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Effectiveness of biochar on degraded irrigated soils in Southeast Kazakhstan

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ABSTRACT

The article reports on field studies investigating the impact of different doses of birch biochar on the agro-physical and agrochemical properties of degraded irrigated soils in the Akdalinsky irrigation massif in Southeast Kazakhstan. Applying biochar at rates of 15-20 ton ha^{-1} as part of the primary soil treatment enhances soil bulk density. It increases the proportion of agriculturally valuable and water-stable aggregates in the plow layer. Notable improvements were observed in the content of labile humus and available phosphorus. These enhancements in soil properties lead to increased productivity in rice crop rotations due to both the immediate and residual effects of biochar application under moldboard plowing. Rice and spring wheat yields rise mainly due to improved tillering, while soybean yields benefit from increased pod formation.

Keywords: Biochar, Irrigated agriculture, Crop yields, Soil fertility, Salinity.
Article type: Research Article.

INTRODUCTION

Kazakhstan is currently facing significant deterioration in its natural resources and environmental conditions across all major ecological indicators (Tulesheva & Yessimov 2024). Nearly one-third of agricultural lands are now degraded or under severe threat, and over 10 million hectares of potentially arable land have been abandoned (Concept of the Republic of Kazakhstan's Transition). Annual monitoring of irrigated lands by hydrogeological and melioration expeditions reveals that more than 50% of these lands are affected by varying degrees of salinization, with over 30% being saline-alkaline. Additionally, large volumes of drainage and wastewater from irrigated areas and settlements (up to 10-30%) contaminate water sources and degrade the ecological and meliorative conditions of irrigated lands and surrounding areas. From 1990 to 2020, the area of irrigated lands in Kazakhstan decreased from 2.5 million hectares to 2.1 million hectares, with only about 1.5 million hectares currently in use. Over 100,000 hectares of irrigated lands have been removed from agricultural production (Kwan *et al.* 2011). Biochar is a bio-fertilizer and a unique soil enhancer primarily composed of carbon derived from burning plant materials. It functions as an organic fertilizer that retains water and nutrients in the soil, significantly improving soil fertility and agricultural productivity. Long-term soil management has led to declining soil quality and capacity to absorb water quickly. The development and use of biochar in agriculture and forestry provide a means to enhance soil fertility rapidly. Biochar is considered one of the most promising fertilizers, as it supports healthy plant growth without contributing to atmospheric carbon dioxide pollution. Due to its high carbon content and stability, researchers often refer to biochar as "black gold" for farming. It is a widely used for soil amendment to increase crop yields and mitigate climate change impacts (Lehmann 2007; Zhang *et al.* 2016; Subedi *et al.* 2017; Guo *et al.* 2019). Using biochar has gained increasing attention as an alternative method for enhancing long-term soil carbon levels while potentially improving soil quality and crop yields (Lehmann *et al.* 2006).

