EFFECTS OF REPLACING CHEMICAL FERTILIZER WITH BIOGAS DIGESTATE ON SOIL RESPIRATION, MOISTURE, AND TEMPERATURE IN WHEAT (*TRITICUM AESTIVUM* L.) FIELDS UNDER EQUAL NITROGEN AND PHOSPHORUS CONDITIONS

ZHANG, M.[1*] – MI, X.[1] – LI, X.[1] – LU, B. L.[2]

[1]*School of Environment and Urban Construction. Lanzhou City University, Lanzhou 730070, Gansu, China*

[2]*Institute of Soil, Fertilizer and Water Saving Agriculture, Gansu Academy of Agricultural Sciences, Lanzhou 730070, Gansu, China*

[*]*Corresponding author*
e-mail: zhangminglbl@163.com

(Received 13th Sep 2025; accepted 23rd Dec 2025)

Abstract. This study aimed to investigate the effects of substituting chemical fertilizer with biogas digestate on soil respiration, moisture, temperature, and yields in wheat (*Triticum aestivum* L.) fields. A field experiment was carried out in 2022 and 2023, with different proportions of biogas digestate replacing chemical nitrogen fertilizer (0%, 20%, 30%, 40%, and 100%) under equal nitrogen and phosphorus conditions, along with a non-fertilization control. The findings indicated that 20% substitution significantly increased yield ($p<0.05$), while 30% substitution stabilized yield ($p>0.05$). However, 40% and 100% substitutions significantly decreased yield ($p<0.05$). Biogas digestate substitution significantly increased soil respiration rate by 5.76-7.99% over the whole growth period (BBCH), with the greatest increase observed under 30% substitution ($p<0.05$). The temperature sensitivity of soil respiration decreased with increasing substitution ratios. At the 20% substitution level, substitution had no significant effect on soil moisture ($p>0.05$), while 30% substitution significantly enhanced soil moisture at the three-leaf stage (BBCH 12-14). In contrast, 40% and 100% substitution increased soil moisture at multiple growth stages ($p<0.05$). Additionally, the explanatory power of soil moisture on soil respiration variations decreased as the substitution ratios increased, with the two-factor model of water-heat explaining soil respiration variation by 63.15% and 62.01% at 20% and 30% substitution, respectively; these values were superior to those at 40% and 100% substitution (44.32% and 39.59%). In summary, replacing 30% of chemical nitrogen fertilizer with biogas digestate enhanced soil respiration while maintaining stable yields and optimizing soil water-heat coupling effects. This is a suitable fertilization strategy for the sustainability of spring wheat production in the Hexi Oasis Irrigation Area of China.
Keywords: *biogas digestate, spring wheat, yield, soil respiration, temperature sensitivity, water effect*

Introduction

Soil respiration is a crucial process in the global carbon cycle and represents the primary form of organic carbon export from agricultural ecosystems. Subtle modifications in soil respiration can significantly influence the carbon cycle of terrestrial ecosystems. These changes represent a substantial source of uncertainty in the assessment of carbon sources and sinks (Xiong et al., 2017; Shi et al., 2025). In recent years, propelled by China's "Dual Carbon" initiative (carbon peaking and carbon neutrality goals), the synergistic advancement of food security and carbon sequestration and emission reduction in croplands has emerged as a focal research theme in agricultural sustainability studies (Lal, 2004). Hexi Oasis serves as the principal commercial grain base in Northwest China, playing an irreplaceable role in guaranteeing regional food security and ecological stability (Xing et al., 2024). As a major food crop in the region, wheat has its

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

soil respiration variations during cultivation that are intrinsically linked to its growth, development, and yield, while also influencing the regional carbon cycle and sustainable development of agriculture (Yang et al., 2024). Notably, organic fertilizer application, as an important farmland management measure, significantly regulates crop growth and soil fertility (Chen et al., 2024). Nevertheless, its role in soil respiration remains debated. Many studies indicate that the application of organic fertilizer can increase the soil respiration rate in agricultural fields (Chen et al., 2022). However, other studies point out that the application of organic fertilizer does not significantly impact soil respiration (Zuo et al., 2023). As a representative form of organic fertilizer, the rational application of biogas digestate is regarded as a vital strategy for promoting sustainable agricultural development. It supports this goal through waste utilization, which helps enhance productivity.

In recent years, the advancement of eco-agriculture has led to the increasing utilization of biogas digestate in wheat growing within the Hexi oasis, making its impact on soil respiration a critical research focus. However, soil respiration is a complex biochemical process influenced by environmental factors, such as soil temperature and moisture (Chen et al., 2022). Although a large number of related studies have been reported, existing conclusions are inconsistent, and soil temperature, its sensitivity, and soil moisture can have positive, negative, or null effects on soil respiration (Yang and Wang, 2006; Lu and Han, 2011; Zhang et al., 2013; Hursh et al., 2017; Wu et al., 2018; He et al., 2018). In the Hexi Oasis Irrigation Area, characterized by abundant solar and thermal resources yet severe water scarcity under arid climate, the impact of biogas digestate as a substitute for chemical fertilizer on soil respiration remains unclear, especially the coupling relationship between soil respiration and environmental factors (temperature and moisture) under different replacement ratios, which remains poorly understood. This study examined the impact of biogas digestate substitution for chemical fertilizers at various ratios on spring wheat yield, soil respiration, moisture and temperature under equal nitrogen and phosphorus in the Hexi Oasis Irrigation Area. We analyzed the responsiveness and sensitivity of soil respiration to soil temperature and soil moisture content, and established model relationships between soil temperature, soil moisture content, and soil respiration when replacing chemical fertilizer with biogas digestate under equal nitrogen and phosphorus conditions. We identified the optimal substitution ratio for spring wheat production by comprehensively balancing yield and soil respiration dynamics. These findings provide a theoretical foundation for replacing chemical fertilizer with the biogas digestate technology in spring wheat cultivation in the Hexi Oasis Irrigation Area.

Materials and methods

Study site

The field experiment was conducted in 2022 and 2023 in Yongfeng Town, Liangzhou District, Wuwei City, Gansu Province, China (38°03′N, 102°42′E) , which belongs to the temperate continental arid climate zone with an altitude of 1,539 m, an annual average temperature of 8.1℃, a frost-free period of about 150 d, and 2873.4 h of sunshine, total annual solar radiation of 139.1 kJ cm^{-2}, an annual average precipitation of 154.6 mm, and an annual average evaporation of 2021.3 mm (Liangzhou District People's Government, 2025). It is a standard natural ecological zone characterized by "insufficient two seasons but surplus one season". The experimental soil is classified as irrigated desert soil, and

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

the physical and chemical properties of the 0-20 cm soil layer were as follows: soil organic matter, 13.21 g kg^{-1}; total nitrogen, 1.36 g kg^{-1}; total phosphorus, 0.72 g kg^{-1}; total potassium, 20.17 g kg^{-1}; alkaline-hydrolyzable nitrogen, 74.28 mg kg^{-1}; available phosphorus, 15.36 mg kg^{-1}; available potassium, 143.27 mg kg^{-1}; and pH, 8.23.

Experimental design

The field experiment began in 2021, using a single-factor completely randomized block design with six treatments: (1) control (CK) with no fertilization; (2) conventional fertilization (N100B0), sole application of chemical nitrogen fertilizer; (3) biogas digestate replacing 20% of chemical nitrogen fertilizer (N80B20); (4) biogas digestate replacing 30% of chemical nitrogen fertilizer (N70B30); (5) biogas digestate replacing 40% of chemical nitrogen fertilizer (N60B40); (6) sole application of biogas digestate (N0B100). Except for the control, all treatments maintained consistent nitrogen and phosphorus application rates at pure N 225 kg hm^{-2} and P_2O_5 150 kg hm^{-2}, and the insufficient nutrients of biogas digestate were supplemented with urea (46.0% N) and triple superphosphate (46.0% P_2O_5). Biogas digestate, triple superphosphate, and part of the urea (total nitrogen from biogas digestate and urea accounted for 60% of the total nitrogen application) were used as basal fertilizers, evenly spread on the soil surface before sowing and incorporated into the 0-20 cm soil layer during plowing. The remaining urea (accounting for 40% of the total nitrogen application) was top-dressed during the first irrigation. Detailed fertilization amount for each treatment are shown in *Table 1*. The biogas digestate used in the experiment was produced by the anaerobic fermentation of cow dung, consisting of a mixture of liquid digestate and solid digestate. The tested biogas digestate contained 19.25 g kg^{-1} of organic matter, 9.55 g kg^{-1} of nitrogen (N), 4.26 g kg^{-1} of phosphorus pentoxide (P_2O_5), 8.62 g kg^{-1} of potassium oxide (K_2O), and 95.06% moisture content. The plot area was 24.0 m² (6.0 m×4.0 m) with three replications. The variety of spring wheat used in the trial was Ningchun No.4, sown on 20 March, 2022 and harvested on 14 July 2022, and on 23 March, 2023 and harvested on 15 July, 2023. The sowing density was 9 million seeds hm^{-2} with a row spacing of 15 cm.

