IRSTI: 68.33.01

DOI: 10.51886/1999-740X_2026_4_74

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SOIL MICROBIAL RESPONSES FOLLOWING SULFONYLUREA HERBICIDE APPLICATION IN SEMI-ARID AGROECOSYSTEMS

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Abstract. A field experiment on a southern carbonate chernozem under semi-arid conditions evaluated the effects of tribenuron-methyl and thifensulfuron-methyl on soil microbial and agrochemical properties. Soil samples were collected 10, 30, 50, and 70 days after application. Sampling date and the herbicide × sampling date interaction significantly affected soil microbial properties ($p<0.001$). Early declines in microbial biomass carbon and nitrogen were most pronounced under thifensulfuron-methyl, which also increased the microbial metabolic quotient (qCO_2) on some sampling dates. By day 70, microbial biomass carbon under tribenuron-methyl did not differ significantly from the untreated control, whereas it remained significantly lower under thifensulfuron-methyl. Available phosphorus varied considerably over time, while soil organic carbon and pH remained relatively stable. Changes in soil microbial properties depended on the herbicide active ingredient and time since application.

Keywords: sulfonylurea herbicides, tribenuron-methyl, thifensulfuron-methyl, soil microbial biomass, basal respiration, redundancy analysis.

INTRODUCTION

Wheat (Triticum aestivum L.) a cereal crop is cultivated over the largest global land area, on approximately 220-221 million hectares globally, with South Asia, the Middle East, North Africa, and Central and West Asia representing major wheat-growing regions [1], contributing substantially to global food and nutritional security. Wheat provides approximately 18% of global dietary calories and 19% of dietary protein, highlighting its importance as a major source of human nutrition [2-4]. However, wheat production in semi-arid environments is constrained by multiple abiotic stresses, including limited water availability, high temperatures, low soil organic matter, and poor soil fertility [5]. Improving wheat productivity while maintaining soil health is therefore essential for ensuring sustainable food production in these regions.

Among the major constraints to wheat production, weed infestation is an important biotic stress. Weeds compete with wheat for light, water, nutrients, and growing space, and the resulting yield loss depends on weed species, density, emergence time, duration of competition, crop competitiveness, and environmental conditions [6]. Weed infestation has been reported to reduce wheat grain yield by up to 40% under severe conditions in northern Kazakhstan. Field observations at Surayev

farm, originally documented by FAO and subsequently reported by Hickmann (2006), further highlight the extent of weed pressure under different seeding practices [7]. At the tillering stage, spring wheat grown after wheat under conventional seeding exhibited a total weed density of 124 plants m^{-2}, comprising 80 wild oat, 26 sow-thistle, and 18 other weed plants m^{-2}. In contrast, weed density under direct seeding at the same farm was 28 plants m^{-2}.

Consequently, the use of chemical control methods (herbicides) has become a widely adopted weed management strategy in modern wheat production systems because they provide effective and selective weed control while minimizing crop competition [8].

Despite their agronomic benefits, herbicides have raised concerns regarding their effects on non-target soil organisms and microbial functions. Herbicide exposure can alter the composition, abundance, and activity of soil microbial communities, with possible consequences for nutrient cycling and plant–soil interactions [9, 10].

Experimental studies have shown that some herbicides can alter soil microbial populations, soil organic-matter measurements, and dehydrogenase activity under specific soil and application conditions. These effects may be particularly relevant in semi-arid soils, where limited moisture can suppress microbial activity and slow biologically mediated herbicide degradation. Soil organic-matter content and mineral composition also influence herbicide sorption, bioavailability, mobility, and degradation, although the direction and magnitude of these effects depend on the herbicide's chemical properties and the characteristics of the soil [11, 12].

Soil biological health reflects the capacity of soil to sustain diverse and active microbial communities that contribute to organic matter decomposition, nutrient cycling, and the formation and maintenance of soil structure [13]. Common indicators of soil biological quality include soil microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), soil organic carbon (SOC), and microbial CO_2 respiration. MBC and MBN quantify microbial biomass, whereas microbial CO_2 respiration provides an estimate of microbial metabolic activity; the ratio of MBC to SOC can additionally indicate the proportion of soil organic carbon contained in the microbial biomass [14, 15]. Hence, a decline in an indicator does not necessarily mean an equivalent decline in soil fertility or crop productivity; the relationship depends on nutrient availability, soil type, climate, crop management, and other factors. These indicators may respond to changes in soil management and agrochemical exposure, although their sensitivity and response time vary with soil properties, environmental conditions, and the compound applied. For example, Sulfonylurea (SU) herbicides have been evaluated for their effects on soil enzyme activity, including urease activity [16].

Persistent declines in microbial biomass or respiration may reduce nutrient-transforming capacity and contribute to reduced soil fertility, although effects on crop productivity should be evaluated using complementary chemical, biological, and plant-growth measurements.