Biochar refers to charcoal or carbonized biomass used to sequester carbon in soil and enhance soil fertility (O'Toole & Rasse 2016). Meta-analyses confirm that biochar can improve soil physical and hydrological functions (Omondi *et al.* 2016) and reduce N_2O and CH_4 emissions (Cayuela *et al.* 2014; Jeffery *et al.* 2016). Studies have shown that biochar increases crop yields by an average of 25% in tropical regions but has no effect in temperate regions (Jeffery *et al.* 2017). In Norway, biochar is recognized as one of the few methods capable of significantly reducing the carbon footprint of the agricultural sector (Rasse *et al.* 2017). Previous agronomic research has demonstrated that biochar can enhance water retention (Peake *et al.* 2014; Sun & Lu 2014), often due to its large surface area and internal porosity, as well as its ability to alter interparticle porosity in mineral soils (Liu *et al.* 2017). Biochar has been shown to increase saturated hydraulic conductivity (Ksat) in clay soils and decrease it in sandy soils (Barnes *et al.* 2014; Lim *et al.* 2016) by either filling pore spaces in sand or opening pore channels in clay (Masiello *et al.* 2015). However, results on biochar's impact on Ksat vary widely depending on soil type, the type of biochar used, and the application rate (Obia *et al.* 2016). Some studies report improvements in soil structure, including increased aggregate stability (Busscher *et al.* 2010; Herath *et al.* 2013; Liu *et al.* 2017) and reduced penetration resistance (Obia *et al.* 2017; Ahmed *et al.* 2017). The mechanisms involved depend on interactions between biochar and soil properties. In clay soils, biochar has been shown to reduce soil tensile strength and plasticity index (degree of swelling/shrinkage), though it typically requires higher application rates (Chan *et al.* 2008; Zong *et al.* 2014). The European Union recognizes biochar as a viable technology for long-term carbon storage in soils, aiming to mitigate climate change (Lehmann & Joseph 2009). Additionally, using biochar as a soil amendment is a promising agricultural practice that reduces nitrogen losses, improves nitrogen fertilizer efficiency, and promotes soil organic carbon accumulation (Montanarella & Lugato 2013; Field *et al.* 2013). Applying biochar as a soil amendment could even restore agricultural lands by addressing issues such as acidity, low organic carbon content, and insufficient water (Lehmann & Joseph 2012). Many studies have demonstrated that adding biochar can enhance crop yields, dry matter accumulation, and nitrogen uptake, primarily by improving soil structure, fertility, moisture, and temperature (Gaskin *et al.* 2010; Lehmann & Joseph 2012; Haider *et al.* 2017; Al Wabel *et al.* 2018; Wang *et al.* 2021). Research indicates that biochar's effects are more pronounced in heavily weathered, degraded, and nutrient-poor soils compared to well-structured, nutrient-rich, and high-quality soils (Kookana *et al.* 2011; Jien & Wang 2013; Abiven *et al.* 2014). Research on biochar in Kazakhstan is limited and has mainly focused on rehabilitating soils contaminated with heavy metals from mining and metallurgical industries in Ridder, East Kazakhstan region (Kozybaeva *et al.* 1914). Studies on fertile dark chestnut soils have shown significant effectiveness of biochar application for vegetable crops (Sarkulova 2019). However, targeted research on the effectiveness of biochar for major field crops in Kazakhstan's irrigated areas has not yet been conducted, nor have its meliorative qualities been assessed for restoring degraded, low-fertility lands in southern and southeastern Kazakhstan, particularly typical chestnut soils with close-lying pebbles and takyr-like soils, which are characterized by very low organic matter content (less than 1%). This article discusses the results of field studies conducted on degraded takyr-like soils in the Akdalinsky irrigation massif, a rice-growing region in southeastern Kazakhstan.

MATERIALS AND METHODS

Research Conditions

The field experiment was conducted at the experimental site of "Birlik" LLP in the Balkhash District of the Almaty Region, Southeast Kazakhstan (coordinates N 44.38.260 E 76.43.966) from 2022 to 2024. The study focused on soils in the Akdalinsky irrigation massif that had been removed from agricultural use due to degradation from secondary salinization. The Akdalinsky massif, like the entire delta plain of the Ili River, is characterized by a general lack of groundwater drainage. Climatically, it falls into the northern desert subprovince, where evaporation exceeds precipitation by 8-10 times. These conditions are accompanied by well-developed vertical water and salt exchange, with a tendency towards salt accumulation (Kornenko *et al.* 1977).

Meteorological conditions

The climate of the Akdalinsky massif is sharply continental, with significant temperature variations between day and night and between summer and winter. Winters are cold with minimal snowfall, while summers are hot and dry. The highest average monthly temperature is 23-25 °C in July, with an absolute maximum reaching 40-45 °C; the lowest average temperature is -13 to -15°C in January, with an absolute minimum of -45 °C. The average annual temperature is positive, ranging from +5.1 to +7.5 °C. According to meteorological data from the village of Bakanas, the sum of temperatures above +5 °C is 3800-4000 °C, and above 10 °C is 3400-3500 °C, supporting the cultivation of crops with long growing seasons. The frost-free period averages 150-160 days. Spring frosts typically end by April 25, while autumn frosts begin in early October but can occur as early as mid-September. On average, temperatures fall below 15 °C in mid-October and remain so until the end of November. Annual precipitation averages 250 mm, with most falling in the spring and summer—161 mm or about 64% of the total. Summer precipitation is often torrential, with up to 50-60 mm falling daily. These rains generally have minimal impact on vegetation.