Table 1. *Fertilizer amount of different treatments (kg hm^{-2})*

Treatments	Base fertilizer			Topdressing fertilizer
	Biogas digestate	**Urea**	**Triple superphosphate**	**Urea**
CK	0	0	0	0
N100B0	0	293.48	326.09	195.65
N80B20	4712.04	195.65	282.45	195.65
N70B30	7068.06	146.74	260.63	195.65
N60B40	9424.08	97.83	238.81	195.65
N0B100	23560.21	0	107.90	0

Measurement items and methods

Spring wheat yield measurements

During the ripening stage (BBCH 87-89) of spring wheat, yield and yield components for each experimental plot were systematically measured, three 1 m row-length sample sections were randomly chosen within each plot, the number of effective spikes in the

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

sample section was counted one by one, and subsequently converted to the number of spikes per unit area based on the planting row spacing set in the experiment. Following marginal rows were excluded to eliminate edge effects, the remaining plants within each plot were then harvested in the whole plot. Subsequent to threshing and natural air-drying constant weight, grain dry weight was precisely measured, and converted into grain yield per unit area (hectare) based on the actual harvest area of the plot. Meanwhile, 20-plant uniformly developed, representative plants with typical growth were randomly selected, following manual threshing, the total number of grains for all spikes was counted to calculate grain number per spike. Furthermore, 1,000 grains were randomly selected from the air-dried grains in each plot and weighed as the plot's thousand-kernel weight.

Soil respiration rate measurements

The soil respiration rate of the wheat field was measured using the SRS-SD1000 soil respiration measurement system manufactured by ADC BioScientific Ltd (UK) during the seedling emergence stage (BBCH 07-09), three-leaf stage (BBCH 12-14), jointing stage (BBCH 33-35), booting stage (BBCH 51-53), heading stage (BBCH 55-59), filling stage (BBCH 73-75) and ripening stage (BBCH 87-89). Measurements were conducted between 9:00 a.m. and 11:00 a.m. on three consecutive days. After spring wheat sowing, according to the experimental design, a PVC respiration ring was pressed vertically to a depth of 2 cm into the soil in the central area of each plot, with peripheral soil compaction to ensure air-tight seals. To equilibrate soil gases within the ring and avoid measurement disturbances from soil disruption, the PVC respiration ring remained fixed post-installation. All living plants and litter within the respiration ring were removed 24 hours before each measurement.

Soil temperature measurements

In each experimental plot, curved-tube type soil thermometers were vertically buried at 5 cm depth between wheat rows, and soil temperature was measured simultaneously during soil respiration monitoring.

Soil respiration temperature sensitivity coefficient (Q_{10})

The temperature sensitivity coefficient indicates the multiplicative increase of soil respiration per a 10°C increase in temperature. The relationship between soil temperature and soil respiration rate was fitted using an exponential function:

$$R_s = a \times e^{bt} \quad \text{(Eq.1)}$$

$$Q_{10} = e^{10b} \quad \text{(Eq.2)}$$

where R_s is the soil respiration rate (μmol m^{-2} s^{-1}), t is the soil temperature (°C), a and b are the regression parameters.

Soil moisture measurements

On the same morning of the soil respiration rate measurements, soil moisture (0-10 cm depth) of each experimental plot was measured using the oven-drying method. The response of soil respiration to moisture was modeled using a quadratic function:

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

$$R_s = a \times W^2 + \beta \times W + \gamma \quad \text{(Eq.3)}$$

where R_s is the soil respiration rate (μmol m^{-2} s^{-1}), W is the soil water content (%), and a, β, and γ are the fitted parameters.

Comprehensive effect of soil water and heat

The response of soil respiration to soil temperature and moisture can be modeled using a two-factor composite function:

$$R_s = z + aW + bT + cW^2 + dT^2 \quad \text{(Eq.4)}$$

where R_s is the soil respiration rate (μmol m^{-2} s^{-1}), W is the soil water content (%), t is the soil temperature (°C), and a, b, c, and d are the fitted parameters.

Statistical analysis

Data were statistically analysed using Excel 2003 and SPSS 19.0 software. Analysis of variance (ANOVA) and multiple comparisons (α=0.05) were performed using LSD (Least Significant Difference). Graphs were generated using Excel 2003 and Origin 2019 software.

Results

Dynamic variations of soil respiration rate in wheat field

The two-year experimental results (*Fig. 1*) demonstrated that soil respiration rates of all treatments exhibited similar trends, characterized by a unimodal curve where soil respiration rates initially increased and subsequently decreased with spring wheat development. From seedling emergence (BBCH 07-09) to jointing stages (BBCH 33-35), soil respiration rates of each treatment remained relatively low, followed by a rapid rise, and reached a peak from heading (BBCH 55-59) to filling stages (BBCH 73-75), then gradually declined until ripening (BBCH 87-89). Compared with the conventional fertilization treatment, replacing chemical fertilizer with biogas digestate significantly affected the soil respiration rate in wheat fields under equal nitrogen and phosphorus conditions. The soil respiration rate increased significantly (p<0.05) at all growth periods when 20% and 30% of the chemical nitrogen fertilizer was replaced with biogas digestate, with the 30% replacement treatment showed the most significant enhancement; the two-year average increased by 7.99%. The soil respiration rate of 40% and 100% replacement treatments increased significantly during the early growth stage (before heading (BBCH 55-59)) but significantly decreased or remained unchanged in the late stage (after filling (BBCH 73-75)) compared with the conventional fertilization treatment. Nevertheless, the two-year average values of the soil respiration rate of spring wheat during the entire growth period were still significantly increased by 6.32% and 5.76%, respectively (p<0.05).

Dynamic variations of soil temperature in wheat field

As shown in *Figure 2*, lower biogas digestate substitution ratios (20% and 30%) for chemical nitrogen fertilizer did not have a significant effect on the soil temperature of the wheat field (p>0.05). However, higher substitution ratios (40% and 100%) significantly affected soil temperature during early and late growth stages (p<0.05). Notably, the soil temperature significantly decreased at the seedling emergence stage (BBCH 07-09) when replacing 40% of chemical nitrogen fertilizer with biogas digestate compared with the conventional fertilization treatment, but increased significantly at the ripening stage (BBCH 87-89) only in 2023. When 100% of the chemical nitrogen fertilizer was replaced with biogas digestate, the soil temperature decreased significantly at the seedling emergence stage (BBCH 07-09), while soil temperature increased significantly at the ripening stage (BBCH 87-89). Thus, the effect of replacing chemical fertilizers with biogas digestate under equal nitrogen and phosphorus conditions on the soil temperature of wheat fields intensified with increasing substitution ratios.

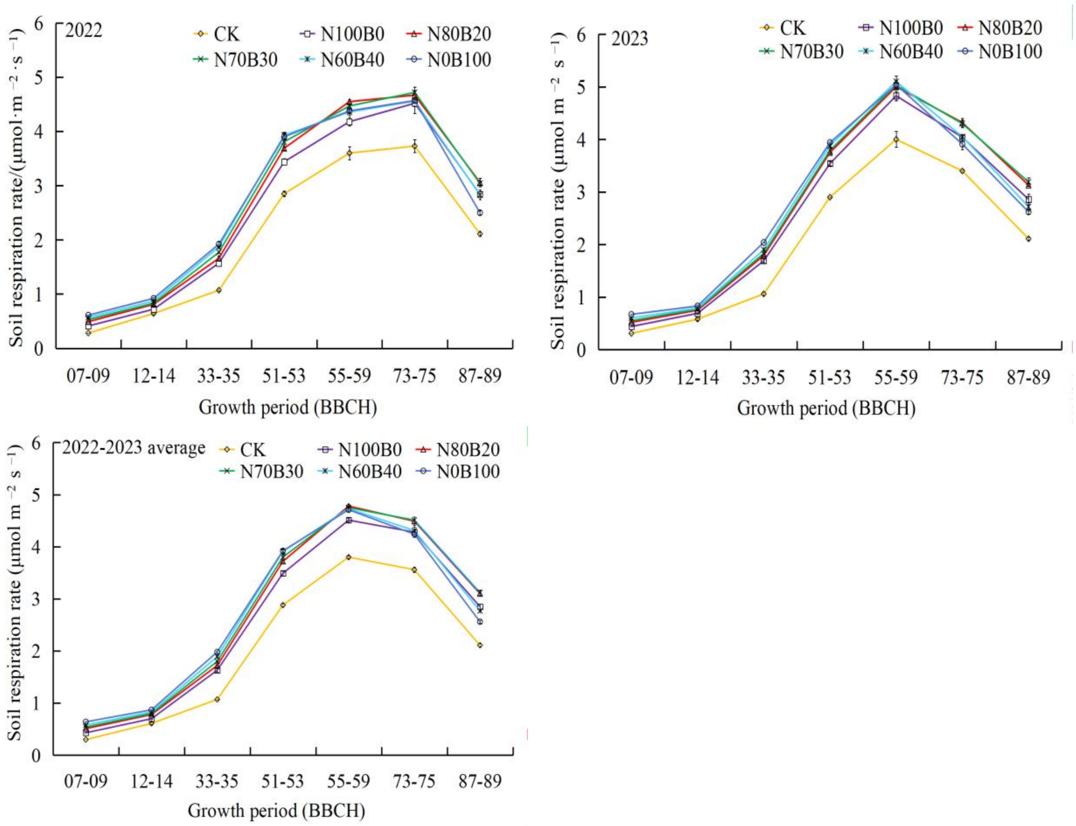

Figure 1. *Dynamic variations of soil respiration rate in wheat field when biogas digestate substitution for chemical fertilizer under equal nitrogen and phosphorus conditions*

Relationship between soil respiration rate and soil temperature in wheat fields

As shown in *Figure 3*, soil respiration rates and soil temperature exhibited highly significant positive correlations in all treatments (p<0.01), which were effectively fitted by exponential equations (*Eq.1*). Soil temperature explained 24.09%-38.81% of the variation in soil respiration rate, indicating its significant role in driving this variation in soil respiration rate. The temperature sensitivity of soil respiration Q_{10} (*Eq.2*) ranged from 2.11 to 3.49, consistently lower than the Q_{10} value of conventional fertilization treatment (3.64), when chemical fertilizer was substituted with biogas digestate under equal nitrogen and phosphorus conditions. These indicate that biogas digestate application

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

effectively reduces the temperature sensitivity of soil respiration, thereby weakening the impact of external temperature fluctuations on the soil respiration rate. Further analysis revealed that Q_{10} values decreased progressively with increasing biogas digestate substitution rates, indicating that the temperature sensitivity of soil respiration diminishes with increasing substitution ratios.

