Agriculture and Food

https://www.aimspress.com/journal/agriculture

AIMS Agriculture and Food, 11(2): 300–319.
DOI: 10.3934/agrfood.2026016
Received: 12 March 2026
Revised: 30 April 2026
Accepted: 18 May 2026
Published: 29 May 2026

Research article

Soil management and weed control affect wheat productivity and resilience in semi-arid systems

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Abstract: Soil management and herbicide selection are vital to wheat production in semi-arid agroecosystems; however, their relative contributions to crop physiology and yield formation remain poorly quantified under field conditions, particularly in semi-arid environments. This study, conducted during the 2025–2026 growing season, evaluated three sulfonylurea-based treatments: Metsulfuron methyl, tribenuron methyl + metsulfuron methyl (mixture), and thifensulfuron methyl in spring wheat under two management systems, conventional tillage (CT) and stubble retention (SR), across two sites in Northern Kazakhstan. Results indicated that canopy development, physiological performance, and grain yield were significantly enhanced ($p < 0.05$) under CT compared with stubble retention, with yield increases ranging from 14% to 65% depending on site and treatment. Herbicide-treated plots recorded a significant 24%–30% higher grain yield than the untreated control, although differences among active ingredients were generally modest. Physiological indices indicated no evidence of herbicide-induced stress at recommended rates, as chlorophyll content (SPAD) and the effective quantum yield of photosystem II remained stable at heading. Strong and moderate positive correlations were observed between grain yield and tillering coefficient and grains per spike ($r = 0.86^{***}$ and $r = 0.47^{**}$, respectively). Yield path analysis further revealed site-specific mechanisms, with tillering coefficient exerting the strongest direct effect on yield at Site A ($\beta = 0.60$), and grains per spike dominating at Site B ($\beta = 0.55$). Hierarchical clustering further revealed that soil management defined overall trait structure, whereas herbicide-related differences were secondary and expressed primarily under favorable conditions. The research findings highlight the predominant role of soil management in regulating wheat productivity and physiological performance. This further emphasizes the importance of integrating effective weed control with adaptive soil management strategies to improve yield stability in semi-arid agroecosystems.

Keywords: wheat; sulfonylurea herbicide; soil management; grain yield; chlorophyll fluorescence

1. Introduction

Wheat (*Triticum aestivum* L.) constitutes a primary cereal crop of global significance, serving as a major component of food security, livestock feed, and agricultural economies across temperate and semi-arid regions [1]. In Kazakhstan, wheat cultivation covers approximately 12.4–13.5 million hectares of arable land [2], producing over 14 million tons of grain annually [3]. However, Northern Kazakhstan, a key agroecological zone contributing more than 75% of the nation's cereal production [4], remains constrained by climatic instability, soil degradation, and, notably, the persistent pressure from broad-leaf and grassy weed species [5]. Weeds represent one of the most significant biotic constraints on wheat production. Globally, yield losses attributable to weed competition are estimated at approximately 13.1% [6]. In Kazakhstan, however, weed infestation remains one of the major constraints to wheat production, particularly in the northern grain-growing regions. Severe weed pressure has been reported to substantially reduce productivity, with weed densities reaching up to 124 plants/m^2, resulting in grain yield decreases of up to 40% in heavily infested fields [7]. Weeds such as field sow thistle (*Cirsium arvense*), field bindweed (*Convolvulus arvensis*), couch grass (*Elytrigia repens*), and especially wild oats (*Avena fatua*) [8] are considered the most harmful, causing wheat yield losses of 30%–40% when not effectively controlled [9]. These substantial yield losses highlight the importance of effective weed management strategies to maintain stable wheat productivity.

Chemical weed control remains indispensable in contemporary wheat production systems [10,11]. Within Kazakhstan's rainfed agroecosystems, numerous investigations have assessed the performance of broad-leaf herbicides in managing weed infestations and improving wheat productivity. Several studies within the rainfed agroecosystem of Kazakhstan have demonstrated the effectiveness of herbicide-based weed control in improving the productivity of wheat, while reducing weed density up to 87.5% [12,13]. However, continued reliance on chemical control has shifted attention toward understanding not only their weed-suppressing capacity but also their broader effects on crop physiology and yield performance [14]. In this context, sulfonylurea (SU) herbicides have become particularly important due to their widespread use, high selectivity, and efficacy at low application rates compared to conventional herbicides [15]. These post-emergence herbicides function by inhibiting the acetolactate synthase (ALS) enzyme, thereby disrupting cell division in meristematic tissues. As a result, plant growth halts shortly after application, followed by chlorosis and subsequent necrosis of affected tissues [16].

While herbicides are vital for weed management, they can also affect primary and secondary metabolism in crops. Their application may alter key physiological functions and, like other abiotic stresses, induce oxidative imbalance [17]. ALS-inhibiting sulfonylurea herbicides, in particular, can cause phytotoxic symptoms as they are absorbed by leaves and translocated to meristematic tissues, where they disrupt growth [18]. Assessing crop responses through physiological indicators is crucial to detecting changes in canopy function beyond yield measurements alone.

In semi-arid systems, studies on several soil management practices have been shown to significantly influence soil water availability, nutrient cycling, grain yield, and canopy development [19,20]. Previous studies have largely examined herbicide and soil management effects separately, with limited investigation of how their combined effect influences wheat physiological response and yield formation. To address this gap, the present study integrates physiological indicators with multivariate analytical approaches to better explain wheat yield responses across contrasting soil management systems. Physiological indices, such as normalized difference vegetation index (NDVI), leaf chlorophyll content, and effective quantum yield of photosystem II, provide sensitive measures of canopy development, chlorophyll status, and photochemical efficiency [21]. These parameters are closely linked to plant photosynthetic capacity and stress response [22], providing valuable insight into crop physiological performance under herbicide application within contrasting soil management systems.

Therefore, the present study aimed to investigate the effects of different sulfonylurea herbicides on wheat physiology, growth, and grain yield, comparing their efficiency under contrasting soil management practices. We further hypothesized that soil management would exert a stronger influence on wheat growth and physiological performance than variation among sulfonylurea herbicides, and that ALS-inhibiting herbicides applied at recommended rates would not induce measurable physiological stress in wheat.

2. Materials and methods

2.1. Study area and climate

The research was conducted during the 2025–2026 growing season at the A.I. Barayev Grain Institute, Shortandy, and Akmola Phoenix Research Experimental Field, both located in the Akmola region of Northern Kazakhstan, with coordinates 51°37’41N, 71°02’14E and 51°01’13N, 70°38’30E, respectively. The climate profiles of both experimental sites (Figure 1) reflect a strongly continental regime characterized by severe winters, rapid spring warming, and moderate summer conditions. Winter temperatures routinely fall below -20 °C, whereas summer maximum temperatures exceed 30 °C. Humidity remains high during winter and declines through summer as evaporative demand increases. Precipitation is concentrated between April and August, coinciding with the main crop-growing period. Total warm-season rainfall is approximately 233.7 mm at the Barayev Grain Institute and 344.4 mm at the Akmola Phoenix Research Experimental Field, providing essential but variably distributed moisture.