Soil properties

Takyr-like saline soils have high levels of exchangeable sodium in the upper horizons, which affects their water-physical properties. These soils feature a dense, porous, or crusty surface layer up to 6-7 cm thick, typically cracked into polygons, with low humus content and high carbonate levels. At 70-100 cm depths, buried humus horizons and rusty spots formed during the floodplain hydromorphic stage are common. The soil-forming parent materials are layered ancient alluvial deposits of varying mechanical compositions. Takyr-like non-saline soils are low in organic matter, with surface humus content not exceeding 0.7%. The distribution of humus in the profile is often uneven due to the ancient alluvial genesis of these soils and the presence of buried horizons. Total nitrogen content is also low (0.06-0.13%), with the highest levels found in horizons with the greatest humus content. Cation exchange capacity in surface horizons is low—less than 10 mg-eq per 100 g of soil, increasing to 15 mg-eq per 100 g in buried humus horizons. The soil complex is primarily saturated with calcium and magnesium, with roughly equal amounts in the surface horizon and a noticeable predominance of calcium in the subsurface horizons (up to 85% of the total). The soils are carbonate at the surface, with carbonate distribution in the profile being uneven. Carbonate peaking in the surface horizons and layers with heavier mechanical composition but gradually decreasing with depth. Soil suspensions exhibit alkaline to weakly alkaline reactions. Takyr-like saline-alkaline soils are characterized by easily soluble salts in the profile from 60-70 cm depths, while saline soils are found in the subsurface horizon. Takyr-like saline-alkaline and saline soils typically feature a dense, nut-like, or blocky saline horizon, with elevated levels of exchangeable sodium in the soil-absorbing complex. Regarding salinization chemistry, chloride-sulfate and soda-sulfate types are predominant, with moderate to strong salinity levels (see Table 1). Changes in salinization chemistry over time are also observed. For instance, in May, sulfate-soda salinization was noted in the upper 0-20 cm soil layer under rice, transitioning to chloride-soda salinization by August during the rice tillering phase, indicating a potential for transformation in salinization types over a relatively short period.

Table 1. Chemistry and degree of salinization of takyr-like soils at different developmental stages (0-20 cm layer).

Development Stages	**Sample points**	**Total salts (%)**	**Ratio (mg-eq)**			**Salinization Chemistry**	**Degree of Salinization**
			$\frac{Cl'}{SO4''}$	$\frac{HCO3'}{Cl'}$	$\frac{HCO3'}{SO4''}$		
28.05.2022	1	0.51	0.17	0.81	0.14	Sulfate	Medium
	2	0.62	0.17	1.98	0.34	Soda-Sulfate	Strong
	3	0.98	0.15	1.17	0.18	Soda-Sulfate	Very Strong
31.08.2022	1	0.10	-	1.71	-	Sulfate	-
	2	0.21	1.18	2.48	2.93	Chloride-Soda	Medium
	3	0.32	0.73	1.34	0.98	Soda-Sulfate	Medium

Experimental Design

The field experiment was designed as follows

Five biochar application rates, expressed in tons per hectare (ton ha^{-1}), were tested: 0, 5, 10, 15, and 20.

The effectiveness of these biochar rates was evaluated on three crops:

2022: Soybean, variety Zhansaya (first-year effect);

2023: Rice, variety Regul (second-year residual effect);

2024: Spring wheat, variety Kazakhstan 10 (third-year residual effect);

Each plot measured 30 m² (10 m long by 3 m wide) and had four replications. The total area, including buffer zones, was 800 m².

As per the experimental design, biochar was manually applied in the autumn of 2021 before moldboard plowing. The biochar used was birch charcoal (*Betula alba*) with the following characteristics:

Carbon content: 88%;
Porosity: 80%;
Bulk density: 0.38 g cm^{-3};

Soybean was sown on May 3, 2022; rice on April 26, 2023; and spring wheat on April 22, 2024.

Fertilizer (amorphous with N: 12%, and P_2O_5: 46%) was applied concurrently with seeding using a small-scale seeder, Vtnce-Tudo-7500, at a rate of 100 kg ha^{-1}.

Irrigation was carried out using micro-dispersed sprinkler systems.

Recommended agronomic practices for each crop were followed.

Agrophysical and agrochemical analyses were conducted using the following methods:

Total Humus: Determined by I.V. Tyurin's method as modified by V.N. Simakov. Refer to GOST 26213-91 for Soil Organic Matter Determination.

