct impact on weed competition and the crop's competition ability (7). Increased nitrogen levels enhance the efficacy of herbicides, while nitrogen scheduling influences not only crop growth but also the density and biomass of weeds. Furthermore, proper N splitting and timing ensure continuous availability to the crop and increase nitrogen use efficiency. So, there is a greater need for new formulated herbicides with nitrogen splitting to determine the effect of treatments on the growth and yield of wheat.

Materials and Methods

The field experiment was conducted during the *rabi* (winter) season of 2018-19 and 2019-20 at the Research Farm of Mata Gujri College, Shri Fatehgarh Sahib (76°46' E, 30°39' N and at an elevation of 246 m amsl), Punjab. The average annual rainfall of about 688.7 mm is received from July to September by the southwest monsoon. The normal time of the onset of the monsoon is the last week of July to the first week of August. The region is typically warm and temperate with hot summers from June to September, monsoons in July and cold winters from December to February. The mean daily minimum and maximum temperatures varied between 2.8 to 18.3 °C and 17.2 to 34.3 °C, respectively, in 2018-19, whereas in 2019-20 they were 4.1 to 20.1 °C and 10.2 to 35.6 ° C, respectively, during the growing season (November to April). During 2018-19 and 2019-20, the total rainfall in the crop growing season was 206.8 mm and 210.4 mm, respectively. The experimental site falls in sub-tropical plains of Punjab (Fig. 1). The soil of the experimental field was clay loam with slightly alkaline pH (7.4), EC (0.60 dS m^{-1}), medium level of organic carbon (0.72 %), medium available nitrogen (375 kg ha^{-1}), phosphorus (17.54 kg ha^{-1}) and potassium (177 kg ha^{-1}). The experiment was conducted in split plot design (SPD) replicated thrice with nitrogen scheduling as primary plot treatment, *viz.,* ½ Basal + ¼ at 4 weeks after sowing (WAS) + ¼ at 8 WAS (N_1); ⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS (N_2); and ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS (N_3), while weed management treatments were kept in sub plots, *viz.,* weedy check (W_0); weed free (W_1); clodinafop at 60 g ha^{-1} (W_2); sulfosulfuron at 25 g ha^{-1} (W_3); and carfentrazone at 20 g ha^{-1} (W_4). Wheat variety "PBW 725" was chosen due to its high yield potential, relatively short stature, as well as the fact that this variety responds well to a split N application, which could potentially establish a more competitive canopy, suppressing weed growth. Besides, there was no indication that PBW 725 would have any specific incompatibility with the aforementioned herbicides when applied at recommended rates. It was sown on 10 November 2018 and 11 November 2019 with the *Kera* method at row spacing of 22.5 cm using a seed rate of 100 kg ha^{-1}. A uniform dose of 120, 60 and 40 kg ha^{-1} of N, P_2O_5 and K_2O, respectively, was applied to all treatments. Nitrogen