The effects of sulfonylurea herbicides on soil microorganisms vary among herbicide compounds, application rates, soil properties, and environmental conditions. Previous studies have reported limited changes in the overall soil bacterial community one month after application of a formulated SU herbicide [17], whereas other studies have observed dose-, soil-, and time-dependent changes in respiration and microbial-community structure following triasulfuron treatment [18]. These findings indicate that microbial responses are not uniformly inhibitory and may change during herbicide dissipation. In semi-arid soils characterized by low organic-matter content and limited moisture, such responses may be particularly important because soil conditions can influence

microbial activity, herbicide bioavailability, and nutrient-transforming processes. However, the extent to which short-term microbial responses affect long-term soil fertility and wheat productivity remains insufficiently understood [19]. Although research on herbicide–soil microbiome interactions has increased, important knowledge gaps remain regarding the effects of SU herbicides on soil biological quality in semi-arid agroecosystems. In particular, relatively little information is available for dryland wheat systems with alkaline soils, low organic-matter content, and distinct microbial communities. Consequently, the responses of microbial biomass, soil organic carbon, enzyme activities, and their relationships with wheat productivity under these conditions remain poorly characterized.

Therefore, this study evaluated the effects of recommended application rates of Sulfonylurea herbicides on soil biological properties in a semi-arid agroecosystem. Specifically, the changes in microbial biomass carbon, microbial biomass nitrogen, microbial respiration, soil organic carbon, to improve understanding of sustainable herbicide management in semi-arid wheat production systems.

MATERIALS AND METHODS

The study was carried out during the 2025 growing season at the A.I. Barayev Grain Institute in Shortandy, Akmola Region, Northern Kazakhstan (51° 37′41″N, 71°02′14″E). The experimental site experiences a strongly continental climate, characterized by long, harsh winters, rapid spring warming, and moderately warm summers. Winter temperatures frequently drop below -20°C, while summer temperatures often rise above 30°C. Relative humidity is generally high during the winter months but decreases throughout the summer as evapotranspiration intensifies. Most precipitation occurs between April and August, aligning with the principal crop-growing season (figure 1).

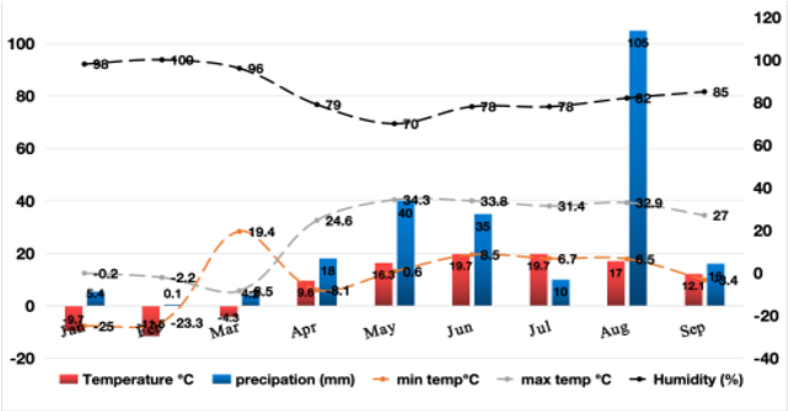


Figure 1 - Mean monthly Temperature and Rainfall data, A.I Barayev Grain Research Center, 2025. Source: www.kazhydromet.kz

During this period, the site received approximately 233.7 mm of rainfall, providing the primary source of moisture for crop growth despite its uneven temporal distribution

The soil at the experimental site was a southern carbonate chernozem with a pH (H_2O) of 8.11 and an organic carbon content of 2.6%. Available phosphorus was 21 mg kg^{-1}. Soil moisture content and temperature were 26% and 16°C, respectively. The soil was further classified as clay loam, with reported particle-size fractions of 18% sand, 47% silt, and 35% clay. The physiochemical properties characterize the soil conditions under with responses to Sulfonylurea herbicide application were evaluated.

Experimental Design and Treatment. The field experiment was established using a randomized complete block design (RCBD) to evaluate the effects of two commercial sulfonylurea herbicides on soil biological and physicochemical properties. The experiment comprised three treatments: Baron 750, containing 750 g kg^{-1} tribenuron-methyl (Alem Agro, Kazakhstan); Alcion, containing 750 g kg^{-1} thifensulfuron-methyl (Avgust, Russia); and an untreated control. Each treatment was replicated three times across three blocks, with each block containing one plot per treatment, resulting in nine experimental plots. Individual plots measured 4×10 m (40 m^2). Treatments were randomly allocated to plots within each block to minimize potential bias associated with spatial variability. Additionally, treatment (Herbicide) and sampling days, were fixed factors and their interaction (treatment × days) was used to determine treatment responses between sample time. Finally, block and experimental plot nested within block were included as random effect.

Spring wheat (Triticum aestivum L.), cultivar Taimas, was sown in mid-spring (15 May) using an LV-Service mechanical grain drill calibrated to a seeding rate of 260 viable seeds m^{-2} and a uniform sowing depth of 6 cm. Tribenuron-methyl and thifensulfuron-methyl were applied separately (24 May) at their recommended field application rates (table 2).