Labile Humus: Measured using I.V. Tyurin's method as modified by V.V. Ponomareva and T.A. Plotnikova.

Easily Hydrolyzable Nitrogen: Determined by the method of I. Tyurin and N. Kononova, as detailed in "Practical Handbook on Agronomic Chemistry," A.V. Petersburgsky, Moscow, 1968, and "Agrochemical Methods for Soil Analysis," Moscow, 1975.

Nitrate Nitrogen: Measured by ionometric method as per GOST 26951-86.

Available Phosphorus and Exchangeable Potassium: Assessed using B.P. Machigin's method as modified by TSNAO, as described in GOST 26205-91.

Bulk Density: Measured using A.S. Kachinsky's method.

Soil Structural (Aggregate) Analysis: Performed by dry sieving following Savvinov's method (Vadyunina & Korchagina 1973). Soil samples (~200 g) were shaken on sieves with mesh size of 10, 5, 2, and 0.25 mm for 3 minutes using a shaker. The fractions were weighed with an accuracy of 0.01 g, and the weight percentage of each fraction was determined (Mi, %). Aggregates 10–0.25 mm are considered agronomically valuable as they influence soil structure and fertility (Theories and Methods of Soil Physics 2007).

Water Extract: Analyzed using methods outlined in "Modern Methods of Chemical Analysis and Plants," Kyiv, 1984, and GOST 26423-85 – GOST 26428-85 to determine the cation-anion composition of water extracts.

Before harvesting, plant samples were collected from three replicates to determine the key elements of the crop structure.

Yield accounting was performed on individual plots using test plots of 6 m^2 (3 × 2 m).

Data processing for yields followed the methodology outlined by Dospekhov (1985).

RESULTS AND DISCUSSION

Several studies have noted improvements in soil structure, manifested by increased aggregate stability (Herath *et al.* 2003; Obia *et al.* 2016) and reduced penetration resistance (Busscher *et al.* 2010; Obia *et al.* 2017). The mechanisms involved again depend on the interaction between biochar and soil properties. The bulk density of the upper soil horizon (0-10 cm) during the study years ranged from 0.95 to 1.17 g cm^{-3}, indicating low to moderate soil compaction in the takyr-like soils. The introduction of biochar has a significant effect on the compaction of the arable layer of tachyrovid soil (0-10 and 10-20 cm), especially in the second and third years (Fig. 1). The effectiveness of the biochar on the compaction of tachyrovid soil is most clearly shown under rice and spring wheat crops. Thus, in the arable layer (0-10 and 10-20 cm), the reduction of soil compaction due to the effect of 15-20 ton ha^{-1} of biochar is 7-11% under rice, 14-15% under spring wheat, while Doz pod kulturoi soya, soil compaction is 3-10%. Agronomically valuable soil is characterized by water stability, which means the ability of soil aggregates to resist water erosion over an extended period. The most crucial indicators are the water stability of the soil structure in the plow layer, specifically the stability of soil aggregates in the 0-30 cm layer. Soil aggregates are only indicative of a particular physical regime in the soil when they are water-stable, i.e., capable of withstanding the destructive effects of water. The most agronomically significant fraction in terms of erosion-resistant plowland is the water-stable fraction of 7-0.25 mm, as aggregates of this size can resist erosion. The content of this fraction varied among the experimental treatments in our studies. In our experiments, as shown in Figure 3, biochar at 15-20 kg ha^{-1} increased the content of water-stable aggregates in the plow layer of takyr-like soils. Specifically, under soybean, the increase was 58-63% in the year of application; under rice, it was 28-52% in the second year of residual effects; and under spring wheat, it was 55% in the third year of residual effects, compared to the control without biochar. A slight positive effect of biochar on the content of water-stable aggregates was also observed in the sub-plow layer (20-40 cm). Applying biochar before plowing significantly affects the organic matter content, which is crucial for restoring fertility in the organic-poor takyr-like soils of the rice-growing zone. The increase in humus content is primarily observed in the plow layer of these soils (Table 1). In the 0-20 cm soil layer under soybean, the control variant had 0.86% humus, while in the variants with 10-20 kg ha^{-1} of biochar, the humus content reached 0.90-1.01%, indicating a significant increase in organic matter in the plow layer of the studied soil. This trend continues with the residual effects of biochar under rice in 2023.