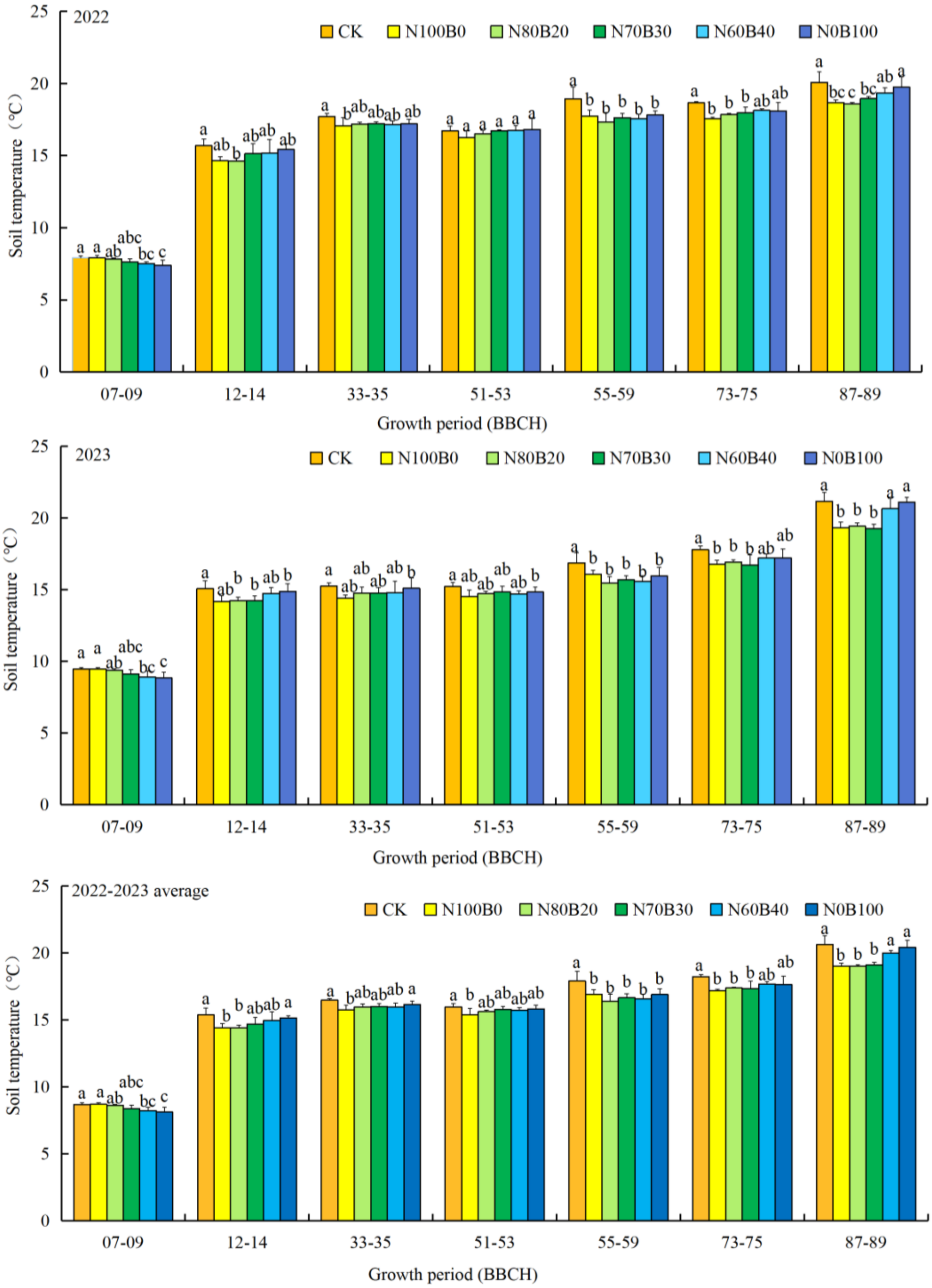

***Figure 2.** Dynamic variations of soil temperature in wheat field when biogas digestate substitution for chemical fertilizer under equal nitrogen and phosphorus conditions. Note: Error bars indicate standard deviation. Different lowercase letters above the bars mean significant differences among treatments in the same growth stage at the 0.05 level*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

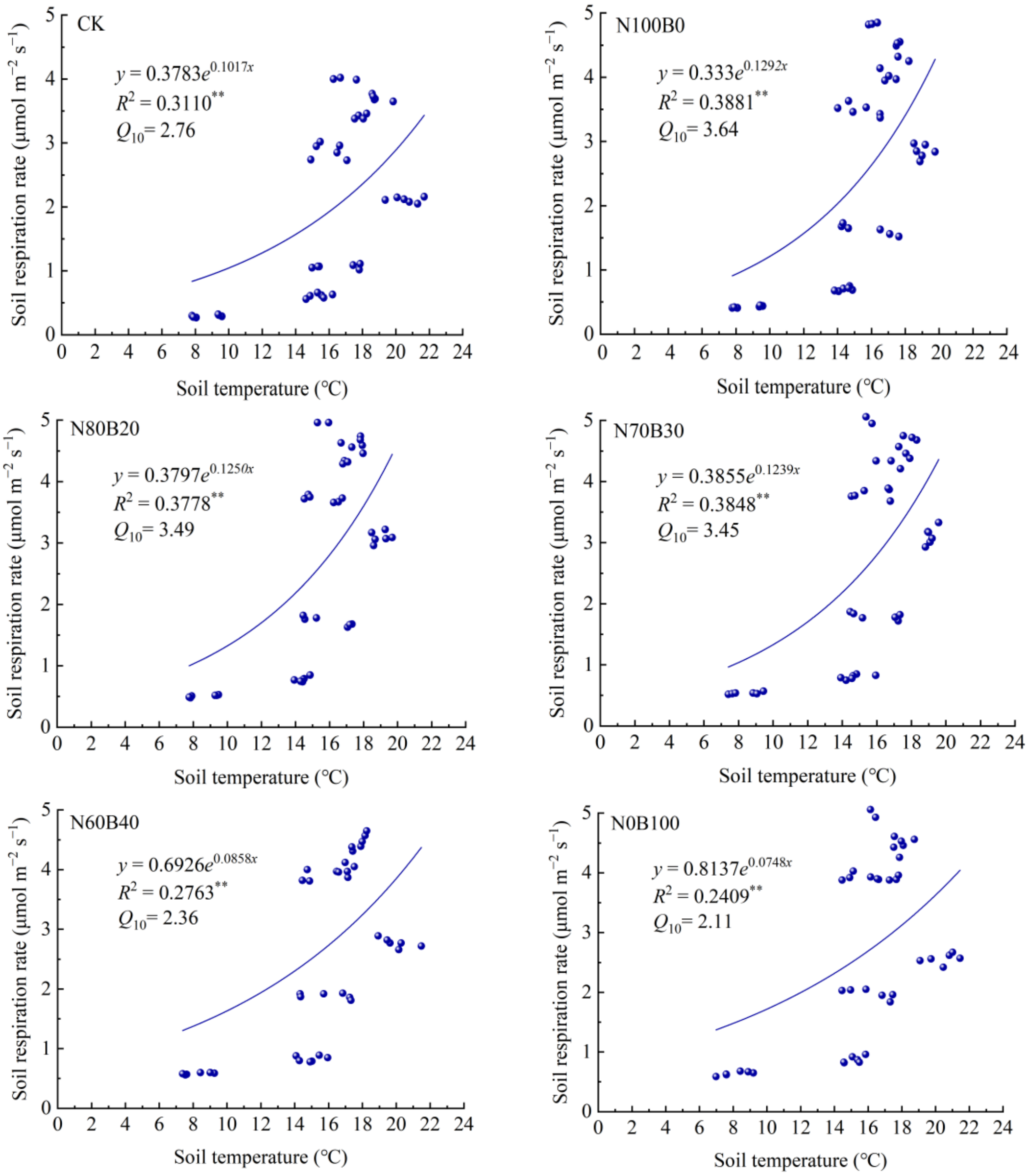

***Figure 3.** Model fitting of soil respiration rate and soil temperature in wheat fields when biogas digestate substitution for chemical fertilizer under equal nitrogen and phosphorus conditions*

Dynamic variations of soil moisture in wheat fields

As shown in *Figure 4*, compared with the conventional fertilization treatment, no significant variation in soil moisture was observed at all growth periods when 20% of chemical nitrogen fertilizer was replaced with biogas digestate. However, replacing 30% of chemical nitrogen fertilizer with biogas digestate significantly increased soil moisture only at the three-leaf stage (BBCH 12-14). When 40% of chemical nitrogen fertilizer was replaced with biogas digestate, the increase magnitude of soil moisture at each growth stage varied with years, but the two-year average soil moisture was significantly increased at both the seedling emergence stage (BBCH 07-09) and the ripening stage (BBCH 87-89). Under complete substitution of chemical nitrogen fertilizer with biogas digestate, the increase magnitude of soil moisture also varied with years at each growth stage; however,

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

the two-year average soil moisture significantly increased at the seedling emergence (BBCH 07-09), three-leaf (BBCH 12-14), booting (BBCH 51-53), and ripening stages (BBCH 87-89). These findings indicate that the effect of biogas digestate substitution for chemical fertilizer on soil moisture in wheat fields intensified with increasing substitution ratios.