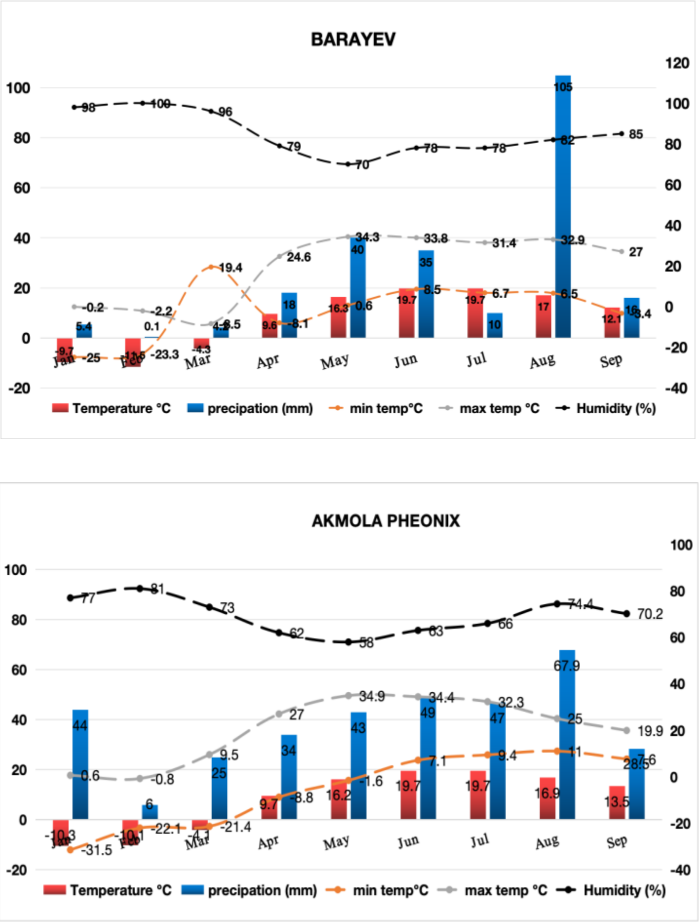


Figure 1. Agrometeorological conditions during the 2025–2026 wheat growing season at the experimental locations (https://www.kazhydromet.kz).

2.2. Experimental design and treatments

A split-plot design was implemented, with soil management as the main plot and herbicide treatment as the subplot factor, with three replications per experimental field. Each field covered 0.06 ha, divided into 15 subplots, each measuring 4 × 10 m (40 m^2). Spring wheat Taimas variety was sown in mid-spring using an LV-Service mechanical grain drill (row seeder), calibrated to a seeding rate of 260 seeds/m^2 and set to place seeds at a uniform depth of 6 cm. The experimental treatments consisted of four sulfonylurea (SU) herbicides and one untreated control plot (weedy control). The herbicides contained three main active ingredients: Metsulfuron methyl, tribenuron methyl, and thifensulfuron methyl, applied at recommended rates of 15 g/ha (Table 1). Treatments were evaluated under two management systems: Conventional tillage (CT) and stubble retention (SR). Herbicides were applied at early tillering, after wheat germination, using a 10-L knapsack sprayer with a flat-fan spray nozzle operated at 2 bar. Within each replicate block, herbicide treatments were randomly assigned to subplot units to avoid positional bias.

Table 1. Herbicide treatments and application rates.

Herbicide	**Active ingredient**	**Dose**
Plugger	Tribenuron methyl 625 g/kg + metsulfuron methyl 125 g/kg	15 g/ha a.i.
Alcion	Thifensulfuron methyl 750 g/kg	
Supermet Extra	Metsulfuron methyl 600 g/kg	
Finito Duet 750	Tribenuron methyl 625 g/kg + metsulfuron methyl 125 g/kg	
	Location	
Site A	A.I. Barayev Grain Institute, Shortandy	
Site B	Akmola Phoenix Research Experimental Field	

2.3. Data collection

Field measurements were taken at three developmental stages: Heading (June), milk ripening (July), and harvest maturity (September). Ten plant samples were randomly selected at each growth stage for structural traits. Sampling was done destructively at each growth stage. Chlorophyll content was measured on flag leaves using a SPAD-502 Plus chlorophyll meter (Konica Minolta, Japan). Vegetative index measurements (NDVI) were obtained using a handheld GreenSeeker crop sensor. Photosynthetic performance was evaluated using a Mini-PAM-II chlorophyll fluorescence analyzer (Walz, Germany) to determine the effective quantum yield Y(II) at different growth stages under light-adapted conditions. The measured parameters were steady-state fluorescence (Fs) and maximal fluorescence under actinic light (Fm'). At crop maturity, quadrat-based sampling (1 m^2) was conducted to determine yield components, including plant height, spike length, number of productive stems, number of grains per spike, 1000-grain weight, grain weight per spike, and final grain yield.

2.4. Statistical analysis

Plant data were subjected to a three-way analysis of variance (ANOVA) to evaluate the effects of location, management practice, and herbicide and their interactions. Location, management practice, and herbicide treatments were treated as fixed effects, while replicate blocks were considered random effects. Normality of residuals was assessed using the Shapiro–Wilk test, while homogeneity of variances was evaluated using Levene's test. Mean separation was conducted using Tukey's HSD test at $p < 0.05$. Multivariate analyses were performed to further characterize treatment responses. A correlation heatmap was used to examine relationships among physiological traits, growth parameters, and yield components. Hierarchical cluster analysis was also used to classify herbicide treatments and management systems based on their similarity in physiological and agronomic responses. A yield component path analysis was developed in R (lavaan/semPlot package) to quantify direct and indirect contributions of physiological traits and yield components to final grain yield. All analyses were conducted using Minitab v17 for ANOVA and post hoc tests, and RStudio for multivariate and path analyses.

3. Results

3.1. Herbicide and soil management effects on plant growth

The main effects of herbicide application, soil management practice, and location were statistically significant ($p < 0.05$) for most wheat growth parameters, except for leaf area and leaf area index (LAI) at heading (Table 2). During heading, herbicide treatments resulted in greater plant height compared with the untreated control. At milk ripening, the control recorded the greatest plant height (75.50 cm), while plots treated with tribenuron methyl + metsulfuron methyl showed the highest value among the treated plots (73.94 cm); however, differences among herbicide treatments were not statistically significant ($p > 0.05$). Plant height during milk ripening was higher at Site A (78.46 cm) than at Site B, despite comparatively lower values at heading. Across both phenological stages, wheat growth was consistently greater under CT than under stubble management.

The three-way interaction among herbicide, soil management, and location (H × SM × L) significantly influenced several growth indices (Table 3). The interaction effect was significant for plant height and leaf area index ($p < 0.001$) at both growth stages, indicating varied responses across experimental sites and management systems.