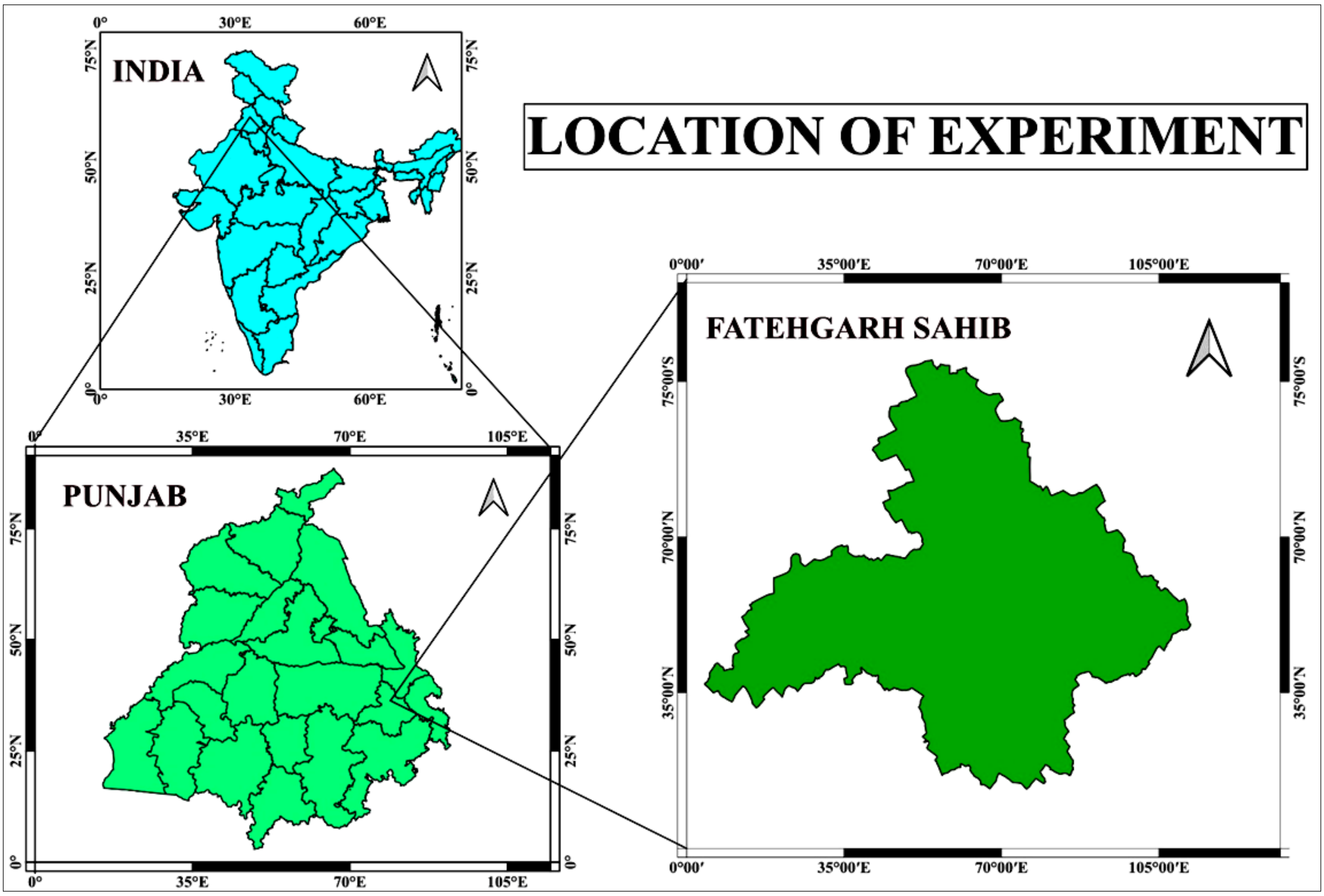

Fig. 1. Location of experimental field conducted at the research farm of Mata Gujri College, Shri Fatehgarh Sahib, Punjab.

was applied as per treatments and full dose of P and K was used as basal at the time of sowing. Due to the critical crop-weed competition stage, weed management treatments were applied at 35 DAS (days after sowing) using a knapsack sprayer fitted with a flat fan nozzle with a spray volume of 500 L ha^{-1}. Field observations were recorded at periodic intervals of 30, 60 and 90 DAS, as well as at the harvest stage. Yield parameters were observed just before the crop was harvested.

Weed dynamics study

Weed density (m^2) and weed biomass (g m^{-2}) were noted for each treatment by using a quadrate of 1 m^2 at periodic intervals (30, 60, 90 DAS and at harvest). The data were transformed using $\sqrt{x+0.5}$ to make the analysis of variance more effective.

Weed control efficiency was estimated based on a reduction in dry matter production in the treated plot compared with the control plot (8).

$$\text{Weed control efficiency (\%)} = \frac{\text{DWC - DWT}}{\text{DWC}} \times 100 \qquad \text{(Eqn. 1)}$$

Whereas, DWC = Weed dry matter in weed check plot, DWT = Weed dry matter in the treated plot, Weed index is the reduction in yield due to the presence of weed in comparison with an unweeded plot (9).

$$\text{Weed Index(\%)} = \frac{\text{X-Y}}{\text{X}} \times 100 \qquad \text{(Eqn. 2)}$$

Whereas, X = Grain yield from the weed-free plot, Y = Grain yield from the treated plot

Yield attributes, yield and economics

The different yield attributes *viz.,* effective tillers (m^2), grain $spike^{-1}$ and 1000-grain weight (g) were recorded before and after the harvesting of the crop and grain and straw yield were recorded from the net plot area of every treatment. Further, an economic analysis was conducted to compare the returns from nitrogen scheduling and weed management. Net returns were determined by subtracting the total production costs from the gross income obtained from wheat grain and straw yield. The expenses of urea, SSP, MOP and all herbicides were calculated. Additionally, various production expenses such as labour (for land preparation, seeding, sowing, weeding, fertilizer application, spraying and harvesting) and chemicals (insecticides and pesticides) were considered.

Statistical analysis

The experiment was laid out in a split-plot design. The mean data for each parameter over two years (2018-19 and 2019-20) were statistically analysed using an analysis of variance (ANOVA) test (10). Additionally, Fisher's test of significance was employed to compare differences between means at the 5 % probability level. All statistical analysis was performed using OP STAT software and graphs were made using MS Excel and R software version 4.2.2.