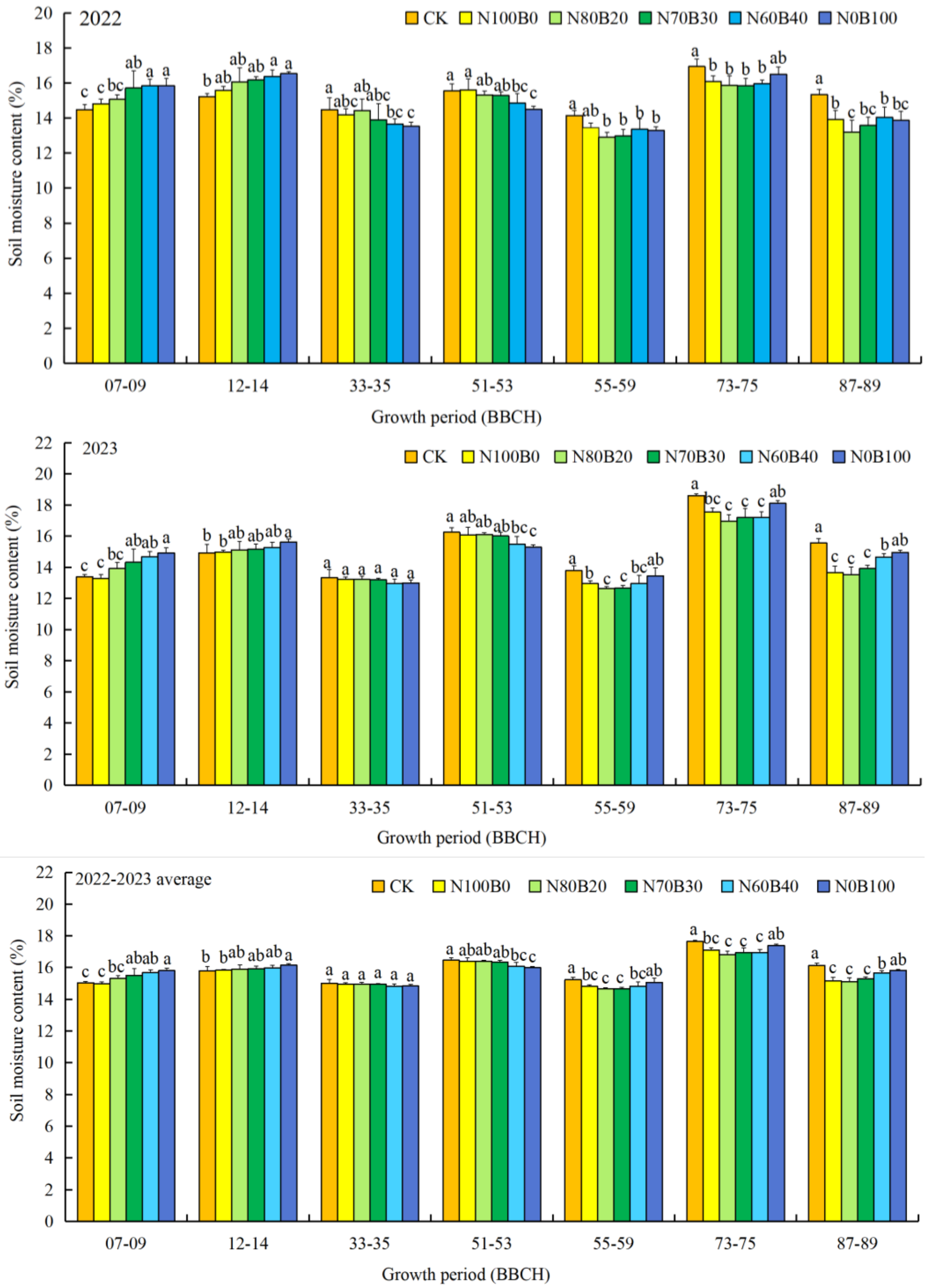

***Figure 4.** Dynamics variations of soil moisture in wheat fields when biogas digestate substitution for chemical fertilizer under equal nitrogen and phosphorus conditions. Note: Error bars indicate standard deviation. Different lowercase letters above the bars mean significant differences among treatments in the same growth stage at the 0.05 level*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

Relationship between soil respiration rate and soil moisture in wheat fields

Nonlinear fitting of soil respiration rates to soil moisture when biogas digestate replacing chemical fertilizer under equal nitrogen and phosphorus conditions (*Eq.3*) revealed that the correlation between soil moisture and soil respiration rate weakened with increasing biogas digestate substitution ratios (*Fig. 5*). Specifically, a highly significant positive correlation (p<0.01) was observed between soil moisture and soil respiration rate when 20% and 30% of chemical nitrogen fertilizer was replaced with biogas digestate, and soil moisture could explain 28.57% and 21.56% of the variation in soil respiration rates, respectively. In contrast, no significant correlation was found when 40% and 100% of chemical nitrogen fertilizer was replaced with biogas digestate (p>0.05), with soil moisture explaining only 10.78% and 12.98% of the variation in soil respiration rate, respectively. Therefore, the explanatory power of soil moisture on soil respiration diminished with increased biogas digestate application.

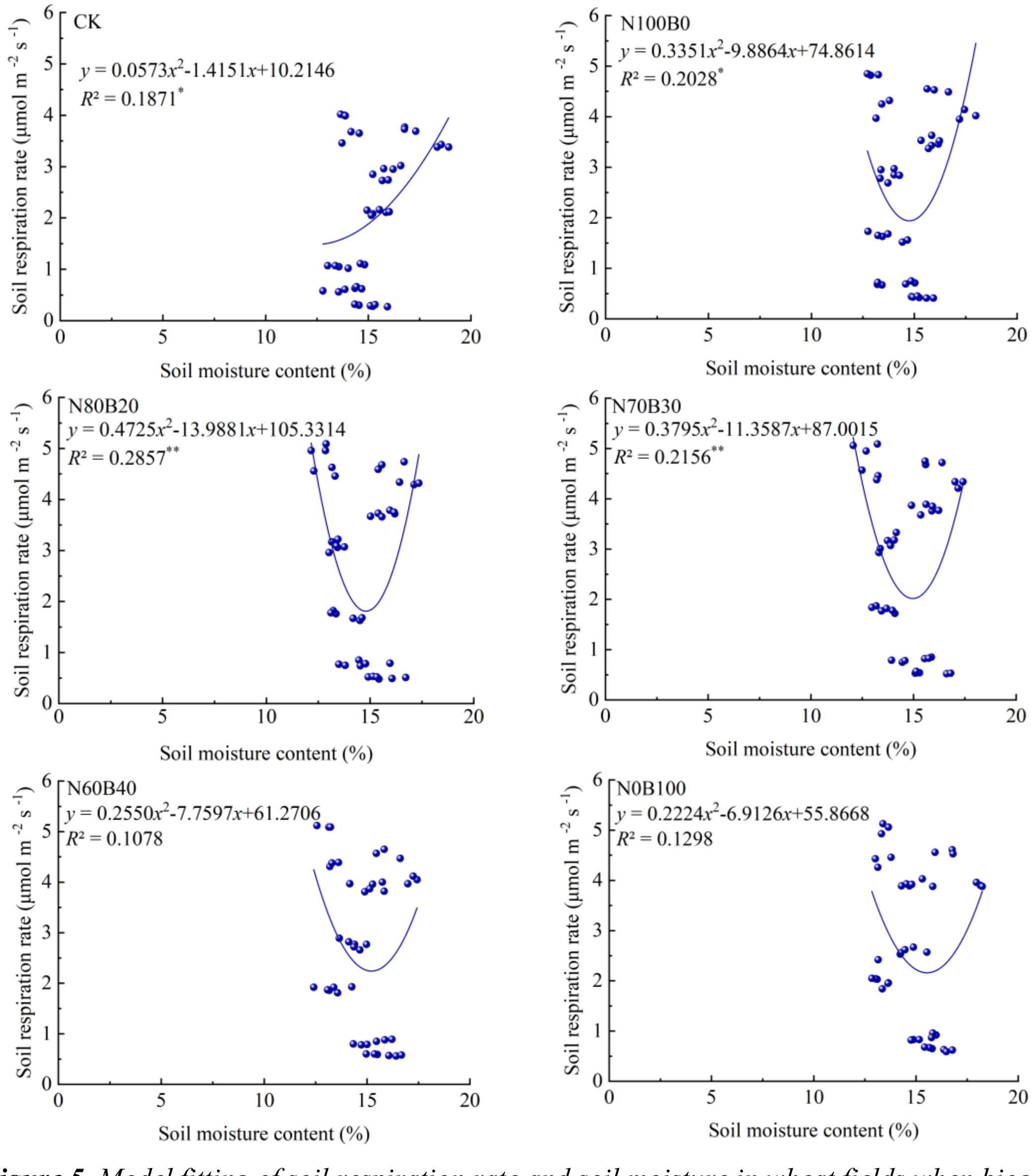

***Figure 5.** Model fitting of soil respiration rate and soil moisture in wheat fields when biogas digestate substitution for chemical fertilizer under equal nitrogen and phosphorus conditions*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