3.2. Herbicide and soil management effects on yield parameters

Herbicide application significantly affected all measured yield parameters ($p < 0.05$) (Table 4). In contrast, soil management practice and location did not significantly influence plant density or the number of grains per spike ($p > 0.05$). Grain yield differed significantly between herbicide-treated plots and the untreated control, with higher values recorded under herbicide application. Yield values in herbicide-treated plots ranged from 15.23 to 15.90 c/ha, compared with 12.27 c/ha in the control; however, differences among the herbicide treatments were not statistically significant ($p > 0.05$). Yield increases were accompanied by higher thousand-grain weight (TGW) and greater numbers of productive stems. TGW values ranged from 32.70 to 33.57 g under herbicide treatments, compared with 31.47 g in the control plots, while the number of productive stems increased from 144 stems/m^2 in the control to 171–177 stems/m^2 in treated plots. Tillering coefficient was significantly higher under tribenuron methyl + metsulfuron methyl, thifensulfuron methyl, and metsulfuron methyl (600 g/kg) treatments than in the untreated control ($p < 0.05$).

Soil management practice exerted a strong influence on yield formation. Conventional tillage significantly increased grain yield (19.56 c/ha), TGW (33.70 g), number of productive stems (200 m^2), and tillering coefficient (1.68) relative to stubble management (10.24 c/ha, 31.94 g, 137 m^2, and 1.16, respectively; $p < 0.05$). Plant density did not differ between management systems, indicating that yield differences were primarily associated with tillering and grain mass rather than stand establishment.

Location had a significant effect on most yield components ($p < 0.05$). Higher grain yield (17.75 c/ha), TGW (33.27 g), number of productive stems (195 m^2), and tillering coefficient (1.61) were observed at Site A compared with Site B (12.05 c/ha, 32.36 g, 143 m^2, and 1.23, respectively). However, the number of grains per spike showed no significant difference between locations (p = 0.588). The interactive effect (H × SM × L) was not significant for yield and yield-related traits ($p > 0.05$) (Table 5), indicating a consistent response of wheat to herbicide application across management systems and experimental sites.

Table 2. Main effects of herbicide treatment, soil management system, and location on wheat growth parameters.

Herbicide	Plant height (heading)	Plant height (milk ripeness)	Leaf area (heading)	Leaf area (milk ripeness)	LAI (heading)	LAI (milk ripeness)
Control	51.49c	75.50a	8.78a	8.35a	0.12a	0.11a
Tribenuron methyl + metsulfuron methyl (P)	63.54a	70.95c	9.12a	8.46a	0.13a	0.12a
Tribenuron methyl + metsulfuron methyl (FD)	61.79a	73.94ab	9.46a	9.26a	0.12a	0.12a
Thifensulfuron methyl	64.12a	72.20bc	9.96a	3.31c	0.12a	0.04c
Metsulfuron methyl	58.43b	70.26c	9.77a	5.61b	0.12a	0.07b
Soil management						
Conventional tillage (CT)	64.48a	84.45a	11.19a	11.81a	0.15a	0.16a
Stubble retention (SR)	55.27b	60.70b	7.64b	2.18b	0.10b	0.02b
Location						
Site B	61.61a	66.68b	10.64a	5.90b	0.14a	0.08b
Site A	58.14b	78.46a	8.20b	8.09a	0.11b	0.11a
***p*-values**						
H	0.000	0.000	0.174^{ns}	0.000	0.540^{ns}	0.000
SM	0.000	0.000	0.000	0.000	0.000	0.000
L	0.000	0.000	0.000	0.000	0.000	0.000

*Note: Means with different letters are significantly different ($p < 0.05$). **H**: Herbicide, **SM**: Soil management, **L**: Location, **ns**; not significant, 0.001***, 0.01**. 1 c/ha = 100 kg/ha. Tribenuron methyl + metsulfuron methyl (P): Plugger, tribenuron methyl + metsulfuron methyl (FD): Finito Duet.

Table 3. Interactive effects of herbicide application and soil management on wheat growth across two experimental sites.

Herbicides	Soil management	Plant height (heading)	Plant height (milk ripeness)	Leaf area (heading)	Leaf area (milk ripeness)	LAI (heading)	LAI (milk ripeness)
Site A							
Control	CT	37.77 ± 1.7^{i}	88.07 ± 1.2^{ab}	10.24 ± 0.4^{ab}	13.73 ± 0.7^{a}	0.14 ± 0.0^{ab}	0.19 ± 0.0^{a}
	SR	55.03 ± 2.8^{ef}	78.70 ± 2.3^{cd}	3.78 ± 0.3^{e}	5.93 ± 1.7^{c}	0.05 ± 0.0^{f}	0.08 ± 0.0^{c}
Tribenuron methyl + metsulfuron methyl (P)	CT	66.33 ± 1.6^{abc}	83.70 ± 1.8^{c}	11.99 ± 0.3^{ab}	14.09 ± 0.4^{a}	0.17 ± 0.0^{a}	0.20 ± 0.0^{a}
	SR	59.63 ± 2.4^{cde}	71.20 ± 2.0^{e}	6.08 ± 0.3^{cde}	5.67 ± 1.1^{c}	0.09 ± 0.0^{ef}	0.08 ± 0.0^{c}
Tribenuron methyl + metsulfuron methyl (FD)	CT	69.47 ± 0.9^{a}	93.67 ± 0.6^{a}	11.55 ± 0.9^{ab}	15.61 ± 1.8^{a}	0.16 ± 0.0^{ab}	0.21 ± 0.0^{a}
	SR	52.23 ± 4.4^{fg}	71.65 ± 5.3^{de}	5.81 ± 0.3^{de}	5.82 ± 1.1^{c}	0.08 ± 0.0^{ef}	0.07 ± 0.0^{c}
Thifensulfuron methyl	CT	69.13 ± 0.6^{a}	82.70 ± 0.3^{bc}	11.02 ± 0.6^{ab}	5.63 ± 1.2^{c}	0.14 ± 0.0^{abc}	0.07 ± 0.0^{c}
	SR	64.83 ± 1.8^{abcd}	64.63 ± 1.9^{ef}	5.90 ± 0.5^{de}	2.01 ± 0.1^{d}	0.08 ± 0.0^{ef}	0.03 ± 0.0^{d}
Metsulfuron methyl	CT	66.73 ± 2.4^{abc}	86.57 ± 0.2^{ab}	10.90 ± 0.7^{ab}	10.04 ± 0.5^{b}	0.14 ± 0.0^{abc}	0.14 ± 0.0^{b}
	SR	40.27 ± 2.1^{hi}	63.80 ± 1.7^{f}	4.72 ± 0.8^{de}	2.40 ± 0.8^{d}	0.06 ± 0.0^{f}	0.03 ± 0.0^{d}
Site B							
Control	CT	66.61 ± 0.9^{abc}	84.50 ± 0.2^{bc}	12.77 ± 1.5^{a}	13.73 ± 0.7^{a}	0.18 ± 0.0^{a}	0.19 ± 0.0^{a}
	SR	46.57 ± 3.1^{gh}	50.77 ± 1.2^{g}	8.33 ± 0.9^{bcd}	0.00 ± 0.0^{d}	0.12 ± 0.0^{cde}	0.00 ± 0.0^{d}
Tribenuron methyl + metsulfuron methyl (P)	CT	66.89 ± 0.6^{ab}	79.10 ± 4.2^{c}	8.50 ± 1.5^{bcd}	14.09 ± 0.4^{a}	0.12 ± 0.0^{cde}	0.20 ± 0.0^{a}
	SR	61.33 ± 2.9^{bcde}	49.83 ± 2.8^{g}	9.94 ± 2.1^{abc}	0.00 ± 0.0^{d}	0.15 ± 0.0^{ab}	0.00 ± 0.0^{d}
Tribenuron methyl + metsulfuron methyl (FD)	CT	67.93 ± 0.4^{ab}	81.47 ± 1.9^{bc}	10.26 ± 0.1^{ab}	15.61 ± 1.8^{a}	0.13 ± 0.0^{abc}	0.21 ± 0.0^{a}
	SR	57.53 ± 2.7^{ef}	49.00 ± 1.4^{g}	10.23 ± 1.8^{ab}	0.00 ± 0.0^{d}	0.13 ± 0.0^{abc}	0.00 ± 0.0^{d}
Thifensulfuron methyl	CT	65.58 ± 1.5^{abc}	82.80 ± 0.9^{bc}	12.78 ± 3.4^{a}	5.60 ± 1.2^{c}	0.17 ± 0.0^{abc}	0.07 ± 0.0^{c}
	SR	56.93 ± 4.4^{ef}	58.67 ± 2.7^{f}	10.18 ± 0.3^{ab}	0.00 ± 0.0^{d}	0.13 ± 0.0^{ab}	0.00 ± 0.0^{d}
Metsulfuron methyl	CT	68.41 ± 0.8^{ab}	81.93 ± 1.1^{bc}	11.97 ± 1.7^{ab}	10.00 ± 0.5^{b}	0.15 ± 0.0^{ab}	0.12 ± 0.0^{b}
	SR	58.33 ± 2.0^{def}	48.77 ± 4.4^{g}	11.50 ± 1.8^{ab}	0.00 ± 0.0^{d}	0.15 ± 0.0^{ab}	0.00 ± 0.0^{d}
***p*-values**							
H × SM × L		0.000***	0.000***	0.067^{ns}	0.019**	0.039**	0.004**