Results and Discussion

Weed studies

The primary weed species observed in the experimental field included *Phalaris minor* Retz. among grassy weeds, whereas *Chenopodium album* L. and *Cirsium arvense* (L.) Scop. among broad-leaved weeds. Other minor weeds included *Anagallis arvensis* L. and *Rumex dentatus* L. Data further revealed that on pooled basis, treatment N_3 (¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS) recorded significantly lowest weed density [17.74 m^{-2}($\sqrt{x+0.5}$=3.72) and 24.73 m^{-2}($\sqrt{x+0.5}$=4.46)] and weed biomass [30.94 g m^{-2} ($\sqrt{x+0.5}$=4.84) and 64.24 g m^{-2} ($\sqrt{x+0.5}$=6.95)] and highest weed control efficiency (64.84 and 63.08 %) at 60 DAS and harvest stage, respectively. It was found statistically at par with treatment N_2 (1/3 at 4 WAS + 1/3 at 8 WAS +1/3 at 10 WAS) at the 5 % level of significance ($p \le 0.05$) (Table 1). Similarly, N_3 (¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS) recorded significantly lowest weed index (16.88 %) and N, P & K (19.10, 2.70 & 16.86 kg ha^{-1}, respectively) depletion by weed (Fig. 2) which was statistical at par with N_2 at the 5 % level of significance ($p \le 0.05$). This might be because split application of nitrogen provided a continuous supply of nitrogen to the wheat crop and therefore, increased its competitive ability against weeds. It significantly enhanced nitrogen use efficiency and improved crop growth apart from weeds (11–13). The highest weed density [23.00 m^{-2}($\sqrt{x+0.5}$=4.31) and 30.70 m^{-2}($\sqrt{x+0.5}$= 4.97)], biomass [38.71 g m^{-2} ($\sqrt{x+0.5}$=5.51) and 87.51 g m^{-2} ($\sqrt{x+0.5}$=8.29 g m^{-2})] and lowest weed control efficiency (59.34 and 57.81 %) at 60 DAS and at harvest stage were observed under treatment N_1 (½ basal + ¼ at 4 WAS + ¼ at 8 WAS). Likewise, maximum N, P & K (38.48, 6.41 & 21.71 kg ha^{-1}, respectively) depletion by weed and weed index (22.95 %) was recorded under the treatment N_1. Amongst the weed management treatments, minimum weed density [11.11 m^{-2} ($\sqrt{x+0.5}$=3.33) and 19.17 m^{-2} ($\sqrt{x+0.5}$=4.40)], weed biomass [20.04 g m^{-2} ($\sqrt{x+0.5}$= 4.47) and 7.47 g m^{-2} ($\sqrt{x+0.5}$=7.47 g m^{-2})] and highest weed control efficiency (78.32 and 70.73 %) at 60 DAS and harvest stage, respectively were observed under W_3 (sulfosulfuron at 25 g ha^{-1}) and was found statistically at par with W_4 (carfentrazone at 20 g ha^{-1}) and W_2 (clodinafop at 60 g ha^{-1}) at the 5 % level of significance ($p \le 0.05$). Similarly, the lowest weed index (11.94 %) and N, P & K (16.58, 3.22 & 7.86 kg ha^{-1}, respectively) depletion by weed were recorded under W_3 (sulfosulfuron at 25 g ha^{-1}) which was statistically similar to W_4 (carfentrazone at 20 g ha^{-1}) and W_2 (clodinafop at 60 g ha^{-1}) at the 5 % level of significance ($p \le 0.05$). These herbicides can enhance weed control efficacy, particularly in wheat and other cereals. Sulfosulfuron, clodinafop and carfentrazone are three herbicides with distinct modes of action, offering effective weed management. Sulfosulfuron, a systemic sulfonylurea herbicide, controls grassy and broadleaf weeds by inhibiting acetolactate synthase (ALS), disrupting amino acid biosynthesis. N-splitting, which entails applying nitrogen fertilizer in multiple doses throughout the crop growth cycle, can influence the physiological status of weeds. By providing nitrogen in stages, weeds become more metabolically active during key growth periods, which enhances the uptake and

Table 1. Weed density (m^{-2}), weed biomass (g m^{-2}), weed control efficiency (%) and weed index (%) at 60 DAS and at harvest as affected by nitrogen scheduling and weed management in wheat during (Pooled data of two years)

Treatments	Weed density (m^{-2})		Weed biomass (g m^{-2})		Weed control efficiency (%)		Weed index (%)
	60 DAS	At harvest	60 DAS	At harvest	60 DAS	At harvest	
MAIN PLOT (Nitrogen scheduling)							
N_1- ½ basal + ¼ at 4WAS + ¼ at 8 WAS	4.31 (23.00)	4.97 (30.70)	5.51 (38.71)	8.29 (87.51)	59.34	57.81	22.95
N_2- ⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS	3.80 (18.94)	4.52 (25.77)	5.01 (33.10)	7.79 (77.86)	64.27	59.05	19.55
N_3- ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS	3.72 (17.74)	4.46 (24.73)	4.84 (30.94)	6.95 (64.24)	64.84	63.08	16.88
LSD (p=0.05)	0.29	0.40	0.37	0.57	4.89	4.66	9.66
SUB PLOT (Weed management)							
W_0- Weedy check	7.36 (53.84)	8.21 (67.22)	9.62 (92.19)	13.82 (190.92)	0.00	0.00	48.92
W_1- Weed-free	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	100.00	100.00	0.00
W_2- Clodinafop at 60 g ha^{-1}	4.60 (20.89)	5.26 (27.22)	5.85 (34.49)	8.47 (72.20)	62.46	62.19	24.53
W_3- Sulfosulfuron at 25 g ha^{-1}	3.33 (11.11)	4.40 (19.17)	4.47 (20.04)	7.47 (56.27)	78.32	70.73	11.94
W_4- Carfentrazone at 20 g ha^{-1}	3.71 (13.61)	4.67 (21.72)	4.97 (24.52)	7.91 (63.29)	73.28	66.99	13.57
LSD (p=0.05)	0.46	0.39	0.57	0.62	6.81	4.99	5.35
N×W	NS						

Where the original values enclosed in parentheses underwent a square root transformation (before being subjected to statistical analysis- (DAS: days after sowing; WAS: weeks after sowing; NS: non-significant at p ≤ 0.05)