Table 2 – Herbicide treatments and application rates

Herbicide	Active ingredient	Field Dose	Active Ingredient
Alcion	Thifensulfuron-methyl 750 g/kg	15 g ha^{-1}	11.25g ha^{-1} a.i
Baron 750	Tribenuron-methyl 750 g/kg		

Herbicide applications were performed at the early tillering stage using a 10-L ha^{-1} knapsack sprayer equipped with a flat-fan nozzle and operated at a pressure of 2 bar. Control plots received no herbicide treatment, while all plots were maintained under otherwise identical agronomic management practices throughout the experimental period.

Soil sampling. Soil samples were randomly collected from three points 10, 30, 50 and 70 days after herbicide application. Within each replicated plot and thoroughly homogenized to form a single composite sample representing the 0-15 cm soil layer. A total of 36 composite soil samples were obtained across four sampling dates from three treatments and blocks. Subsamples collected within each plot were pooled and were not considered independent experimental replicates. The samples were further air-dried, ground, passed through a 2 mm sieve mesh, bagged, and stored for physiochemical analysis.

Separate fresh, field-moist soil samples collected was immediately incubated for 30 days at 25°C for microbial cumulative basal respiration, microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN). Microbial biomass carbon and nitrogen were determined using chloroform fumigation-extraction (CFE) method following 24hours of alcohol-free chloroform fumigation.

Soil Analysis. The air-dried soil samples were analyzed for chemical properties: soil pH measured in water (1:2.5 w/v), available phosphorus measured according to GOST 26205-91 (Machigin), involving extraction with ammonium carbonate ($(NH_4)_2CO_3$) extracting solution, followed by colorimetric determination of phosphorus using the molybdenum blue. Soil organic Matter (SOC) was determined using the Walkley–Black wet oxidation method, followed by titration with $FeSO_4$. Soil Organic matter (SOM) was calculated by multiplying the percentage of organic carbon (Van Bemmelen factor) by 1.724.

20g of fresh soil (16.4g oven dry soil equivalent) with 21.9% moisture content was for soil cumulative basal respiration (C-CO_2) was analyzed via NaOH (Sodium hydroxide) trap and back titration with 0.25 M HCl during a 30-day laboratory incubation period [20]. The total amount of CO_2-C released over the incubation period was calculated and expressed as mg C–CO_2 kg^{-1} fresh soil.

Soil microbial biomass carbon, and Nitrogen (MBC and MBN) were analyzed by placing 7.5g fresh soil in a laboratory vacuum oven connected to an external vacuum pump and fumigated with ethanol-free chloroform (CFE) [21] for 24hours. Both fumigated and Non-fumigated samples were extracted with 0.5 M K_2SO_4. And analyzed using a Shimadzu TOC/TN analyzer [22].

Microbial biomass carbon (MBC) was determined from the difference in extractable organic carbon between chloroform-fumigated and non-fumigated soil samples, using a conversion factor of 2.64 (Eq. 1). Microbial biomass nitrogen (MBN) was calculated from the difference in extractable nitrogen between fumigated and non-fumigated samples, applying an extraction efficiency coefficient of 0.54 (Eq. 2).

$$MBC = 2.64 \times E_C \quad (1)$$

$$MBN = \frac{E_N}{0.54} \quad (2)$$

Microbial metabolic quotient (qCO_2) was further calculated by dividing basal respiration by MBC (Microbial biomass carbon). The formula is given as:

$$qCO2 = \frac{\text{Cummulative} - CO2}{t \times MBC}$$

Data Analysis. Soil measurements measured at 10, 30, 50, and 70 days after herbicide application were analyzed using a Linear mixed-effects model. Herbicide treatment, sampling time, and their interaction were specified as fixed effects, while replicate plot was included as a random effect to account for repeated measurements over time. Pairwise comparisons among estimated marginal treatment means were conducted using Tukey's honest significant difference (HSD) adjusted at the 5% significance level.

The model was given as;

$$Y_{ijk} = \mu + T_i + D_k + (T \times D)_{ik} + B_j + P_{ij} + e_{ikj} \quad (3)$$

where;

T = Herbicide treatment (fixed effect)

D = Sampling days

(T×D) = Herbicide treatment × Sampling days interaction.

B= block effect (random effect)

P= Experimental plot (random effect)

e = residual errror

Model residuals were evaluated for normality using the Shapiro-Wilk test, and homogeneity of variance was evaluated using Levene's test.

Redundancy analysis (RDA) was performed on standardized soil biological and chemical variables to evaluate the multivariate effects of herbicide treatment and sampling time on soil properties. RDA treatment effect were further evaluated using 216 restricted permutation, accounting for the randomized complete block design and repeated measurement by permuting the whole plots within blocks while controlling for sample date. All statistical analyses and visualizations were conducted in R using RStudio Version 2025.05.1+513.