*Note: Means with different letters are significantly different ($p < 0.05$). **H**: Herbicide, **SM**: Soil management, **L**: Location, **ns**; not significant, 0.001***, 0.01**. 1 c/ha = 100 kg/ha. Tribenuron methyl + metsulfuron methyl (P): Plugger, tribenuron methyl + metsulfuron methyl (FD): Finito Duet.

Table 4. Main effects of herbicide treatment, soil management system, and location on wheat yield parameters.

Herbicide	Number of plants per m^2	Number of productive stems	Tillering coefficient (TC)	Grains per spike	TWG	Yield (c/ha)
Control	115b	144b	1.24b	25.47b	31.47b	12.27b
Tribenuron methyl + metsulfuron methyl (P)	127a	177a	1.37ab	25.9ab	33.57a	15.90a
Tribenuron methyl + metsulfuron methyl (FD)	117b	176a	1.49a	25.9b	33.36a	15.40a
Thifensulfuron methyl	116b	177a	1.51a	24.9b	33.26a	15.24a
Metsulfuron methyl	115b	171a	1.49a	28.3a	32.70ab	15.87a
Soil management						
Conventional tillage (CT)	118a	200a	1.68a	28.5a	33.70a	19.56a
Stubble retention (SR)	118a	137b	1.16b	23.4b	31.94b	10.24b
Location						
Site B	121a	143b	1.23b	25.8a	32.36b	12.05b
Site A	115b	195a	1.61a	26.1a	33.27a	17.75a
***p*-values**						
H	0.000	0.000	0.000	0.002	0.001	0.001
SM	0.736^{ns}	0.000	0.000	0.000	0.000	0.000
L	0.000	0.000	0.000	0.588^{ns}	0.004	0.000

*Note: Means with different letters are significantly different ($p < 0.05$). **H**: Herbicide, **SM**: Soil management, **L**: Location, **ns**; not significant, 0.001***, 0.01**. 1 c/ha = 100 kg/ha. Tribenuron methyl + metsulfuron methyl (P): Plugger, tribenuron methyl + metsulfuron methyl (FD): Finito Duet.

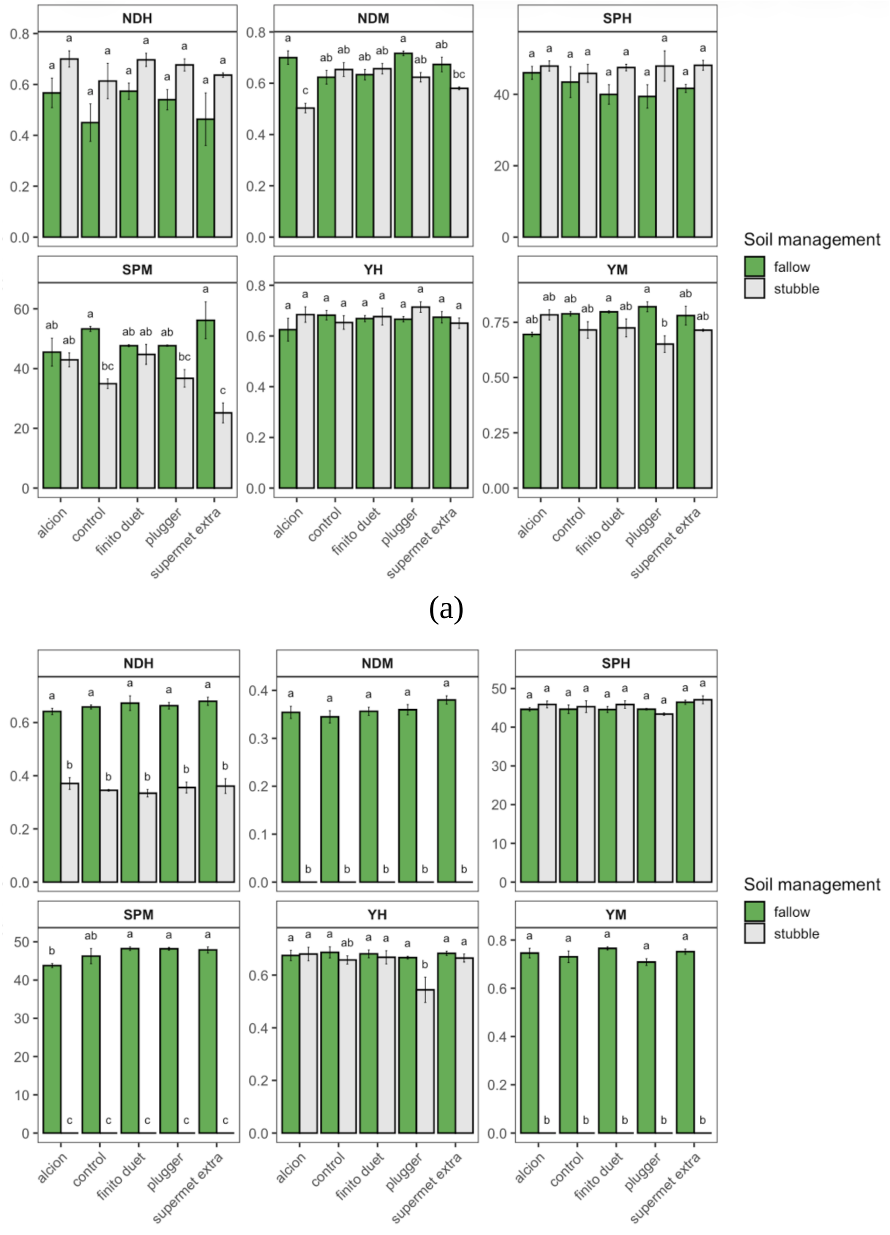
Table 5. Interactive effect of herbicide and soil management effects on yield components and grain yield of wheat across two experimental sites.