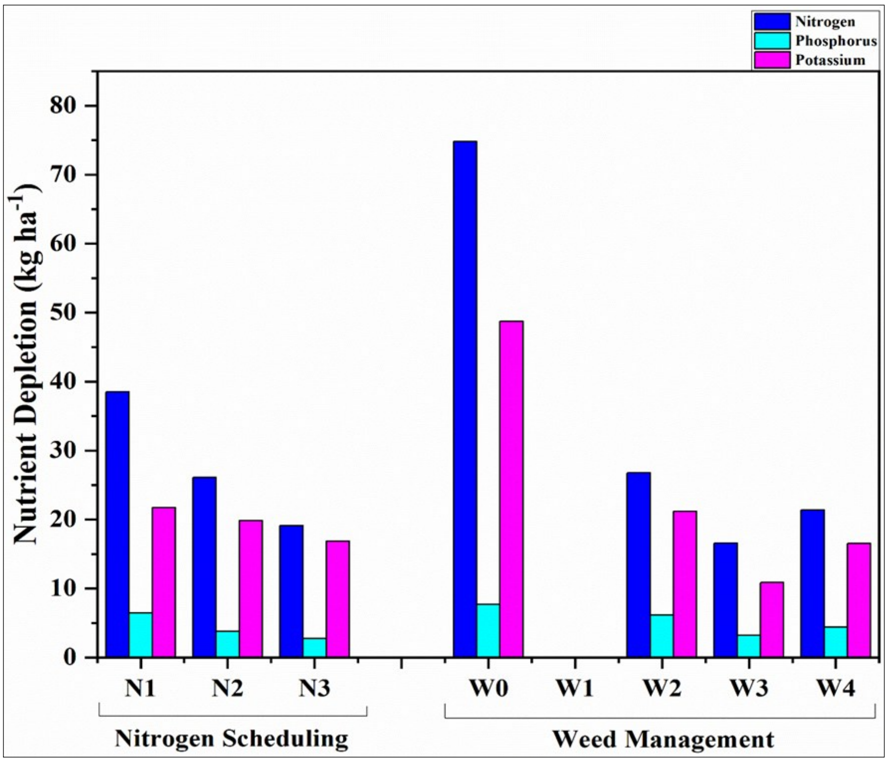

Fig. 2. NPK depletion (kg/ha) by weeds as affected by nitrogen scheduling and weed management in wheat (mean of two years). Treatment symbols indicated by N_1- ½ Basal + ¼ at 4WAS + ¼ at 8 WAS, N_2- ⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS and N_3- ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS, while weed management was kept in sub plots, *viz.* W_0- weedy check, W_1- weed free, W_2- clodinafop at 60 g/ha, W_3- sulfosulfuron at 25 g/ha and W_4- carfentrazone at 20 g/ha. The least significant difference (p=0.05) and standard error of mean between were 2.77; 0.61; 0.68 and 3.58; 0.78; 1.32 respectively.

systemic movement of sulfosulfuron within the plant. This increased activity improves herbicide efficacy, as actively growing weeds are more susceptible to ALS inhibition. Moreover, split nitrogen applications help synchronize weed susceptibility with herbicide application timing, ensuring weeds are targeted when most vulnerable. This approach not only maximizes herbicidal action but also limits early weed competition with crops, contributing to better crop establishment and overall weed management. Besides this, clodinafop also targets grassy weeds by inhibiting acetyl-CoA carboxylase (ACCase), which is essential for lipid synthesis. Similarly, carfentrazone primarily controls broadleaf weeds by inhibiting protoporphyrinogen oxidase (PPO), leading to rapid cell membrane destruction, chlorosis (yellowing of leaves) and eventual plant death (14-16). strategically using these herbicides based on their specific action mechanism, farmers and researchers can optimize weed control. Farmers and researchers can optimize weed control by strategically using these herbicides based on their specific action mechanism while minimizing environmental impact and resistance buildup. The weedy check treatment recorded the highest weed density, weed biomass, NPK depletion by weeds and lowest weed control efficiency due to more infestation of weeds.

ANOVA results showed that the interaction (N × W) between nitrogen scheduling (N) and weed management (W) was non-significant (5 % probability) for weed parameters.

Yield attributes and yield

The yield attributes of wheat, such as effective tillers, grain spike^{-1}, 1000-grain weight, grain and straw yield, were significantly influenced by N schedules and weed management treatments. Significantly higher effective tillers, grains spike^{-1}, 1000-grain weight (132.60 m, 70.00 and 39.98 g, respectively) were observed under N_3 (¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS) and was found statistically at par with N_2 (1/3 at 4 WAS + 1/3 at 8 WAS +1/3 10 WAS) at the 5 % level of significance ($p \leq 0.05$) (Table 2). The minimum yield attributes were recorded under the treatment N_1. This could be attributed to increased nutrient uptake, improved moisture supply and efficient utilization of solar radiations which may have resulted in enhanced growth indices due to nitrogen splitting at the different growth stages of crop and resultant increased productivity through efficient and efficient accumulation of assimilates in the source and improved translocation of photosynthates to the sink and realization of higher economic yield (17). However, in weed management treatments the highest effective tillers, grains spike^{-1}, 1000-grain weight (134.50 m, 74.24 and 39.68 g, respectively) were recorded in W_3 (sulfosulfuron at 25 g ha^{-1}) which was statistically similar with W_4 (carfentrazone at 20 g ha^{-1}) and W_2 (clodinafop at 60 g ha^{-1}) at the 5 % level of significance ($p \leq 0.05$). It could be that effective weed management practices enhance crop growth by minimizing competition between crop and weeds for nutrients, water, space and light. Reduced crop-weed competition improves environmental conditions for the crop's root zone, enabling it to optimize resource utilization. This not only supports vegetative growth but also significantly boosts yield attributes. The weed-free free recorded the highest yield attributes, in contrast to the other treatments. The higher grain and straw yield (4664.50 and 6915.50 kg ha^{-1}, respectively) was recorded in N_3 (¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS) which was statistically at par with N_2 at the 5 % level of significance ($p \leq 0.05$). Application of these treatments increased average grain yield by 21.2 % and 11.5 % over N_1 (½ basal + ¼ at 4 WAS + ¼ at 8 WAS). The correlation analysis showed a significant positive relationship between effective tiller and grain yield at the 5 % level, with a correlation coefficient of 0.94 (Fig. 3). Split application ensures that nitrogen is made available synchronously with key stages of root proliferation and nutrient uptake. This delivery prevents early nitrogen