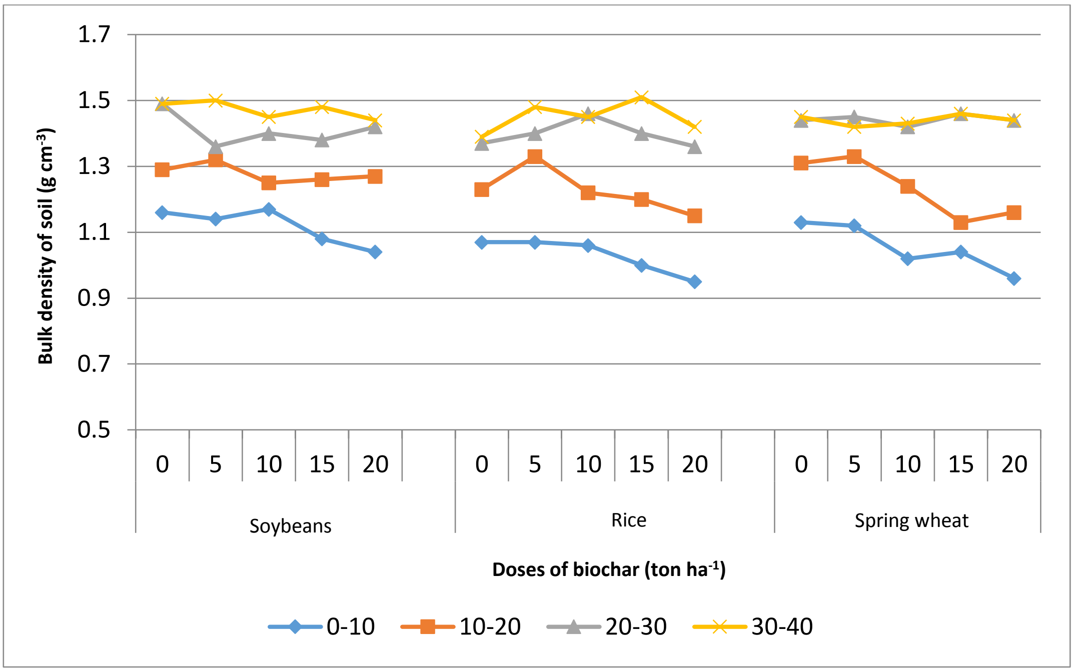

Fig. 1. Dynamics of the volumetric mass of takyr-like soil under crops depending on the action and after-effect of biochar application doses.

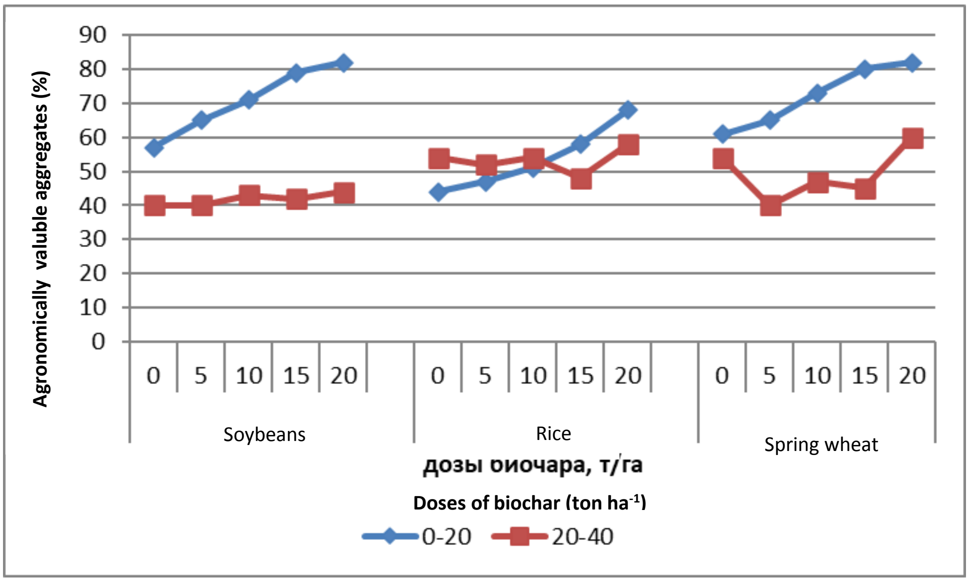

Fig. 2. Dynamics of agronomically valuable aggregates in takyr-like soils under crop cultivation, depending on the effects and residual effects of biochar application rates.