Relationships of soil temperature and moisture with soil respiration rates in wheat fields

The two-factor composite model of soil respiration rate, incorporating soil temperature and moisture as variables when biogas digestate replacing chemical fertilizer under equal nitrogen and phosphorus conditions (*Eq.4*), demonstrated a p-value below 0.01 for each treatment (*Table 2*). These results indicate a strong model fit and high significance, with R^2 values ranging from 0.396 to 0.632, exceeding the values from the single-factor model (R^2 of 0.108-0.388). This suggests that the composite model more effectively explains variations in soil respiration rates. Specifically, the model could explain 63.15% and 62.01% of the variation under 20% and 30% replacement of chemical nitrogen fertilizer with biogas digestate, respectively, which were higher than those under 40% and 100% replacement ratios (44.32% and 39.59%).

Table 2. *Two-factor composite model of soil respiration rate with soil temperature and moisture in wheat fields when biogas digestate substitution for chemical fertilizer under equal nitrogen and phosphorus conditions*

Treatment	Optimal polynomial regression equation	R^2	p
CK	R_s=2.07T+0.59W-0.10TW-0.01T^2+0.05W^2-22.92	0.5277	0.0001
N100B0	R_s=3.14T-4.26W-0.15TW-0.02T^2+0.23W^2+5.40	0.5884	0.0001
N80B20	R_s=-0.84T-12.46W+0.06TW+0.01T^2+0.39W^2+96.97	0.6315	0.0001
N70B30	R_s=-1.46T-12.19W+0.08TW+0.02T^2+0.037W^2+100.22	0.6201	0.0001
N60B40	R_s=0.63T-7.25W-0.01T^2+0.24W^2+49.47	0.4432	0.0002
N0B100	R_s=0.19T-4.53W+0.03TW-0.01T^2+0.14W^2+34.22	0.3959	0.0020

R_s, Soil CO_2 emission rate, W, Soil moisture content; T, Soil temperature

Spring wheat yield and its components

As shown in *Table 3*, compared with conventional fertilization treatment, the effects of biogas digestate replacing chemical fertilizer on spring wheat yield and its components under equal nitrogen and phosphorus conditions were different due to different substitution ratios. Replacing 20% of the chemical nitrogen fertilizer with biogas digestate significantly increased the yield of spring wheat by increasing the grain number per spike (p<0.05), with an average yield increase of 9.10% over two years. Replacing 30% of the chemical nitrogen fertilizer with biogas digestate guaranteed a stable yield by maintaining the stability of the thousand-kernel weight, grain number per spike, and spike number (p>0.05). When 40% and 100% of the chemical nitrogen fertilizer were replaced with biogas digestate, there was no significant effect on the grain number per spike and spike number of spring wheat. Nevertheless, there was a significant decrease in grain yield due to a significant decrease in thousand-kernel weight (p<0.05), with an average decrease of 5.71% and 9.62% over two years. Thus, under the premise of maintaining the stability of spring wheat grain yield, the appropriate replacement ratio of chemical nitrogen fertilizer with biogas digestate is 30%.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

Table 3. *Spring wheat yield and its components when biogas digestate substitution for chemical fertilizer under equal nitrogen and phosphorus conditions*

Treatment		CK	N100B0	N80B20	N70B30	N60B40	N0B100
Thousand-kernel weight (g)	2022	50.57 a	48.65 b	48.69 b	48.01 bc	46.70 cd	45.38 d
	2023	52.20 a	49.87 b	49.82 b	49.90 b	48.66 c	47.80 c
	Average	51.39 a	49.26 b	49.25 b	48.96 b	47.68 c	46.59 c
Grain number per spike	2022	15.87 d	19.62 c	21.49 a	20.60 b	20.45 bc	20.10 bc
	2023	16.77 c	22.23 b	22.89 a	22.07 b	21.94 b	22.29 b
	Average	16.32 c	20.93 b	22.19 a	21.34 b	21.20 b	21.19 b
Spike number ($\times10^4$ hm^{-2})	2022	698.14 b	771.00 a	766.40 a	762.54 a	756.31 a	742.65 ab
	2023	721.73 b	758.94 ab	776.07 ab	784.23 a	785.01 a	766.5 ab
	Average	709.94 b	764.97 a	771.24 a	773.39 a	770.66 a	754.57 ab
Grain yield (kg hm^{-2})	2022	5327.47 d	7003.22 b	7711.04 a	7183.42 b	6431.38 c	6247.68 c
	2023	5532.43 d	7280.94 b	7718.74 a	7491.66 b	7015.83 c	6997.91 c
	Average	5429.95 e	7208.75 b	7864.89 a	7337.54 b	6797.42 c	6515.09 d

Note: The different lowercase letters in the same line are significantly different at $p < 0.05$

Discussion

Effects of biogas digestate replacing chemical fertilizer under equal nitrogen and phosphorus conditions on soil respiration

This study revealed that the soil respiration rate in wheat fields with varying levels of biogas digestate substitution for chemical fertilizer under equal nitrogen and phosphorus conditions exhibited a notable seasonal variation in the Hexi Oasis Irrigation Area. With the advancement of the growth process of spring wheat, the soil respiration rate followed a unimodal curve, initially increasing and subsequently decreasing, consistent with the results of previous studies by Lü et al. (2022) and Yang et al. (2024). The dynamics of soil respiration during the spring wheat growing season were primarily influenced by the synergistic interaction of root development and microbial activity. In the early stages from seedling emergence (BBCH 07-09) to jointing (BBCH 33-35), lower temperatures and smaller plants led to limited root secretion release, resulting in reduced soil respiration rates due to insufficient carbon and energy sources for soil microorganisms. When wheat enters the heading (BBCH 55-59) to filling stage (BBCH 73-75), elevated temperatures stimulate plant growth and enhance root vigor, leading to increased root secretion that enriches the nutrient supply for soil microorganisms. Simultaneously, the aboveground photosynthetic products of wheat increased and are allocated to the root system, resulting in a significant rise in carbon influx into the soil via the roots. This substantially enhanced soil microbial activity and contributed to a peak in soil respiration rate. However, in the late growth stage, despite elevated temperatures, the physiological functions of wheat diminished, root vigor declined, and nutrient availability for soil microorganisms weakened, ultimately leading to a decrease in soil respiration rate (Lü et al., 2022). The results of this study showed that the soil respiration rate of spring wheat was significantly higher throughout the growth period when chemical fertilizer was replaced with biogas digestate under equal nitrogen and phosphorus conditions. Previous studies by Xu and Deng (2017) and Wang et al. (2019) demonstrated that organic fertilizers, such as livestock manure and green manure, could enhance CO_2 emissions

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

from agricultural soils. This phenomenon can be primarily ascribed to two factors: firstly, the application of organic fertilizer markedly elevates soil organic matter content, thereby supplying additional substrates for respiration and consequently augmenting the respiration rate (Chen et al., 2022); secondly, organic fertilizer fosters crop growth, which subsequently intensifies the respiration activity of the plant root system (Li et al., 2022). This study demonstrated that the soil respiration rate following organic-inorganic fertilizer blending was markedly higher than that of treatments using solely chemical or organic fertilizers, corroborating the findings of Zang (2015) and Zhang et al. (2012). Optimal organic-inorganic fertilizer ratios maintained a favorable carbon-to-nitrogen ratio, enhancing soil microbial community diversity (Liu et al., 2015) and optimizing microbial metabolism efficiency (Mooshammer et al., 2014). However, excessive organic material could reduce soil aeration, inhibiting soil microbial activity. Some studies suggested that organic fertilizer alone had a stronger impact on soil respiration than organic-inorganic mixtures (Wang et al., 2009; Xu et al., 2012; Chen et al., 2022). This discrepancy may originate from variations in microbial community structure and crop nutrient requirements in different soil regions. Notably, chemical fertilizers were observed to suppress soil respiration, counteracting the stimulating effect of organic fertilizers (Chen et al., 2022). Therefore, when assessing the impact of organic fertilizer substitution for chemical fertilizers on soil respiration, factors such as specific crop types and organic fertilizer substitution ratios should be comprehensively considered.