Herbicides	Soil management	Number of plants per m^2	Number of productive stems	Tillering coefficient (TC)	Grains per spike	TWG	Yield (c/ha)
Site A							
Control	CT	121.00 ± 3.6^{ab}	202.67 ± 5.7^{bc}	1.68 ± 0.1^{cd}	30.33 ± 2.1^{a}	35.90 ± 0.8^{a}	22.04 ± 0.8^{a}
	SR	111.00 ± 16.7^{b}	118.70 ± 18.0^{e}	1.07 ± 0.0^{e}	25.00 ± 2.6^{cd}	28.63 ± 1.3^{d}	8.44 ± 1.0^{cd}
Tribenuron methyl +	CT	130.67 ± 6.8^{a}	256.30 ± 36.0^{a}	1.96 ± 0.2^{bc}	30.33 ± 1.5^{a}	34.93 ± 0.7^{ab}	27.32 ± 5.3^{a}
metsulfuron methyl (P)	SR	130.33 ± 5.1^{a}	150.00 ± 29.7^{de}	1.15 ± 0.2^{e}	20.00 ± 1.8^{de}	34.00 ± 1.4^{ab}	10.11 ± 1.4^{bcd}
Tribenuron methyl +	CT	120.67 ± 2.5^{ab}	250.00 ± 21.0^{ab}	2.07 ± 0.2^{ab}	29.33 ± 3.2^{a}	34.57 ± 0.8^{ab}	25.39 ± 3.9^{a}
metsulfuron methyl (FD)	SR	120.33 ± 5.5^{ab}	170.00 ± 29.7^{cd}	1.42 ± 0.3^{de}	19.67 ± 1.4^{e}	32.20 ± 0.6^{bc}	10.72 ± 1.5^{bcd}
Thifensulfuron methyl	CT	121.00 ± 4.0^{ab}	259.33 ± 12.4^{a}	2.14 ± 0.1^{ab}	29.00 ± 3.0^{a}	34.57 ± 1.0^{ab}	26.14 ± 4.4^{a}
	SR	116.67 ± 3.8^{ab}	136.67 ± 8.6^{de}	1.17 ± 0.0^{e}	22.33 ± 1.5^{de}	32.10 ± 0.4^{bcd}	9.83 ± 1.3^{bcd}
Metsulfuron methyl	CT	112.33 ± 6.4^{b}	263.70 ± 30.9^{a}	2.35 ± 0.3^{a}	29.00 ± 1.0^{a}	32.73 ± 0.3^{ab}	25.03 ± 3.0^{a}
	SR	126.67 ± 5.9^{ab}	144.27 ± 5.5^{de}	1.14 ± 0.0^{e}	26.33 ± 1.5^{cd}	33.07 ± 0.5^{ab}	12.55 ± 0.6^{bcd}
Site B							
Control	CT	116.33 ± 2.5^{ab}	133.67 ± 4.2^{de}	1.15 ± 0.0^{e}	26.57 ± 0.7^{cd}	32.23 ± 0.7^{bc}	11.45 ± 0.5^{bcd}
	SR	112.33 ± 2.5^{b}	124.00 ± 3.0^{de}	1.10 ± 0.0^{e}	20.00 ± 4.6^{de}	29.10 ± 0.2^{cd}	7.19 ± 1.4^{d}
Tribenuron methyl +	CT	122.00 ± 4.0^{ab}	159.67 ± 6.7^{cde}	1.31 ± 0.0^{de}	28.57 ± 0.7^{ab}	33.37 ± 0.9^{ab}	15.24 ± 1.3^{b}
metsulfuron methyl (P)	SR	125.67 ± 1.5^{ab}	137.00 ± 2.6^{de}	1.09 ± 0.0^{e}	24.97 ± 0.9^{cde}	32.00 ± 1.3^{bcd}	10.95 ± 0.8^{bcd}
Tribenuron methyl +	CT	117.33 ± 2.5^{ab}	162.33 ± 9.1^{cde}	1.38 ± 0.1^{de}	27.40 ± 0.5^{abc}	33.60 ± 0.7^{ab}	14.94 ± 0.7^{bc}
metsulfuron methyl (FD)	SR	111.67 ± 1.5^{b}	124.33 ± 2.5^{de}	1.11 ± 0.0^{e}	25.00 ± 4.0^{cd}	31.90 ± 2.8^{ab}	9.87 ± 1.4^{bcd}
Thifensulfuron methyl	CT	113.67 ± 1.5^{b}	160.33 ± 5.9^{cde}	1.41 ± 0.1^{de}	26.80 ± 0.6^{cd}	32.70 ± 0.3^{ab}	14.06 ± 0.9^{bc}
	SR	114.33 ± 0.6^{ab}	151.67 ± 6.4^{de}	1.33 ± 0.1^{de}	21.43 ± 0.7^{cde}	33.70 ± 1.5^{ab}	10.94 ± 0.4^{bcd}
Metsulfuron methyl	CT	110.33 ± 3.5^{b}	115.7 ± 7.0^{cde}	1.40 ± 2.3^{de}	28 ± 0.4^{ab}	32 ± 0.7^{ab}	14.1 ± 0.7^{bc}
	SR	111.67 ± 2.1^{b}	122.00 ± 3.6^{de}	1.09 ± 0.0^{e}	29.67 ± 0.4^{a}	32.70 ± 1.8^{bc}	11.83 ± 0.5^{bcd}
***p*-values**							
H x SM x L		0.147^{ns}	0.135^{ns}	0.054^{ns}	0.073^{ns}	0.059^{ns}	0.683^{ns}

*Note: Means with different letters are significantly different ($p < 0.05$). **H**: Herbicide, **SM**: Soil management, **L**: Location, **ns**; not significant, 0.001***, 0.01**. 1 c/ha = 100 kg/ha. Tribenuron methyl + metsulfuron methyl (P): Plugger, tribenuron methyl + metsulfuron methyl (FD): Finito Duet.