RESULTS AND DISCUSSION

The analysis of variance showed significant effects of herbicide treatment, sampling time, and their interaction on available phosphorus, cumulative basal respiration, microbial biomass carbon and nitrogen, soil organic carbon, and the microbial metabolic quotient (p<0.001). Soil pH showed a different pattern: the overall effect of herbicide treatment was not significant (F=1.81, p=0.185), whereas sampling time (F=4.29, p=0.015) and the treatment×sampling-time interaction (p= 0.005) were significant (table 3). The significant interactions across all measured

parameters indicate that differences among treatments depended on the sampling date. Accordingly, treatment responses were examined separately at 10, 30, 50, and 70 days after herbicide application.

Table 3 – Analysis of variance of soil chemical properties, microbial biomass, and their responses to herbicide treatments

Parameters	Source	Df	F-value	P-value
AP	Herbicide	2	238.95	0.001
	Days	3	3061.25	0.001
	Herbicide x Day	6	89.02	0.001
C-CO_2	Herbicide	2	983.92	0.001
	Days	3	700.56	0.001
	Herbicide x Day	6	485.14	0.001
MBC	Herbicide	2	270.67	0.001
	Days	3	824.17	0.001
	Herbicide x Day	6	36.22	0.001
MBN	Herbicide	2	420.54	0.001
	Days	3	67.08	0.001
	Herbicide x Day	6	93.24	0.001
Org. C	Herbicide	2	10.32	0.001
	Days	3	20.32	0.001
	Herbicide x Day	6	8.32	0.001
pH	Herbicide	2	1.81	0.185
	Days	3	4.29	0.015
	Herbicide x Day	6	4.19	0.005
qCO_2	Herbicide	2	99.95	0.001
	Days	3	665.83	0.001
	Herbicide x Day	6	553.04	0.001

Soil acidity, Available phosphorus, and Organic carbon. Soil pH differed significantly among treatment × sampling date combinations (p<0.05); however, the magnitude of variation was relatively small, and pH remained broadly stable throughout the 70-day observation period (figure 2). At 10, 30, and 70 days after application, pH values were generally comparable among the control, tribenuron, and thifensulfuron-methyl treatments. At 50 days, soil pH under the thifensulfuron-methyl treatment was significantly lower than that of the control and tribenurontreatments. By 70 days, this difference was no longer evident, indicating that the transient pH response had not persisted until the final sampling date.

Plant-available phosphorus (AP) changed significantly over the sampling period, and the magnitude and direction of these changes differ among treatments (figure 2). At 10 days after herbicide application, AP concentrations were highest in the control and tribenuron-methyl treatments, whereas the thifensulfuron-methyl treatment had a significantly lower concentration. By 30 days, AP had declined substantially in all treatments. The control retained a significantly higher AP concentration than both herbicide treatments while the tribenuron-methyl and thifensulfuron-methyl treatments had similar concentrations of approximately 3 mg kg^{-1}.

At 50 days, AP in the tribenuron-methyl treatment increased to approximately 6 mg kg^{-1}, exceeding the concentrations measured in the control and thifensulfuron-methyl treatments. By 70 days, AP had declined again in all treatments. Both herbicide treatments remained significantly lower than the control, although the tribenuron-methyl treatment had a lower AP concentration than the thifensulfuron-

methyl treatment at this sampling time. Soil organic carbon (SOC) varied among the treatment×sampling-time combinations (figure 2).