Effect of biogas digestate replacing chemical fertilizer under equal nitrogen and phosphorus conditions on soil temperature and soil respiration temperature sensitivity

Temperature is a critical environmental factor influencing soil respiration rate and is commonly utilized to elucidate its dynamic variations (Rodeghiero and Cescatti, 2005; Du et al., 2015). This research demonstrated that under equal nitrogen and phosphorus conditions, the impact of replacing chemical fertilizer with biogas digestate on soil temperature in wheat fields intensified with increasing substitution ratios, and moreover reached a significant level when the proportion reached a certain threshold (≥40%). In terms of the mechanism of action, a low rate of biogas digestate substitution has a limited effect on physical properties such as soil porosity and thermal conductivity, and thus is not sufficient to significantly influence soil temperature dynamics. Conversely, higher rates of biogas digestate substitution enhance soil heat capacity, consequently retarding the rate of soil warming in spring and leading to a significant decrease in soil temperature during the seedling emergence stage (BBCH 07-09). In view of this, during the spring wheat planting process in the Hexi Oasis Irrigation Area, it is necessary to carefully control the proportion of biogas digestate substituting for chemical fertilizers. This is to avoid delaying the seedling emergence stage (BBCH 07-09) due to excessive substitution (≥40%) and thereby reducing wheat yield due to missing the optimal fertility period. Soil respiration temperature sensitivity (Q_{10}) reflects the responsiveness of soil respiration to temperature variations. The impact of organic fertilizer application on soil respiration temperature sensitivity remains inconclusive in existing literature. Wu et al. (2018) observed a significant decrease in soil respiration temperature sensitivity with increasing organic fertilizer application. Our study aligns with these findings, demonstrating that under chemical fertilizer reduction conditions, the combined application of biogas digestate and chemical fertilizers notably reduces soil respiration temperature sensitivity, and this effect is amplified with higher biogas digestate substitution ratios. Mechanistically, organic components like humus and polysaccharides in biogas digestate

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

enhance soil pore structure, stabilize soil aggregates, and create a more stable microhabitat for soil microorganisms, thereby buffering the impact of temperature fluctuations on microbial metabolic activity. Notably, a substantial proportion of biogas digestate (≥40%) increases soil stable organic matter content, such as humic acid and fulvic acid fractions (Leifeld and Fuhrer, 2005), which respond more slowly to temperature changes. Simultaneously, colloidal substances (e.g., humic acid colloids) in biogas digestate adhere to organic matter particles via physical adsorption, creating an organic-inorganic complex that diminishes the contact efficiency between the substrate and extracellular enzymes, thereby attenuating the influence of temperature fluctuations on the soil respiration process. However, certain research studies have reported conflicting results. Lu and Han (2011) discovered that the temperature sensitivity of soil respiration could be markedly augmented by the application of organic fertilizer alongside chemical fertilizer; He et al. (2018) demonstrated that temperature sensitivity escalated with increasing organic fertilizer application. This discrepancy may stem from differences in the type of organic fertilizer (e.g., biogas digestate, manure, green manure), application rate, and soil background conditions. The kind and application rate of organic fertilizer can alter soil microbial metabolic processes, thereby influencing the temperature sensitivity of soil respiration (Wang et al., 2017; Han et al., 2023). Our study further validated that in the spring wheat cropping system of the Hexi Oasis Irrigation Area, the judicious application of biogas digestate, alongside the reduction in chemical fertilizer, not only preserves the stable correlation between soil respiration and temperature but also effectively mitigates the disruption of the soil carbon cycle caused by extreme temperature events through reduced temperature sensitivity. This mechanism stabilizes the soil carbon pool in agricultural ecosystems and diminishes the coefficient of variation of soil carbon fluxes caused by temperature fluctuations, thus providing a crucial theoretical basis for attaining carbon neutrality in regional agriculture.

Response of soil respiration to soil moisture when biogas digestate substitution for chemical fertilizer under equal nitrogen and phosphorus conditions

Soil moisture, a fundamental environmental factor governing soil ecosystem functions, significantly influences soil respiration processes (He et al., 2021). This study demonstrated that the relationship between soil respiration and soil moisture exhibited a substantially declining trend under chemical fertilizer reduction conditions with increasing biogas digestate substitution ratios. Specifically, Soil moisture was highly significantly and positively correlated with soil respiration at lower substitution rates of chemical nitrogen fertilizer (20% and 30%). However, this correlation became non-significant when biogas digestate substitution ratios rose to 40% and 100%. This trend originates from the arid climate of the study area, where moisture primarily limits crop growth. High levels of biogas digestate notably improved soil water and nutrient retention, ensuring a stable water supply for spring wheat growth and alleviating water stress effects on crops. Previous studies by Chen (2022) and Zhou et al. (2021) suggested that soil moisture becomes a critical constraint on soil respiration only when it falls below the permanent wilting point of the crop or exceeds the field water capacity. Further analysis indicated that the explanatory power of soil moisture for the variation in soil respiration rate diminished progressively with increasing biogas digestate substitution ratios. The potential mechanism is that moderate application of biogas digestate supplies an adequate easily decomposable carbon source for soil microorganisms, thereby enhancing microbial activity and sustaining the appropriate carbon-to-nitrogen ratio, rendering microbial

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

metabolic processes highly responsive to moisture fluctuations (Chen et al., 2014). Conversely, excessive biogas digestate application led to substantial dissolved organic carbon accumulation, altering microbial metabolic pathways (Liang et al., 2017) and disrupting the soil carbon-to-nitrogen ratio balance, which prompted microbes to adopt more conservative carbon utilization strategies (Mooshammer et al., 2014). These findings contrast with those of Yan et al. (2019), who reported that fertilization practices did not enhance the ability of soil moisture to explain soil respiration variability. This discrepancy may stem from differences in climatic conditions (arid versus semi-arid zones) and the crop type tested (spring wheat versus sorghum) in the study area. Variances in climatic conditions directly impact soil moisture dynamics, while differences in root distribution, water uptake characteristics, and their interactions with soil microorganisms may lead to significant variations in the response mechanism of soil respiration to water.

Effect of biogas digestate substitution for chemical fertilizer under equal nitrogen and phosphorus conditions on the explanatory power of soil respiration rate model

In this study, we conducted a systematic investigation into the regulatory effects of soil temperature and moisture on soil respiration rates through the development of single-factor and two-factor regression models. Our findings demonstrated that compared with the single-factor model, the two-factor model incorporating soil temperature and moisture could more accurately explain the dynamic variations in soil respiration rate, which was highly consistent with the research findings of Davidson et al. (2006). Further analysis revealed that among different treatments of replacing chemical fertilizer with biogas digestate, there were significant differences in the model explanatory power. At substitution ratios of 20% and 30% with biogas digestate, the explanatory power of the two-factor model for the variations in soil respiration rate was significantly higher than that in treatments with high substitution rates (40% and 100%) and the conventional fertilization treatment. The conventional fertilization treatments constrained the soil microbial activity due to insufficient substrate supply and the lack of continuous replenishment of organic carbon sources. Conversely, moderate nitrogen fertilizer reduction (20% and 30%) combined with biogas digestate application effectively sustained soil microbial community activity and diversity, enhancing the sensitivity of soil respiration to variations in environmental factors. However, an imbalance in the soil carbon-to-nitrogen ratio became evident when chemical nitrogen fertilizer reduction exceeded 40%, potentially leading to a depletion of inorganic nitrogen levels below the critical threshold required for microbial metabolism. This nitrogen deficiency obstructed the carbon decomposition process, and despite increased carbon inputs from biogas digestate, microbes remained unable to overcome metabolic constraints, thereby diminished the explanatory power of the two-factor model for the soil respiration rate. Lan et al. (2021) observed that soil microbial entropy reached its peak when organic fertilizer replaced 30% of chemical nitrogen fertilizer, further confirming the significance of maintaining a balance between carbon and nitrogen inputs for ensuring the activity of decomposers. Our results not only reveal the regulatory mechanism of soil respiration's response to environmental factors but also provide an important theoretical basis for optimizing fertilization management strategies in farmland.

The soil respiration-hydrothermal coupling model established in this study exhibits distinct regional specificity and scenario applicability. Its parameters were calibrated according to the unique climatic conditions, soil properties, and spring wheat cropping system of the Hexi Oasis Irrigation Area. Thus, specific parameters such as regression

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

coefficients and explanatory power cannot be directly extrapolated to other regions, necessitating recalibration based on local climate, soil, and crop characteristics. Nevertheless, the model's core regulatory mechanisms yield universal insights: First, a moderate organic-inorganic fertilizer combination (e.g., 20%-30% substitution with biogas digestate) optimizes soil C/N balance, thereby enhancing soil respiration sensitivity to hydrothermal factors—a principle transferable to arid/semi-arid farmland ecosystems. Second, high organic substitution ratios may induce C/N imbalance, weakening the soil respiration-hydrothermal correlation. This finding provides a critical reference for fertilization optimization in analogous regions.