The increase in humus content in the sub-plow layer (20-40 cm) with high doses of biochar can be attributed to the possible leaching of soluble particles by irrigation water into the deeper soil layers. Contrary to expectations, labile humus content does not significantly depend on the biochar application in either the plow or sub-plow layers under soybean in the year of application. However, a significant increase in labile humus content is observed in both the plow and sub-plow layers, with the residual effects of biochar under rice and spring wheat. In carbonate soils, the most suitable indicator of nitrogen availability is easily hydrolyzable nitrogen, which includes mineral and mobile forms of organic nitrogen. Biochar application does not significantly impact the content of easily hydrolyzable nitrogen, either during or after application. Measures to mitigate harmful environmental nitrogen fluxes are actively being sought. Biochar has been shown to have the potential to reduce inorganic nitrogen leaching (Singh *et al.* 2010), N_2O emissions (Spokas & Reicosky 2009), and ammonia volatilization (Steiner *et al.* 2010), as well as to enhance biological nitrogen fixation (Rondon *et al.* 2007).

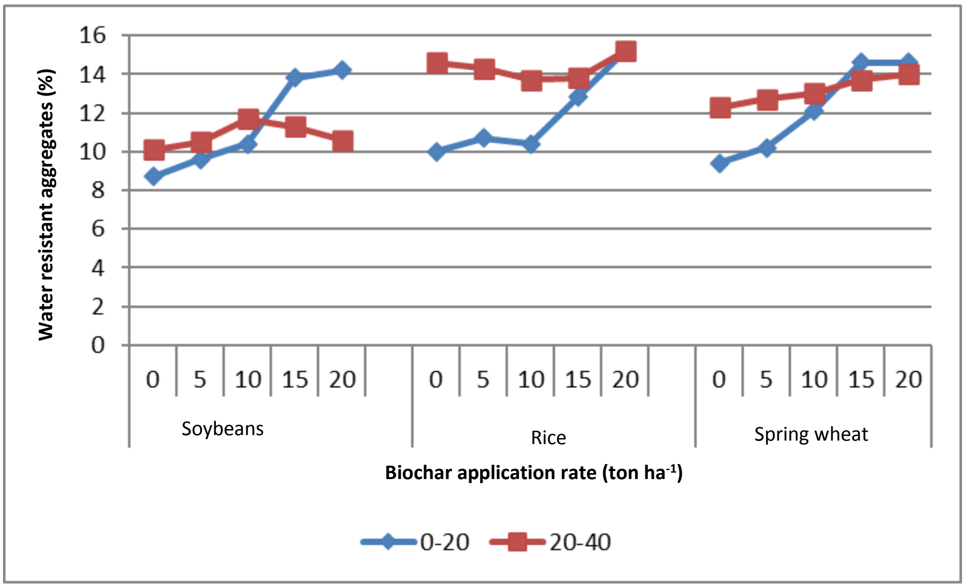

Fig. 3. Dynamics of water-stable aggregate content under crop cultivation, depending on the effects and residual effects of biochar application rates.

Table 2. Agrochemical properties of takyr-like soil under crop cultivation depending on timing and doses of biochar application.