Table 2. Yield attributes and yield and economics as affected by nitrogen scheduling and weed management in wheat during (Pooled data of two years)

Treatments	Effective tillers (m)	Grains spike^{-1}	1000-grains weight (g)	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index (%)	Net returns ($ ha^{-1})	B : C ratio
MAIN PLOT (Nitrogen scheduling)								
N_1- ½ basal + ¼ at 4WAS + ¼ at 8 WAS	99.90	62.87	38.55	3848.504	5944.00	39.10	501.90	0.79
N_2- ⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS	117.40	67.69	38.59	4291.00	6569.00	39.33	625.37	0.98
N_3- ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS	132.60	70.00	39.98	4664.50	6915.50	40.00	720.69	1.13
LSD (p=0.05)	17.17	5.10	2.55	452.00	585.00	2.26	117.82	0.19
SUB PLOT (Weed management)								
W_0- Weedy check	58.17	48.41	37.55	2719.00	5039.50	35.16	251.93	0.43
W_1- Weed-free	174.84	78.21	40.61	5317.50	7554.00	41.46	773.57	1.03
W_2- Clodinafop at 60 g ha^{-1}	94.17	62.51	38.00	4014.50	5939.50	40.36	561.58	0.93
W_3- Sulfosulfuron at 25 g ha^{-1}	134.50	74.24	39.68	4693.00	6987.50	40.22	758.77	1.25
W_4- Carfentrazone at 20 g ha^{-1}	124.67	70.90	39.34	4596.00	6860.50	40.19	734.08	1.22
LSD (p=0.05)	17.59	5.41	1.97	290.50	626.00	2.60	77.39	0.13
N×W				NS				

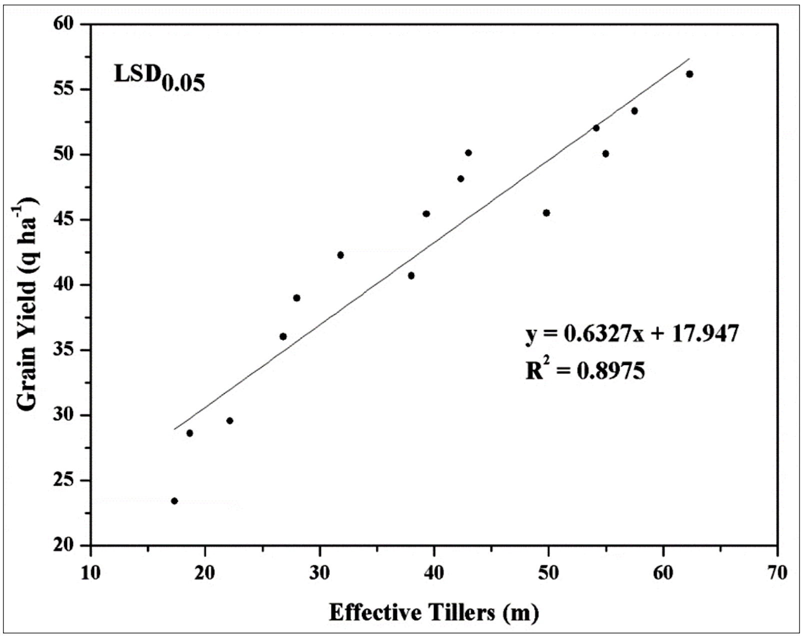

Fig. 3. Linear regression analysis between effective tiller (m) and grain yield (q ha^{-1}) at harvest.

losses such as leaching, volatilization, immobilization and denitrification, promotes deeper root proliferation and also enhances nutrient use efficiency. Due to the continuous availability of nutrients in the root zone, translocation of photosynthates from source to sink among the crop also increased, which contributed to better grain yield (18, 19). The lower grain and straw yield (3848.50 and 5944.00 kg ha^{-1}, respectively) was obtained under treatment N_1 (½ basal + ¼ at 4 WAS + ¼ at 8 WAS). Significantly higher grain and straw yield (4693 and 6987 kg ha^{-1}, respectively) was recorded under treatment W_3 (sulfosulfuron at 25 g ha^{-1}) which was statistically at par with W_4 (carfentrazone at 20 g ha^{-1}) and W_2 (clodinafop at 60 g ha^{-1}) at the 5 % level of significance ($p \leq 0.05$). The average grain yield increased by 72.4, 69 and 46.6 % after the application of W_3 (sulfo-sulfuron at 25 g ha^{-1}) and W_4 (carfentrazone at 20 g ha^{-1}) and W_2 (clodinafop at 60 g ha^{-1}), respectively over weedy check due to higher weed control efficiency (Fig. 4). The correlation analysis showed a significant negative relationship between weed biomass and grain yield at 5 % level, with a correlation coefficient of -0.95 (Fig. 5). The increase in yield attributes was due to minimal crop-weed competition for nutrients, enhanced dry matter accumulation in the crop and effective weed control, all of which contributed to a higher grain and straw yield. The lowest grain and straw yield (2719 and 5039.50 kg ha^{-1}, respectively) was observed in the weedy check treatment. Earlier findings were reported by (20, 21). However, the interaction (N × W) between nitrogen scheduling (N) and weed management (W) was non-significant (5 % probability) for crop yield.