Effect of biogas digestate substitution for chemical fertilizer under equal nitrogen and phosphorus conditions on spring wheat yield

Substituting organic fertilizer for chemical fertilizer is one of the key measures for reducing the amount of chemical nitrogen fertilizer while maintaining crop yield. This study showed that applying biogas digestate under chemical fertilizer reduction conditions promoted spring wheat yield. However, this effect was related to the substitution ratio. Specifically, a moderate substitution level of 20% significantly enhanced yields. However, when the substitution ratio reached 30%, there was no yield-increasing effect, and the yield remained stable. Substitutions of 40% and 100% led to a yield reduction. These results are consistent with the findings of Niu et al. (2024), who observed a significant yield increase when 25% of chemical fertilizer was replaced with manure in the Guanzhong Plain, but noted a decrease with full substitution. However, the range of substitution ratios (50%-75%) that maintained relatively stable wheat yield was higher than those in this study (Niu et al., 2024). This difference may be related to the nutrient release characteristics of the biogas digestate, regional climate, and soil fertility differences. Similarly, Cai and Qin (2006) found that the sole application of organic fertilizer significantly reduced wheat yield. A meta-analysis by Li et al. (2020) indicated that wheat yield was significantly increased when the substitution ratio of organic fertilizer was < 30%, and there was no yield increase effect when the substitution ratio was > 30%. Discrepancies in findings were noted across different regions and organic fertilizer types. For instance, Zhao et al. (2015) reported a significant increase in wheat yield when cow dung replaced 50% of chemical nitrogen fertilizer in the Huanghuaihai Plain; in contrast, Wang et al. (2015) noted a decrease in wheat yields with the substitution of 50% chemical fertilizer by rapeseed cake fertilizer in North China. Meanwhile, Yang et al. (2018) found that replacing 70% of chemical nitrogen fertilizers with cattle manure in the Northwest Loess Plateau maintained stable yields. These findings collectively suggest that the yield-enhancing effects of organic fertilizers depend on the type, substitution ratio, and regional conditions.

From a mechanistic point of view, organic fertilizers release nutrients slowly and exhibit long-term nutrient release characteristics. Although they have lower nutrient supply capacity than chemical fertilizers in the early stage under equal nitrogen and phosphorus conditions, they have an advantage in the later stage by releasing nitrogen, phosphorus, and potassium nutrients, as well as medium and trace elements, in a sustained manner. Moreover, organic fertilizers can enhance soil microbial growth, increase bacterial diversity, and improve soil productivity (Liang et al., 2009). They also facilitate root uptake and crop growth by improving soil structure, water retention, and nutrient retention capacity (Su et al., 2006). However, complete replacement of chemical fertilizers with organic alternatives may lead to an insufficient available nitrogen supply

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_14971516

in the current season, resulting in yield reduction (Xin et al., 2017). Combining organic and chemical fertilizers can harness the benefits of both fertilizer types, ensuring a consistent and stable nutrient supply throughout the entire growth period of wheat, ultimately leading to high yields. In summary, when advocating for organic fertilizer substitution technology, it is crucial to optimize the substitution ratio based on specific crops and regional conditions to achieve a balanced increase in yield, sustainable fertilization, and efficient resource utilization. In the Hexi Oasis Irrigation Area, substituting 30% of chemical nitrogen fertilizer with biogas digestate could maintain a stable spring wheat yield.

Conclusion

Our findings indicate that under equal nitrogen and phosphorus conditions, substituting 30% of chemical nitrogen fertilizer with biogas digestate ensures no yield loss in spring wheat through synergistic modulation of thousand-grain weight, grain number per spike, and spike number, while significantly enhancing soil respiratory activity, increasing soil moisture content during the three-leaf stage (BBCH 12-14), diminishing soil respiration temperature sensitivity, and optimizing soil water-heat coupling. This approach establishes an optimal fertilization regime for sustainable spring wheat production in the Hexi Oasis Irrigation Area. In the future, studies should investigate a more in-depth analysis of the variation characteristics of soil microbial community structure and function under varying substitution ratios of chemical nitrogen fertilizer with biogas digestate to improve the ecological mechanism of biogas digestate utilization.

Acknowledgements. This research was supported by the National Natural Science Foundation of China (42167010).

REFERENCES

[1] Cai, Z. C., Qin, S. W. (2006): Dynamics of crop yields and soil organic carbon in a long-term fertilization experiment in the Huang-Huai-Hai Plain of China. – Geoderma 136(3-4): 708-715. https://doi.org/10.1016/j.geoderma.2006.05.008.

[2] Chen, R. R., Senbayram, M., Blagodatsky, S., Myachina, O., Dittert, K., Lin, X. G., Blagodatskaya, E., Kuzyakov, Y. (2014): Soil C and N availability determine the priming effect: microbial N mining and stoichiometric decomposition theories. – Global Change Biology 20(7): 2356-2367. doi: 10.1111/gcb.12475.

[3] Chen, S. Y., Yang, R., Su, Y. Z., Du, Z. Y. (2022): Characteristics of soil respiration in farmland of Hexi oasis and its response to long-term fertilization. – Journal of Desert Research 42(3): 178-186.

[4] Chen, M. N., Yang, H. L., Yang, Q. S., Li, Y. S., Wang, H., Wang, J. L., Fan, Q. L., Yang, N., Wang, K., Zhang, J. C., Yuan, J. W. (2024): Different impacts of long-term tillage and manure on yield and N use efficiency, soil fertility, and fungal community in rainfed wheat in Loess Plateau. – Plants 13(24): 3477. https://doi.org/10.3390/plants13243477.

[5] Davidson, E. A., Janssens, I. A., Luo, Y. Q. (2006): On the variability of respiration in terrestrial ecosystems: moving beyond Q_{10}. – Global Change Biology 12(2): 154-164. https://doi.org/10.1111/j.1365-2486.2005.01065.x.

[6] Du, S. S., Yang, Q., Zhang, Q. P., Wang, T., Shen, Y. Y. (2015): Effects of conservation tillage on soil respiration in vetch field in rain-fed Loessial tablelands. – Bulletin of Soil and Water Conservation 35(6): 144-148. https://doi.org/10.13961/j.cnki.stbctb.2015.06.025.

[7] Han, C. Y., Zhao, X. C., Hu, Y. J., Zhang, X. X. (2023): Spatiotemporal differences of agricultural carbon income and expenditure, and carbon compensation potential of counties in Hunan Province. – Bulletin of Soil and Water Conservation 43(5): 343-354. https://doi.org/10.13961/j.cnki.stbctb.2023.05.040.

[8] He, M., Wang, L. G., Wang, Y. C., Shen, X., Zhang, Y. T., Zhu, P. (2018): Characteristic of black soil respiration and its influencing factors under long-term fertilization regimes. – Transactions of the Chinese Society of Agricultural Engineering 34(4): 151-161.

[9] He, T. T., Wang, J., Fu, Y. P., Fu, X. Y., Liu, T., Li, Y. K., Li, J. H. (2021): Effects of adding straw and biochar with equal carbon content on soil respiration and microbial biomass carbon and nitrogen. – Environmental Science 42(1): 450-458. doi: 10.13227/j.hjkx.202004196.

[10] Hursh, A., Ballantyne, A., Cooper, L., Maneta, M., Kimball, J., Watts, J. (2017): The sensitivity of soil respiration to soil temperature, moisture, and carbon supply at the global scale. – Global Change Biology 23(5): 2090-2103. doi:10.1111/gcb.13489.

[11] Lal, R. (2004): Soil carbon sequestration impacts on global climate change and food security. – Science 304(5677): 1623-1627. doi: 10.1126/science.1097396.

[12] Lan, X. J., Liu, Y. R., Hou, H. Q., Lü, Z. Z., Ji, J. H., Feng, Z. B., Liu, X. M. (2021): Effect of long-term organic manure application combined with chemical fertilizers on soil microbial biomass and organic matter structure in red paddy. – Journal of Agricultural Resources and Environment 38(5): 810-819.

[13] Leifeld, J., Fuhrer, J. (2005): The temperature response of CO_2 production from bulk soils and soil fractions is related to soil organic matter quality. – Biogeochemistry 75(3): 433-453. https://doi.org/10.1007/s10533-005-2237-4.

[14] Li, Y. H., Wu, X. P., He, G., Wang, Z. H. (2020): Benefits of Yield, Environment and Economy from Substituting Fertilizer by Manure for Wheat Production of China. – Scientia Agricultura Sinica 53(23): 4879-4890.

[15] Li, X. L., He, T. Q., Zhang, C. X., Tian, M. H., Wu, M., Li, C. H., Yang, Q. H., Zhang, X. L. (2022): Effect of organic fertilizer replacing chemical fertilizers on greenhouse gas emission under the conditions of same nitrogen fertilizer input in maize farmland. – Scientia Agricultura Sinica 55(5): 948-961. https://doi.org/10.3864/j.issn.0578-1752.2022.05.009.

[16] Liang, W. J., Lou, Y. L., Li, Q., Zhong, S., Zhang, X. K., Wang, J. K. (2009): Nematode faunal response to long-term application of nitrogen fertilizer and organic manure in Northeast China. – Soil Biology and Biochemistry 41(5): 883-890. https://doi.org/10.1016/j.soilbio.2008.06.018.