3.3. *NDVI, chlorophyll index, and photosynthetic efficiency index*

Normalized difference vegetation index (NDVI), leaf chlorophyll content (SPAD units), and photosynthetic yield Y(II) varied with soil management system, location, and growth stage (Figure 2). Across both sites, NDVI values were consistently higher under conventional tillage (CT) than under stubble management, indicating greater canopy development and biomass accumulation.



(a)

(b)

Figure 2. Normalized Difference Vegetation Index (NDH, NDM), leaf chlorophyll content (SPH, SPM), and photosystem II efficiency (YII) (YH, YM) of wheat at heading (H) and milk ripening (M) under different herbicide treatments and soil management systems. (a) Site A; (b) Site B.

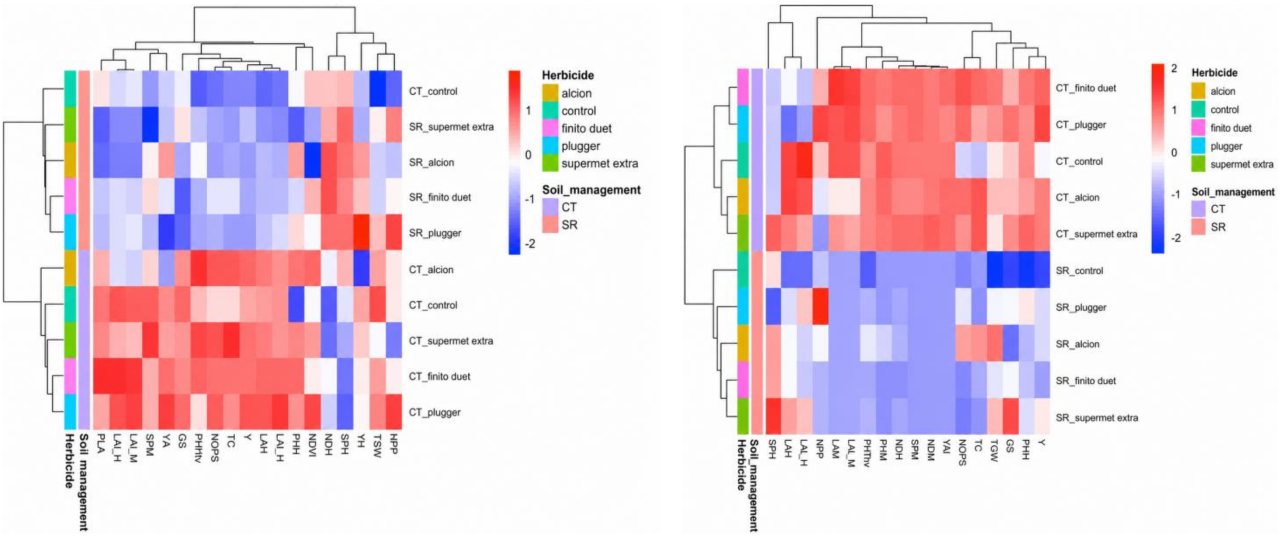
At heading, vegetative index values in the untreated control ranged from 0.35 to 0.62, while herbicide-treated plots showed slightly higher values (0.38–0.70). Generally, NDVI increased from heading to milk ripening, particularly under conventional tillage (CT). Although differences among herbicide treatments within each management system were largely nonsignificant, plots receiving thifensulfuron methyl and tribenuron methyl + metsulfuron methyl exhibited comparatively higher NDVI values at milk ripening, especially at Site A. In contrast, NDVI values under stubble management at Site B remained uniformly low or were not recorded during milk ripening due to early crop maturation and advanced leaf senescence, which reduced green cover and limited the reliability of physiological measurements, affecting both SPAD and Y(II) measurements under the same conditions.

Leaf chlorophyll content (SPAD) also showed limited variation among treatments at heading, declining across all treatments by milk ripening, with values ranging from 40 to 50 units at both sites. Though higher SPAD values were consistently observed under conventional tillage (CT), indicating delayed senescence and improved chlorophyll retention, stubble management was associated with lower values and greater separation between management systems. Photosynthetic efficiency Y(II) equally exhibited similar trends. Y(II) values showed minimal variation among treatments at heading, while at milk ripening, clearer differences emerged. Under conventional tillage (CT), Y(II) remained relatively high, whereas under stubble management, reduced values were observed, particularly in plots receiving tribenuron methyl + metsulfuron methyl. At Site B, Y(II) values under stubble management approached zero or were not recorded due to advanced senescence at the time of measurement.

Photosynthetic efficiency Y(II) varied with herbicide treatment, soil management system, location, and growth stage. At the heading, Y(II) values exhibited limited variation among treatments at both sites. At Site A, YH values under conventional tillage ranged from 0.62 to 0.70, with plots receiving thifensulfuron methyl, tribenuron methyl + metsulfuron methyl, and metsulfuron methyl recording values comparable to or slightly higher than the control. Under stubble management, YH values ranged from 0.64 to 0.72, although plots receiving tribenuron methyl + metsulfuron methyl recorded lower values relative to the control. At Site B, YH values under conventional tillage ranged from 0.66 to 0.70, with no pronounced differences between herbicide-treated plots and the control, whereas under stubble management, lower YH values were again observed in plots receiving tribenuron methyl + metsulfuron methyl.

3.4. Cluster heatmap, yield path analysis, and correlation between plant parameters

Hierarchical clustering of mean values for agronomic, physiological, and yield-related traits demonstrated clear grouping patterns driven primarily by soil management system and secondarily by herbicide treatment at both experimental sites (Figure 3). At Site A, treatments clustered distinctly according to both management systems, with all CT-herbicide combinations forming a coherent cluster characterized by higher standardized values of plant height, leaf area, LAI, NDVI at heading and milk ripening, SPAD, photosynthetic yield (YII), thousand-grain weight, and grain yield. In contrast, stubble-based treatments formed separate clusters associated with comparatively lower standardized values across most measured traits.