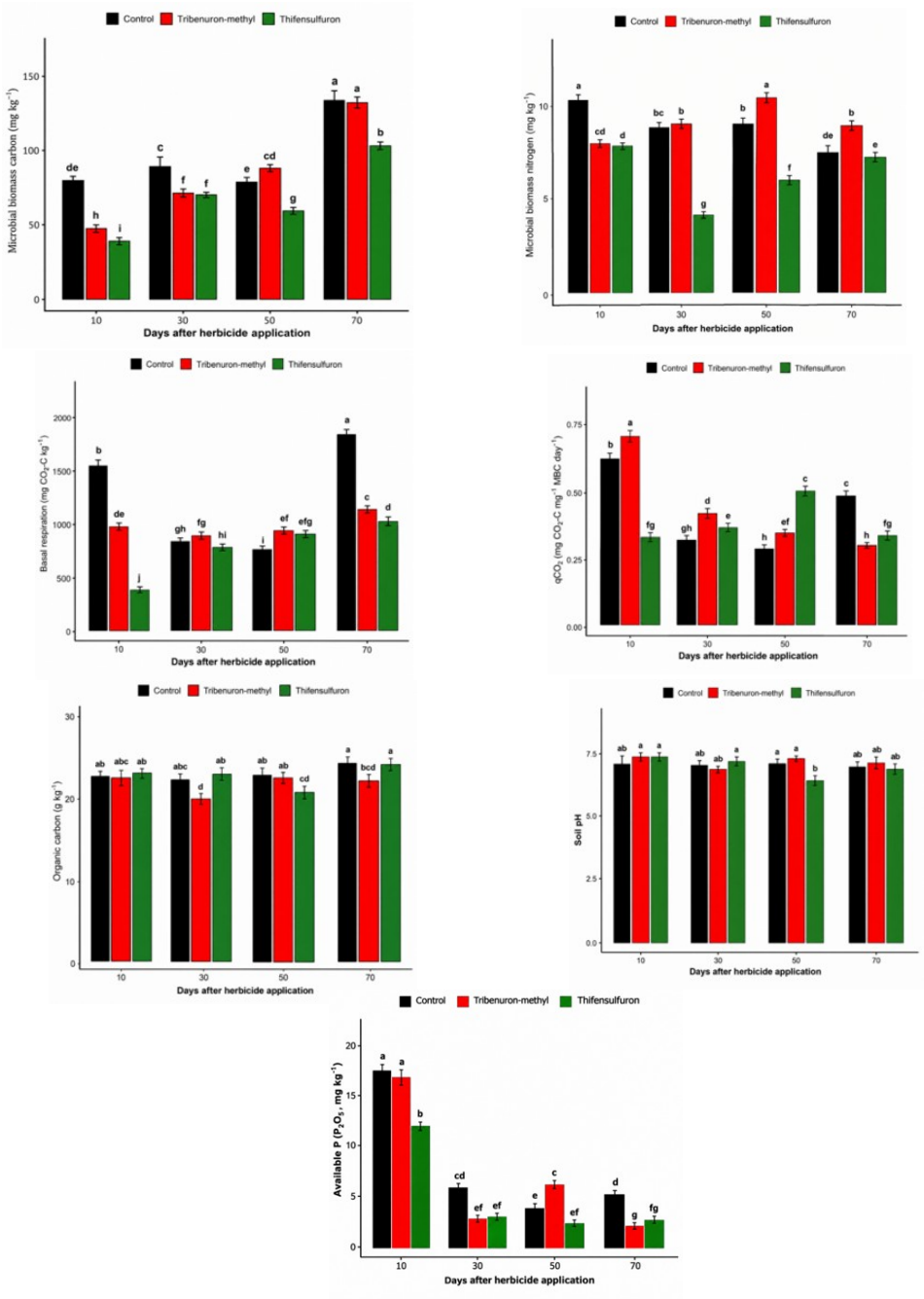


Figure 2 – Changes in soil microbial and chemical properties following application of tribenuron-methyl and thifensulfuron-methyl at 10, 30, 50, and 70 days after application: *(a) microbial biomass carbon, (b) microbial biomass nitrogen, (c) cumulative basal soil respiration, (d) metabolic quotient (qCO_2), (e) soil organic carbon, (f) soil pH, and (g) available phosphorus. Bars represent means ± standard error; whereas the different lowercase letters indicate significant differences among treatments × sampling time interaction (Tukey's test, p<0.05)*

At 30 days, SOC under tribenuron-methyl decreased to approximately 20 g kg^{-1} and was significantly lower than the corresponding control and thifensulfuron-methyl values. At 50 days, SOC under the control and tribenuron-methyl treatments was statistically comparable, whereas the thifensulfuron-methyl treatment had a significantly lower SOC concentration. At 70 days, SOC under thifensulfuron-methyl increased to approximately 24 g kg^{-1} and was statistically comparable with the control, whereas SOC under tribenuron-methyl was significantly lower than in the control. Because SOC is a relatively stable soil-carbon pool, these short-term fluctuations should be interpreted cautiously and should not be taken as evidence of sustained changes in soil carbon status.

Soil microbial biomass carbon, nitrogen, Basal respiration, and microbial metabolic quotient. Soil microbial biomass carbon (MBC) and nitrogen (MBN) varied significantly among herbicide treatments across sampling dates compared with the control (p<0.05; figure 2). Ten days after application, MBC was significantly lower under both tribenuron-methyl and thifensulfuron-methyl than in the control, with mean values of 48 and 38 mg kg^{-1}, respectively. MBN showed a similar early response, with the control recording the highest value and both herbicide treatments producing significantly lower concentrations.

Over the subsequent sampling period, MBC increased overall, although the temporal pattern differed between the two herbicides. Thirty days after application, both herbicide treatments remained significantly lower than the control. By day 50, MBC had increased under tribenuron-methyl but declined under thifensulfuron-methyl. At the final sampling date, MBC under tribenuron-methyl was statistically comparable with the control, whereas the thifensulfuron-methyl treatment remained significantly lower than both treatments.

MBN displayed a more pronounced treatment-dependent response. Its concentration under tribenuron-methyl at day 30 was comparable with the control, while thifensulfuron-methyl caused a marked decline and remained significantly lower than both treatments. The tribenuron-methyl treatment reached its highest MBN value at day 50, significantly exceeding the control and thifensulfuron-methyl treatments. Although MBN under thifensulfuron-methyl increased relative to day 30, it remained significantly lower than the other treatments. By day 70, MBN under tribenuron-methyl had declined but was still significantly higher than under thifensulfuron-methyl, while the control showed an intermediate response.