Biochar application rates (kg ha^{-1})	Depth (cm)	Total humus (%)	Labile Humus (mg kg^{-1})	Easily hydrolyzable nitrogen (mg kg^{-1})	NO_3 (mg kg^{-1})	P_2O_5 (mg kg^{-1})	K_2O (mg kg^{-1})
Soybean (2022, First-Year Effect)							
0	0-20	0.86 ± 0.05	196 ± 10	92.4 ± 6.4	87.1 ± 3.9	21.4 ± 1.2	320 ± 15
	20-40	0.62 ± 0.03	182 ± 11	75.6 ± 3.0	45.7 ± 2.1	20.3 ± 1.3	227 ± 12
5	0-20	0.87 ± 0.03	203 ± 12	90.6 ± 4.5	56.2 ± 2.5	20.6 ± 1.4	300 ± 16
	20-40	0.61 ± 0.03	174 ± 14	82.3 ± 4.9	30.2 ± 1.2	20.2 ± 0.8	212 ± 10
10	0-20	0.90 ± 0.05	206 ± 14	85.4±3.8	40.4 ± 2.0	20.4 ± 1.5	251 ± 10
	20-40	0.60 ± 0.02	185 ± 7	70.3 ± 3.9	17.7 ± 0.7	22.1 ± 1.1	180 ± 9
15	0-20	0.94 ± 0.05	208 ± 19	72.8 ± 2.7	36.6 ± 2.2	23.7 ± 1.8	191 ± 8
	20-40	0.68 ± 0.02	177 ± 12	67.2 ± 3.0	21.8 ± 1.1	18.8 ± 0.8	191 ± 9
20	0-20	1.01 ± 0.06	212 ± 16	95.3 ± 6.6	22.3 ± 1.1	23.4±1.8	164 ± 10
	20-40	0.73 ± 0.02	189 ± 11	74.2 ± 3.3	15.2 ± 0.7	19.2 ± 0.6	144 ± 7
Rice (2023, Second-Year Residual Effect)							
0	0-20	0.82 ± 0.05	154 ± 6	76.6 ± 3.5	71.2 ± 2.6	32.3 ± 2.0	256 ± 9
	20-40	0.64 ± 0.04	143 ± 6	63.7 ± 2.2	54.4 ± 2.4	24.2 ± 0.8	201 ± 6
5	0-20	0.78 ± 0.04	167 ± 6	80.4 ± 3.1	76.6 ± 2.8	30.0 ± 1.3	243 ± 11
	20-40	0.66 ± 0.03	159 ± 5	52.3 ± 4.2	43.2 ± 1.6	20.8 ± 0.9	188 ± 8

10	0-20	0.88 ± 0.03	167 ± 10	69.6 ± 3.5	70.3 ± 3.2	30.1 ± 2.2	266 ± 15
	20-40	0.70 ± 0.06	160 ± 11	50.4 ± 2.1	36.7 ± 1.7	25.5 ± 1.3	200 ± 10
15	0-20	0.92 ± 0.06	206 ± 12	72.4 ± 4.3	32.4 ± 1.4	33.4 ± 2.4	217 ± 9
	20-40	0.73 ± 0.06	172 ± 12	78.0 ± 4.1	30.9 ± 1.0	27.2 ± 1.1	228 ± 12
20	0-20	1.05 ± 0.08	208 ± 14	63.2 ± 2.1	34.3 ± 1.5	35.2 ± 2.0	239 ± 12
	20-40	0.72 ± 0.04	183 ± 10	60.6 ± 2.7	41.2 ± 2.1	20.6 ± 0.8	188 ± 9
Spring Wheat (2024, Third-Year Residual Effect)							
0	0-20	0.73 ± 0.04	164 ± 8	73.4 ± 2.9	46.2 ± 2.1	30.1 ± 2.2	300 ± 17
	20-40	0.54 ± 0.03	168 ± 8	54.2 ± 2.1	57.3 ± 2.8	22.5 ± 1.5	224 ± 12
5	0-20	0.80 ± 0.04	182 ± 8	69.5 ± 3.6	50.2 ± 3.3	33.6 ± 1.3	286 ± 12
	20-40	0.61 ± 0.02	156 ± 6	60.6 ± 2.1	61.4 ± 3.0	22.9 ± 1.0	235±9
10	0-20	0.96 ± 0.06	178 ± 6	66.2 ± 2.0	42.9 ± 1.3	28.3 ± 1.7	290 ± 14
	20-40	0.66 ± 0.03	162 ± 4	52.1 ± 2.8	56.6 ± 2.4	25.6 ± 1.7	252 ± 11
15	0-20	0.93 ± 0.05	170 ± 5	70.3 ± 3.3	47.7 ± 2.1	30.1 ± 1.2	305 ± 15
	20-40	0.58 ± 0.02	142 ± 3	63.6 ± 3.9	52.2 ± 3.3	22.0 ± 0.8	240 ± 9
20	0-20	0.98 ± 0.05	193 ± 7	58.4 ± 3.3	50.3 ± 1.4	33.3 ± 2.0	287 ± 16
	20-40	0.74 ± 0.05	154 ± 4	52.2 ± 2.2	65.9 ± 2.5	21.6 ± 1.1	259 ± 12