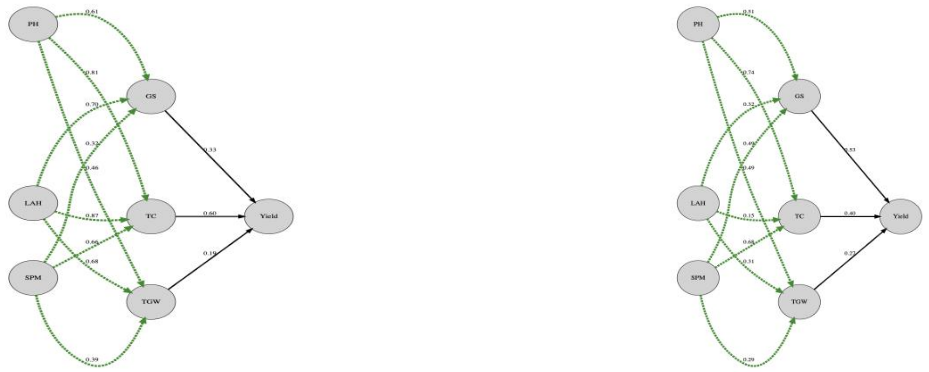
(a) (b)

Figure 3. Hierarchical cluster heatmap of agronomic, physiological, and yield-related traits across herbicide and soil management treatments at (a) Site A and (b) Site B. Trait abbreviations are defined as follows: CT, conventional tillage; SR, stubble retention; PHH, PHM, and PHHrv represent plant height measured at heading, milk ripening, and harvest, respectively; LAH and LAM denote leaf area at heading and milk ripening; LAI_H and LAI_M indicate leaf area index at heading and milk ripening; NDH and NDM correspond to normalized difference vegetation index (NDVI) at heading and milk ripening; SPH and SPM represent SPAD chlorophyll index at heading and milk ripening; YH and YM indicate the effective quantum yield of photosystem II at heading and milk ripening; GS, grains per spike; NOPS, number of productive stems; TC, tillering coefficient; TGW, thousand-grain weight; NPP, number of plants per plot; and Y, grain yield.

Within the CT cluster at Site A, herbicide treatments showed close similarity. However, CT plots treated with tribenuron methyl + metsulfuron methyl and thifensulfuron methyl were closely associated with yield-related traits, including grain yield, thousand-grain weight, and number of productive stems. CT treatments with metsulfuron methyl showed stronger associations with physiological traits, particularly NDVI, SPAD, and Y(II). Stubble-control treatment formed distinct sub-clusters, reflecting consistently lower standardized values across both physiological and yield-related parameters.

A similar clustering structure was observed at Site B, where CT-treated plots were grouped apart from stubble-managed treatments. CT-herbicide combinations were associated with higher standardized values of NDVI, SPAD, Y(II), and yield components. Stubble treatments formed a compact cluster characterized by uniformly lower physiological indices and reduced yield-related traits. Control treatment and stubble-based plots subjected to tribenuron methyl + metsulfuron methyl application clustered most closely, reflecting similarly low values across most measured variables.

Yield path analysis revealed site-specific patterns in yield formation between Site A and Site B (Figure 4). Grain yield at site A was predominantly governed by the tillering coefficient (TC), exerting the strongest direct positive effect on yield ($\beta = 0.60$). Grains per spike (GS) contributed directly, with a lower magnitude ($\beta = 0.33$), while thousand-grain weight (TGW) showed a comparatively weak direct effect ($\beta = 0.18$). Morphological and physiological traits, including plant height (PH), leaf area at heading (LAH), and SPAD at milk ripeness (SPM), influenced yield mainly through indirect pathways, acting primarily via TC and, to a lesser extent, GS and TGW, indicating that yield formation was largely regulated by tillering capacity.



(a) (b)

Figure 4. Yield path diagram showing direct and indirect effects of yield components on grain yield at Site A and Site B.

Conversely, at Site B, the structure of yield determination differed. Grains per spike (GS) exhibited the strongest direct influence on yield (β = 0.55), followed by TC (β = 0.40) and TGW (β = 0.22). Relative to Site A, indirect effects were more pronounced at Site B, with canopy-related traits such as SPM and LAH contributing indirectly to yield through their positive associations with TC and TGW. This pattern reflects a more balanced integration of yield components and physiological traits in determining grain yield.

Spearman correlation analysis showed meaningful relationships among physiological traits, yield components, and grain yield at $p < 0.05$, $p < 0.01$, and $p < 0.001$ significance levels (Figure 5). Grain yield had a strong positive correlation with tillering coefficient (r = 0.85***) and grains per spike (r = 0.75***). This correlation highlights the key role of sink number and sink strength in determining yield. Yield also positively correlated with physiological indicators: leaf chlorophyll content (SPAD) (r = 0.68***) and photosynthetic efficiency Y(II) (r = 0.43**).

Tillering coefficient significantly correlated with SPAD (r = 0.51**), Y(II) (r = 0.42**), and grains per spike (r = 0.47***). This suggests that improved physiological status enhanced both tiller survival and spike productivity. Leaf chlorophyll content (SPAD) showed a strong association with Y(II) (r = 0.65***), indicating a close connection between chlorophyll status and photochemical efficiency. Interestingly, NDVI showed weak and non-significant correlations with most yield components and grain yield ($r = 0.18^{ns}$), suggesting that canopy greenness alone was not a strong predictor of final yield. Leaf area index (LAI) showed moderate positive correlations with yield (r = 0.54**), tillering coefficient (r = 0.32*), and grains per spike (r = 0.62**).

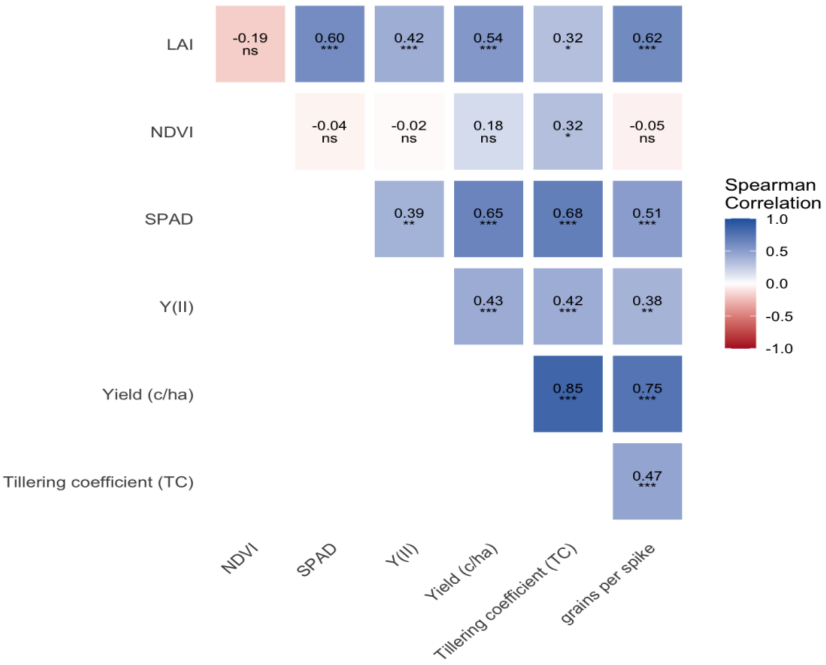


Figure 5. Correlation matrix among yield, yield components, and physiological traits.