Overall, thifensulfuron-methyl produced lower MBC and MBN values than tribenuron-methyl at most sampling dates. By day 70, MBC under tribenuron-methyl was statistically comparable with the control, whereas MBC under thifensulfuron-methyl remained significantly lower than the control.

Basal respiration and the microbial metabolic quotient (qCO_2) varied significantly among herbicide treatments and sampling dates (p<0.05; figure 2).

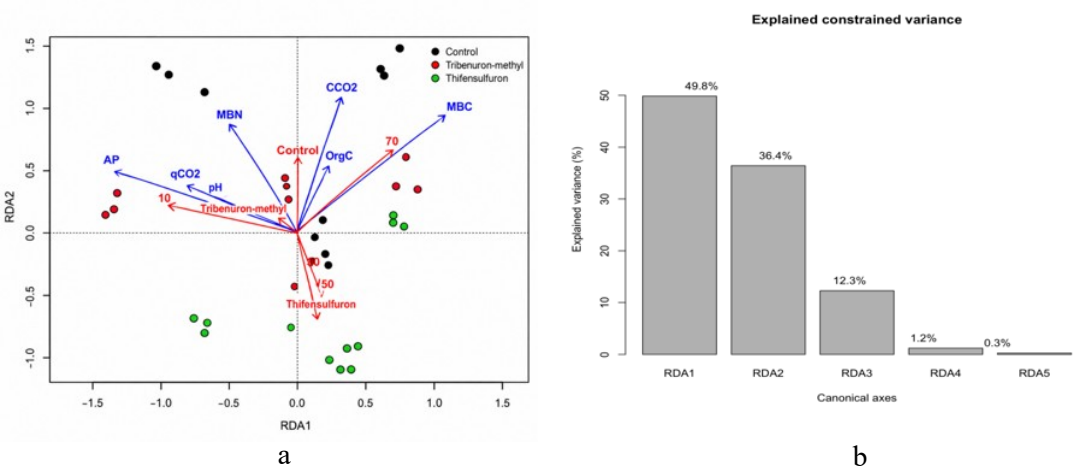
Basal respiration was highest in the control 10 days after application, whereas thifensulfuron-methyl produced the lowest value. Respiration under both herbicides increased during the observation period, whilst the magnitude and timing of the response differed between products. At 30 days, cumulative basal respiration was lower in the control than in both herbicide treatments, with tribenuron-methyl showing the highest value.

This pattern persisted at 50 days, when respiration under both herbicide treatments exceeded the control and the tribenuron-methyl treatment remained numerically highest. After 70 days, cumulative C–CO_2 respiration in the control had increased to approximately 1,100 and

1,000 mg C–CO_2 kg-1 for tribenuron-methyl and thifensulfuron-methyl, respectively.

The microbial metabolic quotient (qCO_2) also differed significantly among treatment x sampling-time combination (p<0.05). At 10 lays after application, qCO_2 was significantly higher under tribenuron-methyl than in the control, whereas thifensulfuron-methyl produced the lowest value. At the 30 days measurement, both herbicide treatments had higher qCO_2values than the control. The strongest response occurred at 50 days under thifensulfuron-methyl, which recorded the highest qCO_2, while the control had the lowest value. By the final sampling date, qCO_2 was recorded lowest under tribenuron-methyl, followed by thifensulfuron-methyl, whereas the control recorded the highest value.

RDA Analysis. Redundancy analysis (RDA) (figure 3) indicated that herbicide treatment and sampling time significantly influenced multivariate variation in the measured soil properties (F=8.75, p= 0.001), and explained 59.32% of the total variation (r^2=0.5932). The first two canonical axes were both highly significant (p=0.001) and explained 86.26% of the constrained variation, with RDA1 and RDA2 accounting for 49.85% and 36.41%, respectively (Table 4). RDA1 was positively associated mainly with microbial biomass carbon (MBC), cumulative C–CO_2 respiration, and soil organic carbon (SOC), whereas available phosphorus (AP), microbial metabolic quotient (*qCO2*), pH, and microbial biomass nitrogen (MBN) showed negative associations with this axis.



a b

Figure 3 – Redundancy analysis (RDA) of soil microbial and chemical properties under different herbicide treatments and sampling times: (a) RDA biplot showing the associations among treatments, sampling dates, and measured soil variables; (b) percentage of constrained variance explained by each canonical axis

RDA2 was positively associated with C-CO_2 respiration, MBC, and MBN. These associations indicate that the canonical axes represented contrasting patterns among microbial, carbon, phosphorus, and soil-acidity variables.

The ordination showed clear separation among the herbicide treatments and sampling times. Thifensulfuron-methyl observations were distributed mainly in the negative RDA2 region, whereas the control observations were more strongly associated with the positive RDA2 region.

Table 4 – Summary of redundancy analysis (RDA) axes showing eigenvalues, explained constrained variance, and cumulative variance

Axis	Eigenvalue	Canonical variance explained	Cumulative (%)
RDA1	2.0699	49.85	49.85
RDA2	1.5120	36.41	86.26

R^2 = 0.5932 (59.32%). Adjusted R^2 = 0.5254 (52.54%).