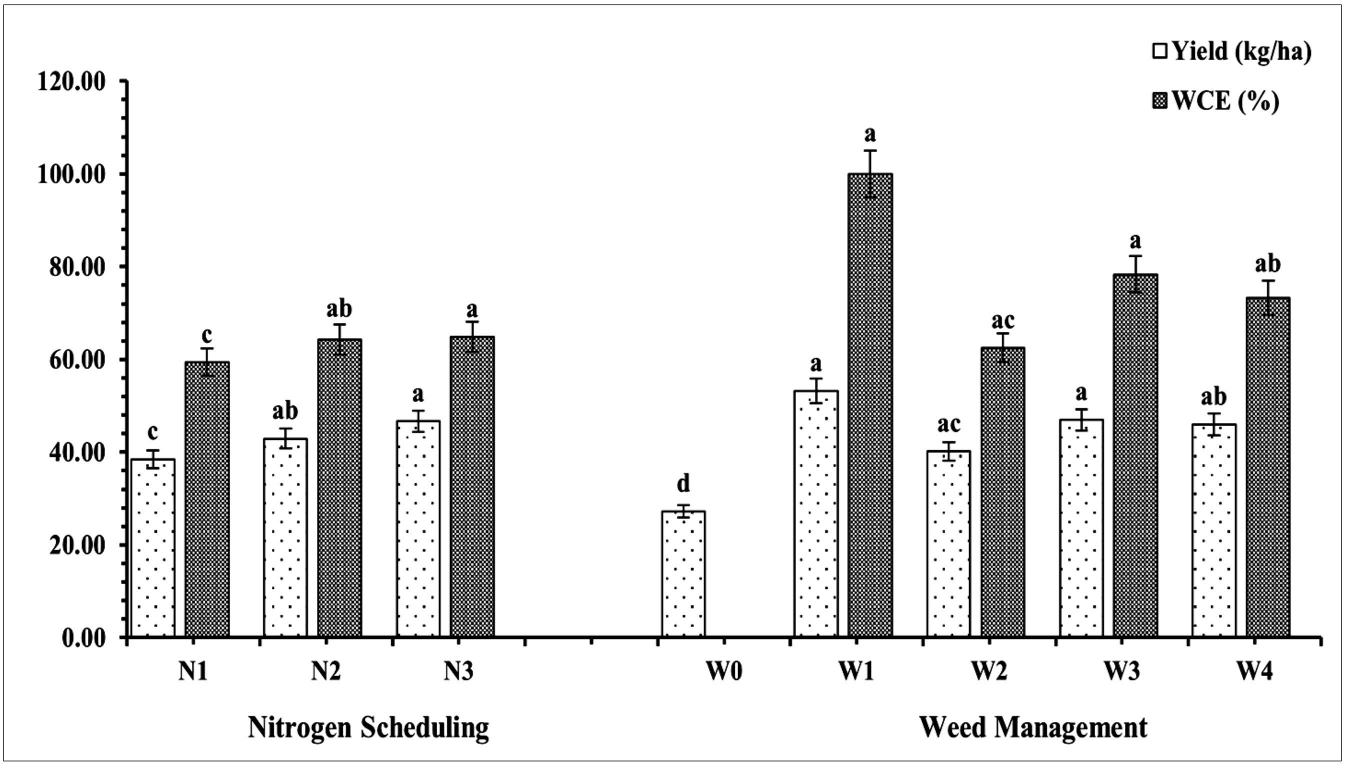

Fig. 4. Comparative graphical representation of grain yield and weed control efficiency.

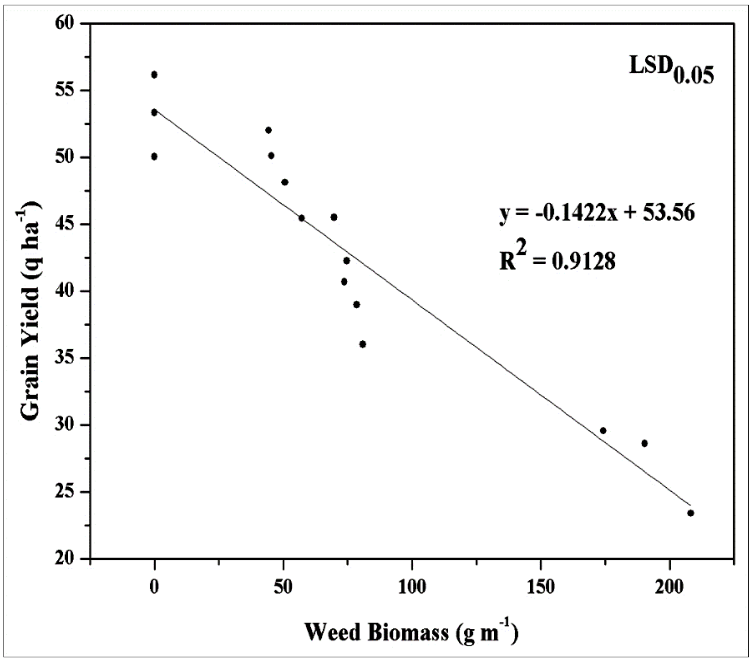

Fig. 5. Linear regression analysis between weed biomass (g m^{-1}) and grain yield (q ha^{-1}) at harvest.

Economics

Nitrogen scheduling and weed management treatments significantly influenced the net returns and B: C ratio. Among nitrogen scheduling treatments, N_3 (¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS) recorded higher net return ($ 720.69) and B: C ratio (1.13) which was statistically at par with that of N_2 (1/3 at 4 WAS + 1/3 at 8 WAS +1/3 10 WAS) on the pooled basis at the 5 % level of significance $(p \leq 0.05)$ (Table 2). Apart from this, weed-free treatment obtained higher net returns ($773.57), whereas the B : C ratio (1.25) was higher under treatment W_3 (sulfosulfuron at 25 g ha^{-1}). This might be the fact that higher grain yield is attained due to continuous nutrient supply and effective weed control and lower cultivation costs. Significantly lower net returns ($501.90) and B: C (0.43) were obtained under N_1 (½ basal + ¼ at 4 WAS + ¼ at 8 WAS) and weedy check treatment. The higher economic returns observed in the treatments above can be linked to the higher yield. factors. These enhancements resulted from nitrogen splitting and effective weed management in the treated plots, which reduced crop-weed competition for nutrients, water, space and light. As a result, the crop demonstrated improved physiological performance, producing superior produce quality and ultimately higher financial returns (22, 23).