4. Discussion

The present study evaluated the effects of sulfonylurea herbicide application on wheat growth, yield formation, and physiological performance under contrasting soil management systems and environmental conditions. The key finding from our study indicates that the effects of herbicide application on wheat overall performance were strongly modulated by soil management, suggesting that crop responses to weed control are contingent upon underlying soil water and nutrient dynamics. Therefore, while herbicide application contributed to variability through its weed-suppressing ability, soil management exerted dominant control on wheat yield formation and overall crop growth across both experimental sites. Across both experimental sites, the superior performance of wheat observed under conventional tillage (Bare fallow) reflects more favorable soil resource conditions.

In semi-arid systems, such as those in northern Kazakhstan, where soil moisture is a primary limiting factor, conventional tillage (bare fallow) promotes moisture accumulation and enhances nutrient availability through organic matter mineralization, thereby supporting plant growth [23]. However, stubble retention is widely recognized for conserving soil moisture and improving long-term nutrient dynamics, often contributing to increased crop productivity and yield in grain crops [24,25]. Despite these benefits, the present results indicate that these advantages were not fully realized under the study conditions. Retained residues have been reported to have a high C:N ratio, likely leading to nitrogen immobilization and reduced nutrient availability [26], which can limit overall yield formation. Consistent with this, the observed wheat growth parameters and grain yield were significantly greater under conventional tillage than under stubble retention (Tables 2 and 3). In addition, residue cover may have influenced herbicide performance by intercepting spray droplets, creating spatial variability, reducing weed control efficiency, and subsequently lowering crop yield [27]. This reduced efficiency may have further limited crop performance under residue conditions. Our findings corroborate Dao et al. [28] and Wolf et al. [29], who showed that residue presence can reduce herbicide effectiveness.

The effects of sulfonylurea herbicides applied at recommended rates were primarily indirect and associated with their ability to reduce weed competition, as effective weed control during early growth stages decreases the crop's competition for water and nutrients, allowing for optimal resource allocation. Consequently, herbicide-treated plots were associated with higher yield and growth values compared to weedy control (Table 4), although differences among herbicide treatments remained relatively small. Our study revealed higher grain yield under tribenuron methyl + metsulfuron methyl and metsulfuron methyl treatments, reflecting weed suppression efficiency. When yield and yield-related traits were considered collectively, treatments generally followed the performance gradient of tribenuron methyl + metsulfuron methyl > metsulfuron methyl > thifensulfuron methyl > weedy control. These findings are consistent with Zargar et al. [30], who documented significant yield increases with metsulfuron methyl and tribenuron treatments compared with a weedy check. Several authors have reported higher grain yield under the herbicide mixture, largely due to its broader spectrum and more effective weed suppression compared with single active ingredients [31–33], which likely contributed to the higher yield observed under tribenuron methyl + metsulfuron methyl in the present study.

Despite these improvements relative to weedy control, variations in growth-related traits among herbicide treatments remained limited, indicating that their effect were constrained by soil resource conditions. Yield formation was primarily associated with sink-related traits, particularly tiller number and grains per spike, rather than direct herbicide effects. Consequently, differences among treatments are best explained by variation in weed suppression efficiency. This interpretation is consistent with previous studies showing that sulfonylurea herbicides improve crop performance mainly through weed control while maintaining crop safety [34,35], and that yield variation is largely governed by resource availability and sink development [36,37].

Yield path analysis revealed site-specific mechanisms of yield determination, with tillering coefficient (TC) and grains per spike exerting a stronger influence at both experimental sites (Figure 4). These shifts are consistent with reports showing that yield-attributing characters exert both direct and indirect effects on grain yield and thousand kernel weight [38–40]. Correlation analysis supported this pattern, as grain yield showed a strong positive relationship with TC and a moderate association with grains per spike. These results demonstrate that sink strength, rather than herbicide treatment, was the primary determinant of yield variation (Figure 5). The positive correlation observed between leaf area index (LAI) and SPAD further indicates coordinated canopy expansion and chlorophyll retention, which likely supported assimilate production during grain filling [41].

Physiological responses showed that herbicide application at recommended rates imposed no measurable stress on wheat photosynthetic function. Chlorophyll content, NDVI, and photosynthetic yield [Y(II)] remained comparable across herbicide treatments and the weedy control, demonstrating that photochemical efficiency and chlorophyll integrity were maintained following application. This response is expected, as the mode of action of sulfonylurea herbicides is not directly related to photosynthetic processes, and consequently does not impair photosystem II function [42].

The positive association between SPAD and Y(II) with grain yield suggests that sustained chlorophyll retention supported continued light absorption and maintained photosystem II efficiency during grain filling. This physiological stability is consistent with the selective action of acetolactate synthase (ALS)-inhibiting herbicides, which primarily target weed species while maintaining crop tolerance [41]. Consequently, the observed physiological responses are best explained by improved crop–weed balance rather than direct biochemical effects of the herbicides. Similar findings have been reported, where variation in photosynthetic traits was linked to abiotic stress rather than herbicide toxicity, and selective herbicides caused no significant changes in photosynthetic performance in wheat [42,43].

Multivariate analysis showed that treatment separation was driven primarily by soil management, with plots under conventional tillage (bare fallow) consistently associated with higher physiological and yield-related traits. Tribenuron methyl + metsulfuron methyl clustered closely with grain yield, indicating that herbicide effects were expressed within, rather than across, management systems. This pattern confirms that soil management defined the primary structure of trait variability.

5. Conclusions

The study demonstrated that soil management exerted a stronger influence on wheat growth, physiology, and yield than variation among sulfonylurea herbicides under semi-arid conditions. Conventional tillage (bare fallow) was consistently associated with higher growth and yield compared with stubble retention, highlighting the importance of soil resource availability. Sulfonylurea herbicides improved yield relative to the weedy control but did not induce measurable physiological stress, and differences among active ingredients were limited.

These findings emphasize that optimizing soil management, alongside effective weed control, is critical for improving wheat productivity and resilience in water-limited agroecosystems.

Author contributions

Kelvin Harrison Diri: Performed research and wrote the first draft of this manuscript and statistical analysis; Gani Stybayev and Aliya Baitelenova: Supervised, responsible for conceptualization and funding; Zargar Meisam, Saltanat Kulzhanova, and Bekzak Amantayev: Reviewed and supported in writing this manuscript; Yeldos Kulzhabayev, Rakhiya Yelnazakyzy: Supported the first author in data collation, and analysis of plant samples for both physiological, structural, and yield indices. All authors have read and approved the final version of the manuscript for publication.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgements

This study was funded by the Ministry of Higher Education and Science of the Republic of Kazakhstan (Project AP23488514). The authors express their sincere gratitude to the funding body for its support and acknowledge the valuable contributions of all co-authors to the successful completion of this research.

Conflict of interest

The authors declare no conflict of interest.

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