Tribenuron-methyl occupied a comparatively intermediate position, suggesting a less distinct overall multivariate response than thifensulfuron-methyl. Sampling time also contributed to the ordination pattern: where observations from10 and 70 days were positioned mainly toward the positive RDA2 region, while those from 30 and 50 days occurred more frequently toward the negative RDA2 region.

Table 5 – Restricted permutation test of overall treatment effect from partial redundancy analysis

Component	df	F value	P value	Significance
Treatment	2	6.6748	0.032	*
RDA1	1	10.6266	0.115	ns
RDA2	1	2.8138	0.115	ns

The results of the study indicates, that herbicide application significantly influenced soil biological properties, although the magnitude of the responses depended on herbicide type and time elapsed after application. Both MBC and MBN declined shortly after application, with the strongest early reductions mostly observed under thifensufuron. This pattern is consistent with previous reports of short-term changes in microbial biomass and nitrogen-related processes following sulfonylurea exposure. A study by El-Ghamry et al. [23] similarly reported reductions in microbial biomass C and N during the early stages following sulfonylurea herbicide application. Similarly, thifensulfuron-methyl has also been shown to affect soil microbial biomass and metabolic activity, although the magnitude of the response depends strongly on application rate, soil properties, and exposure conditions [24]. Furthermore, the significant short-term decline in MBC and MBN following herbicide application may reflect an initial disturbance of the soil microbial community. Interactions between herbicide molecules and soil organic matter can modify herbicide bioavailability, mobility, and thus influence their effects on soil microorganisms, potentially contributing to microbial responses [25].

The subsequent recovery of MBC and MBN during the later sampling period between 30 and 70 days suggests that the initial disturbance was temporary, potentially reflecting declining herbicide exposure and the reestablishment of microbial activity. However, this interpretation should be treated cautiously because herbicide residues, microbial community composition, substrate availability, soil moisture, and plant inputs were not measured simultaneously, additional measurements of herbicide dissipation, microbial community structure, and mineral nitrogen would be required to confirm the mechanism of recovery [26].

On the other hand, the temporally contrasting response of basal respiration and qCO_2 further indicates disturbance in microbial functioning. Changes in basal respiration may reflect altered microbial activity or substrate utilization rather than necessarily indicating a beneficial micro-

bial response. The increase in qCO_2 under thifensulfuron-methyl at specific sampling times suggests increased respiratory cost and possible physiological stress [27]. By 70 day, qCO_2 was lower under both herbicide treatments than in the control; however, this difference alone does not demonstrate complete recovery of microbial functioning. This is consistent with evidence that herbicide effects on soil microbial functioning can be short-term and depend on application rate and environmental conditions [28]. Temporal variation in AP, along with the relative stability of soil pH and SOC, suggests that herbicide effects occurred alongside broader changes in soil nutrient dynamics. This is particularly relevant for sulfonylureas, as their persistence and biological activity are strongly influenced by soil pH, SOC, and other soil properties [29].

Available phosphorus also varied over time and among treatments, whereas soil pH and SOC were comparatively stable. This pattern suggests that herbicide-related microbial responses occurred alongside broader temporal changes in nutrient dynamics rather than causing an immediate and sustained alteration of soil acidity or total organic-carbon status. The temporary changes in AP may reflect plant uptake, microbial immobilization and release, mineralization of organic phosphorus, or changes in phosphorus sorption and desorption. These mechanisms cannot be distinguished from the present data because phosphorus fractions, plant phosphorus uptake, and phosphatase activity were not measured. Sulfonylurea persistence and biological activity are strongly influenced by soil pH, SOC, moisture, temperature, and other soil properties.

The RDA integrated these responses and showed that herbicide treatment and sampling time were jointly associated with variation in the measured soil variable. The first canonical gradient was associated primarily with MBC, $C–CO_2$ respiration, and SOC, while AP, qCO_2, pH, and MBN contributed to the contrasting direction of the ordination. The second gradient was associated mainly with $C–CO_2$ respiration, MBC, and MBN. The separation of treatment groups and sampling times indicates that the relationships among soil biological and chemical variables changed dynamically during the post-application period rather than representing a uniform, persistent shift in soil fertility.

This is in tandem with evidence that sulfonylureas can alter soil microbial functioning in a time- and soil-dependent manner, with microbial and enzymatic responses varying substantially during the period following application [30].

The stronger separation of thifensulfuron-methyl observations from the control is consistent with the comparatively lower MBC and MBN values observed under that treatment at several sampling times. tribenuron-methyl occupied a more intermediate position, suggesting a less distinct or more variable multivariate response. Nevertheless, the RDA identifies associations among variables and treatments. This, however, does not by itself establish causal relationships. Sulfonylurea effects on soil microbial functioning and enzymic activities have likewise been shown to vary with time, soil type, herbicide identity, and application conditions. Further studies incorporating herbicide-residue dissipation, microbial community sequencing, enzyme activities, nutrient-transforming process, and wheat productivity would help to determine whether the observed short-term responses have longer-term consequences for soil biological quality.