Principal component analysis and Pearson's correlation among weed attributes, yield attributes and yield of wheat

Based on mean data from two years (Fig. 6), PCA analysis revealed that the first and second principal components accounted for 89.04 % and 7.08 % of the variation in the weed attributes, yield attributes and yield of wheat, respectively. The results showed a positive correlation between the grain yield, straw yield, effective tillers, grains $spike^{-1}$, test weight and negative correlation with weed density and biomass. Furthermore, the increase in yield attributes and yield was observed under the treatment combination of N_3W_3 than all the other treatments.

Pearson's correlation analysis proved a significant positive correlation among grain yield, straw yield, effective tillers, grains $spike^{-1}$, test weight and a negative correlation with weed density and biomass (Fig. 7).

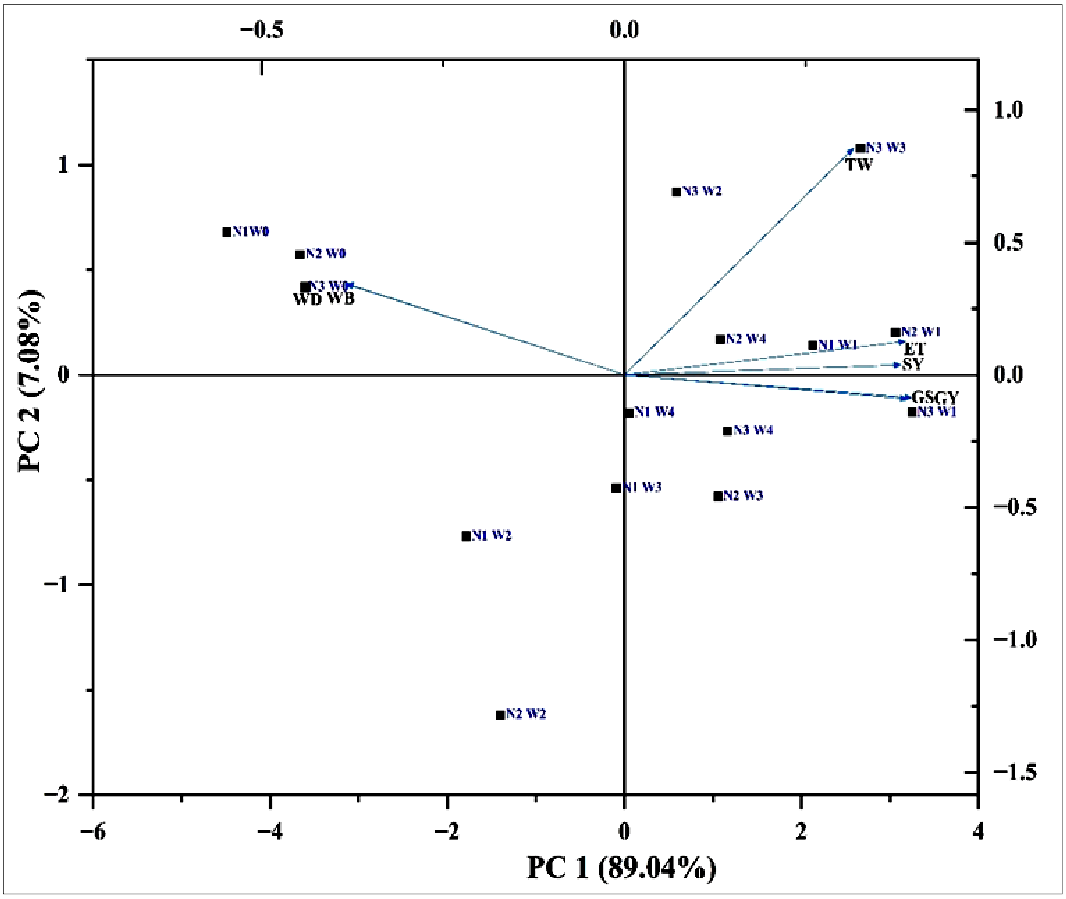

Fig. 6. Principal component analysis (PCA), among weed attributes, yield attributes and wheat yield. GY: grain yield, SY: straw yield, ET: effective tillers, GS: Grains $spike^{-1}$, WD: weed density and WB: weed biomass, N_1W_0: ½ basal + ¼ at 4WAS + ¼ at 8 WAS + Weedy check, N_1W_1: ½ basal + ¼ at 4WAS + ¼ at 8 WAS + Weed free, N_1W_2 : ½ basal + ¼ at 4WAS + ¼ at 8 WAS + Clodinafop at 60 g ha^{-1}, N_1W_3: ½ basal + ¼ at 4WAS + ¼ at 8 WAS + Sulfosulfuron at 25 g ha^{-1}, N_1W_4: ½ basal + ¼ at 4WAS + ¼ at 8 WAS + Carfentrazone at 20 g ha^{-1}, N_2W_0: ⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS + Weedy check, N_2W_1: ⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS + Weed free, N_2W_2 : ⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS + Clodinafop at 60 g ha^{-1}, N_2W_3: ⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS + Sulfosulfuron at 25 g ha^{-1}, N_2W_4: ⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS + Carfentrazone at 20 g ha^{-1}, N_3W_0: ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS + Weedy check, N_3W_1: ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS + Weed free, N_3W_2 : ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS + Clodinafop at 60 g ha^{-1}, N_3W_3: ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS + Sulfosulfuron at 25 g ha^{-1}, N_3W_4: ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS + Carfentrazone at 20 g ha^{-1}.