[17] Liang, C., Schimel, J. P., Jastrow, J. D. (2017): The importance of anabolism in microbial control over soil carbon storage. – Nature Microbiology 2: 17105. https://doi.org/10.1038/nmicrobiol.2017.105.

[18] Liangzhou District People's Government. Material resources. (2025): http://www.gsliangzhou.gov.cn/col/col2877/index.html.

[19] Liu, Z. X., Liu, P., Jia, X. C., Cheng, Y., Dong, S. T., Zhao, B., Zhang, J. W., Yang, J. S. (2015): Effects of irrigation and fertilization on soil microbial properties in summer maize field. – Chinese Journal of Applied Ecology 26(1): 113-121.

[20] Lu, S. J., Han, X. Z. (2011): The Effect of Fertilization on Soil Respiration. – System Sciences and Comprehensive Studies in Agriculture 27(3): 366-370.

[21] Lü, M. F., Ma, X. C., Cai, T., Jia, Z. K. (2022): Effects of biochar application on soil hydrothermal environment and soil respiration in winter wheat field. – Agricultural Research in the Arid Areas 40(3): 197-206.

[22] Mooshammer, M., Wanek, W., Hämmerle, L., Fuchslueger, L., Hofhansl, F., Knoltsch, A., Schnecker, J., Takriti, M., Watzka, M., Wild, B., Keiblinger, K. M., Zechmeister-Boltenstern, S., Richter, A. (2014): Adjustment of microbial nitrogen use efficiency to carbon: nitrogen imbalances regulates soil nitrogen cycling. – Nature Communications 5: 3694. https://doi.org/10.1038/ncomms4694.

[23] Niu, J. C., Saeed, Q., Wang, W. N., Zhang, R. Z., Liu, L., Lü, F. L., Xu, J. X., Han, Y., Zhang, P. X., Hu, C. L., Xu, H., Sun, B. H., Yang, X. Y., Zhang, S. L. (2024): Manure replacing synthetic fertilizer improves crop yield sustainability and reduces carbon footprint under winter wheat-summer maize cropping system. – Journal of Environmental Management 358: 120936. https://doi.org/10.1016/j.jenvman.2024.120936.

[24] Rodeghiero, M., Cescatti, A. (2005): Main determinants of forest soil respiration along an elevation/temperature gradient in the Italian Alps. – Global Change Biology 11(7): 1024-1041. DOI:10.1111/j.1365-2486.2005.00963.x.

[25] Shi, H. L., Jiang, L. S., Tan, X. H., Gan, F. L., Xia, Y. Y., Li, W. Y., Xu, X. Y., Yan, Y. J., Fan, Y. C., Pu, J. B. (2025): Changes in vegetation types alter soil respiration under the erosion and deposition topography in karst trough valley. – Catena 255: 109027. https://doi.org/10.1016/j.catena.2025.109027.

[26] Su, Y. Z., Wang, F., Suo, D. R., Zhang, Z. H., Du, M. W. (2006): Long-term effect of fertilizer and manure application on soil-carbon sequestration and soil fertility under the wheat-wheat-maize cropping system in northwest China. – Nutrient Cycling in Agroecosystems 75: 285-295. https://doi.org/10.1007/s10705-006-9034-x.

[27] Wang, Y. P., Gao, J. X., Feng, C. Y., Du, X. G. (2009): Soil respiration characteristics of different fertilization types in peach farms in Beijing suburb. – Journal of Zhejiang University (Agric & Life Sci) 35: 77-83. https://doi.org/10.3785/j.issn.1008-9209.2009.01.011.

[28] Wang, J. Y., Yan, X. Y., Gong, W. (2015): Effect of long-term fertilization on soil productivity on the North China Plain. – Pedosphere 25(3): 450-458. https://doi.org/10.1016/S1002-0160(15)30012-6.

[29] Wang, C. X., Yu, P., Zhang, Y. L., Fan, Q. F., Yu, N., Zou, H. T., Zhang, Y. L. (2017): Effect of combined application of nitrogen fertilizer and manure on soil respiration in greenhouse cultivation. – Chinese Journal of Soil Science 48(1): 146-154.

[30] Wang, X. J., Zhang, R. Z., Qi, P., Jiao, Y. P., Cai, L. Q., Wu, J., Xie, J. H. (2019): Meta-analysis on farmland soil CO_2 emission in Northern China affected by organic fertilizer. – Transactions of the Chinese Society of Agricultural Engineering 35(10): 99-107.

[31] Wu, R. J., Wang, Y. C., Zhu, P., He, M., Huang, C. C., Wang, L. G., Zhang, F. L. (2018): Effects of long-term fertilization on soil respiration in spring maize field in the central part of northeast China. – Journal of Plant Nutrition and Fertilizers 24(1): 44-52. DOI:10.11674/zwyf.17109.

[32] Xin, X. L., Qin, S. W., Zhang, J. B., Zhu, A. N., Yang, W. L., Zhang, X. F. (2017): Yield, phosphorus use efficiency and balance response to substituting long-term chemical fertilizer use with organic manure in a wheat-maize system. – Field Crops Research 208: 27-33. https://doi.org/10.1016/j.fcr.2017.03.011.

[33] Xing, M. Q., Ma, K., Chen, C. L., Li, J. (2024): Measurement and coupling coordination promotion path of agricultural green development level in the Hexi Region. – Journal of Desert Research 44(6): 207-219.

[34] Xiong, Y., Wang, L., Zhao, L., Du, J., Zhang, S., Zhou, Q. (2017): Soil respiration and carbon balance in fava bean farmland under conservation tillage. – Acta Prataculturae Sinica 26(1): 13-22.

[35] Xu, Y. M., Liu, H., Wang, X. H. (2012): The soil respiration characteristics of grey desert soil under different long-term fertilization. – Xinjiang Agricultural Sciences 49(7): 1294-1300.

[36] Xu, D. B., Deng, J. Q., Peng, W. X., Si, G. H., Peng, C. L., Yuan, J. F., Zhao, S. J., Wang, R. (2017): Effect of application of cow manure and green manure on corn yield and soil

physical-chemical properties in land restoration area. – Chinese Journal of Applied Ecology 28(3): 856-862. DOI:10.13287/j.1001-9332.201703.024.
[37] Yan, J. X., Zhang, Y., Jiao, X. Y. (2019): Effect of fertilization on soil respiration and its temperature sensitivity in a sorghum field. – Environmental Science 40(12): 5515-5523. doi: 10.13227/j.hjkx.201905138.
[38] Yang, J. Y., Wang, C. K. (2006): Effects of soil temperature and moisture on soil surface CO_2 flux of forests in northeastern China. – Journal of Plant Ecology 30(2): 286-294. DOI:10.17521/cjpe.2006.0038.
[39] Yang, Y., Zhang, S. L., Yang, X. Y. (2018): Effects of long- term fertilization on winter wheat yield and soil nutrients in rainfed loess soil. – Chinese Journal of Soil Science 49(2): 402-408.
[40] Yang, X. H., Yu, A. Z., Chai, J., Li, Y., Wang, F., Wang, P. F., Lü, H. Q., Wang, Y. L., Shang, Y. P. (2024): Effects of green manure incorporation combined with nitrogen fertilizer reduction on soil respiration and its temperature sensitivity in regard to wheat fields. – Chinese Journal of Eco-Agriculture 32(1): 61-70. DOI:10.12357/cjea.20230313.
[41] Zang, Y. F., Hao, M. D., Zhang, L. Q., Zhang, H. Q. (2015): Effects of wheat cultivation and fertilization on soil microbial biomass carbon, soil microbial biomass nitrogen and soil basal respiration in 26 years. – Acta Ecologica Sinica 35(5): 1445-1451. DOI:10.5846/stxb201305070967.
[42] Zhang, Q. B., Yang, L., Wang, J., Luo, H. H., Zhang, Y. L., Zhang, W. F. (2012): Effects of different irrigation methods and fertilization measures on soil respiration and its component contributions in cotton field in arid region. – Scientia Agricultura Sinica 45(12): 2420-2430.
[43] Zhang, D. C., Cai, D. X., Dai, K., Feng, Z. H., Zhang, X. M., Wang, X. B. (2013): Soil respiration and its responses to soil moisture and temperature under different tillage systems in dryland maize fields. – Acta Ecologica Sinica 33(6): 1916-1925. https://doi.org/10.5846/stxb201110071460.
[44] Zhao, J., Dong, S. T., Liu, P., Zhang, J. W., Zhao, B. (2015): Effects of long-term mixed application of organic and inorganic fertilizers on canopy apparent photosynthesis and yield of winter wheat. – Chinese Journal of Applied Ecology 26(8): 2362-2370.
[45] Zhou, H., Shi, H. B., Zhang, W. C., Wang, W. G., Su, Y. D., Yan, Y. (2021): Effects of the combined application of organic and inorganic fertilizers on soil microbial biomass and soil respiration in saline soil. – Transactions of the Chinese Society of Agricultural Engineering 37(15): 86-95.
[46] Zuo, X. Y., Xiao, Q., Wu, L., Yang, G. R., Zhang, W. J. (2023): Response of soil basal respiration to fertilization across China's croplands. – Journal of Plant Nutrition and Fertilizers 29(8): 1379-1389. DOI:10.11674/zwyf.2023015.