CONCLUSION

The study investigated soil microbial responses to sulfonylurea herbicides, particularly tribenuron-methyl and thifensulfuron-methyl. Sulfonylurea herbicides caused temporal and herbicide-specific changes in soil microbial functioning, with more pronounced effects observed under thifensulfuron-methyl. By day 70, MBC under

tribenuron-methyl was statistically comparable with the control, whereas MBC under thifensulfurol-methyl remaind significantly lower. These results indicate that the duration of the microbial response differed between the two herbicides within the 70-day observation period. Redundancy analysis (RDA) further confirmed that treatment and sampling time jointly structured the soil response, highlighting microbial and nutrient-related properties as major components of this variation. However, herbicide residues were not directly quantified; therefore, the observed recovery cannot be conclusively attributed to herbicide dissipation. Future studies should combine herbicide residue analysis with longer-term monitoring of soil microbial responses to clarify the persistence and mechanisms of sulfonylurea effects under semi-arid conditions.

ACNOWLEDGEMENTS

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

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ЖАРТЫЛАЙ ҚУАҢ АГРОЭКОЖҮЙЕЛЕРДЕГІ ТОПЫРАҚ МИКРООРГАНИЗМДЕРІНІҢ СУЛЬФОНИЛМОЧЕВИНА ТОБЫНДАҒЫ ГЕРБИЦИДТЕРДІ ҚОЛДАНУҒА ЖАУАБЫ

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Далалық тәжірибеде жартылай қуаң жағдайда оңтүстік карбонатты қара топырақтың микробиологиялық және агрохимиялық көрсеткіштеріне трибенурон-метил мен тифенсульфурон-метилдің әсері зерттелді. Топырақ үлгілері гербицидтерді қолданғаннан кейін 10, 30, 50 және 70-тәуліктерде алынды. Үлгі алу мерзімі және оның гербицид түрімен өзара әрекеттесуі микробиологиялық көрсеткіштерге статистикалық тұрғыдан елеулі әсер етті ($p<0,001$). Бақылаудың бастапқы кезеңінде микробтық биомассадағы көміртек пен азот мөлшерінің төмендеуі тифенсульфурон-метил қолданылған нұсқада айқынырақ байқалды. Осы нұсқада кейбір үлгі алу мерзімдерінде метаболизм коэффициенті (qCO_2) жоғарылады. 70-тәулікте трибенурон-метил қолданылған нұсқада микробтық биомасса көміртегінің мөлшері бақылау нұсқасынан статистикалық тұрғыдан ерекшеленбеді, ал тифенсульфурон-метил қолданылған нұсқада бақылаудан едәуір төмен болды. Сіңімді фосфор мөлшері уақыт бойынша едәуір өзгерді, ал топырақтағы органикалық көміртек мөлшері мен pH салыстырмалы түрде тұрақты болды. Микробиологиялық көрсеткіштердің өзгеруі гербицидтің әсер етуші затына және оны қолданғаннан кейінгі уақытқа байланысты болды.

Түйінді сөздер: сульфонилмочевина гербицидтері; трибенурон-метил, тифенсульфурон-метил, топырақтың микробтық биомассасы, базальды тыныс алу, редунданттық талдау.

РЕЗЮМЕ

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РЕАКЦИЯ ПОЧВЕННЫХ МИКРООРГАНИЗМОВ НА ПРИМЕНЕНИЕ ГЕРБИЦИДОВ ГРУППЫ СУЛЬФОНИЛМОЧЕВИН В ПОЛУЗАСУШЛИВЫХ АГРОЭКОСИСТЕМАХ

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В полевом опыте на чернозёме южном карбонатном изучали влияние трибенурон-метила и тифенсульфурон-метила на микробиологические и агрохимические показатели почвы в полузасушливых условиях. Пробы отбирали на 10-е, 30-е, 50-е и 70-е сутки после обработки. Срок отбора и его взаимодействие с видом гербицида значимо влияли на микробиологические показатели ($p<0,001$). В первые сроки наблюдений снижение содержания углерода и азота микробной биомассы было наиболее выражено при применении тифенсульфурон-метила. В отдельные сроки в этом варианте повышался метаболический коэффициент (qCO_2). На 70-е сутки содержание углерода микробной биомассы в варианте с трибенурон-метилом статистически не отличалось от контроля, а в варианте с тифенсульфурон-метилом оставалось достоверно ниже. Содержание доступного фосфора заметно менялось, тогда как содержание органического углерода и pH почвы оставались относительно стабильными. Таким образом, изменения микробиологических показателей зависели от действующего вещества и срока после обработки.

Ключевые слова: сульфонилмочевинные гербициды, трибенурон-метил, тифенсульфурон-метил, микробная биомасса почвы, базальное дыхание, анализ избыточности (RDA).

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