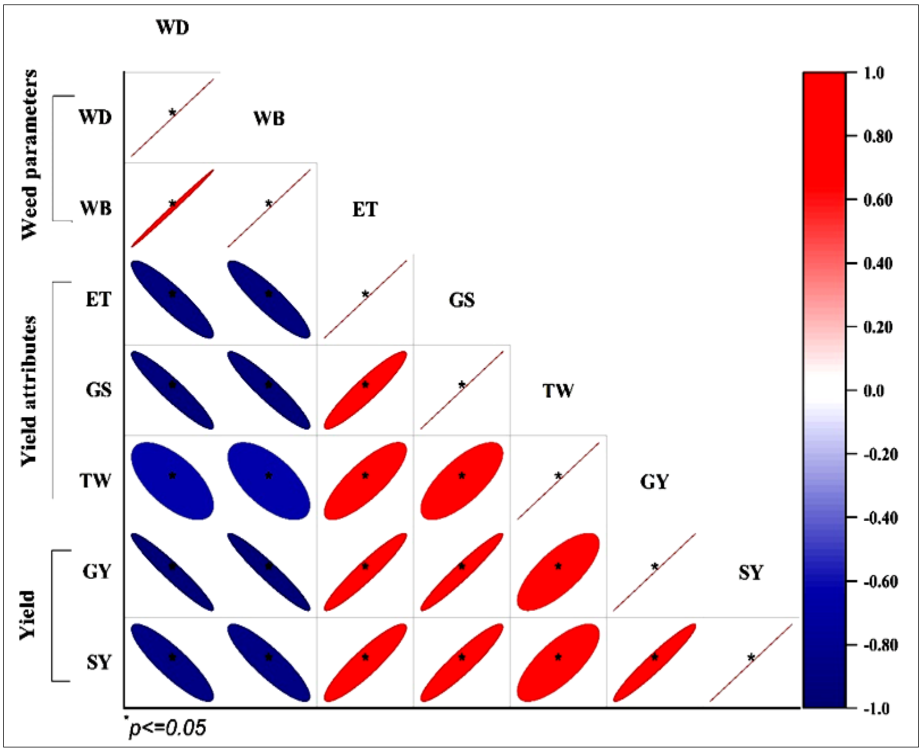

Fig. 7. Pearson's correlation among weed attributes, yield attributes and wheat yield. GY: grain yield, SY: straw yield, ET: effective tillers, GS: Grains spike^{-1}, WD: weed density and WB: weed biomass, N_1W_0: ½ basal + ¼ at 4WAS + ¼ at 8 WAS + Weedy check, N_1W_1: ½ basal + ¼ at 4WAS + ¼ at 8 WAS + Weed free, N_1W_2: ½ basal + ¼ at 4WAS + ¼ at 8 WAS + Clodinafop at 60 g ha^{-1}, N_1W_3: ½ basal + ¼ at 4WAS + ¼ at 8 WAS + Sulfosulfuron at 25 g ha^{-1}, N_1W_4: ½ basal + ¼ at 4WAS + ¼ at 8 WAS + Carfentrazone at 20 g ha^{-1}, N_2W_0: ⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS + Weedy check, N_2W_1: ⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS + Weed free, N_2W_2: ⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS + Clodinafop at 60 g ha^{-1}, N_2W_3: ⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS + Sulfosulfuron at 25 g ha^{-1}, N_2W_4: ⅓ at 4 WAS + ⅓ at 8 WAS + ⅓ at 10 WAS + Carfentrazone at 20 g ha^{-1}, N_3W_0: ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS + Weedy check, N_3W_1: ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS + Weed free, N_3W_2: ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS + Clodinafop at 60 g ha^{-1}, N_3W_3: ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS + Sulfosulfuron at 25 g ha^{-1}, N_3W_4: ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS + Carfentrazone at 20 g ha^{-1}.

Conclusion

Based on the above results, it may be concluded that split application of nitrogen as ¼ at 4 WAS + ¼ at 6 WAS + ¼ at 8 WAS + ¼ at 10 WAS along with sulfosulfuron 25 g ha^{-1} was found to be most effective against the complex weed flora in wheat crop besides giving higher weed control efficiency and grain yield. The correlation studies revealed a significant positive correlation between yield attributes, seed yield, weed density and biomass in the wheat crop. N-splitting and herbicidal application are promising for advancing sustainable and efficient crop production systems. With growing emphasis on resource use efficiency and environmental stewardship, nitrogen splitting offers a strategic approach to match crop nutrient demand more precisely throughout different growth stages. This not only enhances nitrogen use efficiency and minimizes leaching, volatilization and other forms of nutrient loss. When integrated with herbicidal application, it creates a synergistic effect that improves weed control by targeting weeds at their most susceptible stages of growth. This approach has the potential to reduce input cost, enhance yields and promote ecological balance by reducing the risk of herbicide resistance and nutrient runoff.

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Authors' contributions

VB and SK designed and carried out the experiment and wrote the manuscript. MG, RB and B reviewed the manuscript. VK, SJ and DP participated in the sequence alignment. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

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