Biochar has a significant residual effect on nitrate levels in takyr-like soils. Dempster *et al.* (Dempster *et al.* 2012; Dempster *et al.* 2012) found that biochar did not affect nitrogen levels leached from sandy soil initially containing 18.8 mg N kg^{-1} at 0–10 cm depth. The authors suggest that the observed reductions in NO_3^- leaching were due to decreased nitrification rates rather than NO_3^- adsorption, as biochar is also known to inhibit nitrification. The addition of biochar to the soil could potentially increase hydraulic conductivity or preferential flow around larger particles, leading to increased NO_3^- leaching. On the other hand, it has been shown that biochar addition increases water-holding capacity (Kammann *et al.* 2011; Lehmann *et al.* 2003), which may reduce NO_3^- leaching. Our experiments also observed a significant reduction in nitrate levels in the plow and subsurface soil layers with biochar application. Specifically, in the soybean cultivation in the year of biochar application, nitrate content in the 0-20 cm soil layer ranged from 22.3 to 56.2 mg kg^{-1}, compared to 87.1 mg kg^{-1} in the control. The higher the biochar dose applied, the lower the nitrate content in the plow layer under soybean cultivation. This trend is also observed in the subsurface soil layer. A similar pattern is seen in the dynamics of nitrate levels under rice cultivation, where significant reductions in nitrate levels were noted with high doses (10-20 ton ha^{-1}) of biochar. However, the behavior of nitrates in takyr-like soils under spring wheat cultivation differs, with biochar application not having a significant impact on nitrate levels in the plow layer. Higher nitrate levels were observed in the subsurface soil layer compared to the plow layer.

The available phosphorus content in takyr-like soils did not significantly depend on biochar application. However, exchangeable potassium decreased in takyr-like soils with biochar application, most notably in the high-dose soybean and rice cultivation treatments. Improvements in agrophysical and agrochemical properties of degraded irrigated takyr-like soils in the rice-growing zone of Southeastern Kazakhstan due to biochar application in primary soil tillage ultimately reflect in the formation of grain yields of the studied crops. As shown in Table 3, the application of biochar, depending on the dose, leads to an increase in soybean yield by 0.16-1.48 ton ha^{-1}, or 10-96%; rice yield by 0.17-0.97 ton ha^{-1}, or 6-36%; and spring wheat yield by 0.05-1.8 ton ha^{-1}, or 2-65%. Over the three years, using biochar resulted in an additional 1.34-3.68 tons of grain from rice, wheat, and soybean combined. The increased rice yield is attributed to enhanced tillering productivity and 1000-grain weight, while the increase in spring wheat yield is due to improved productive tillering and spikelet density (see Table 4).

Table 3. Crop yield under drip irrigation depending on biochar application methods and rates.

Experimental Treatments (ton ha^{-1})	Yield (ton ha^{-1})			Total Yield (ton ha^{-1}) for 3 years	± Increase
	Soybean	Rice	Spring Wheat		
No Biochar (Control)	1.54	2.73	2.76	7.03	-
Biochar 5 (ton ha^{-1})	1.77	2.45	2.81	7.03	-
Biochar 10 (ton ha^{-1})	2.03	2.90	3.44	8.37	+1.34
Biochar 15 (ton ha^{-1})	3.06	3.64	3.87	10.57	+3.54
Biochar 20 (ton ha^{-1})	3.02	3.63	4.06	10.71	+3.68
HCP$_{0,05}$, (ton ha^{-1})	0.21	0.36	0.52		

Table 3. Structure of Grain Crops Depending on Biochar Application Methods and Doses.

Biochar application rates (ton ha^{-1})	Number of plants (pcs m^{-2})		Productive Tiller Density		Spikelet Density, pcs		1000-Grain Weight (g)	
	Rice	Spring Wheat	Rice	Spring Wheat	Rice	Spring Wheat	Rice	Spring Wheat
0	152 ± 8	186 ± 13	1.64 ± 0.10	1.42 ± 0.09	45 ± 3	35 ± 3	32.1 ± 1.6	34.5 ± 1.0
5	165 ± 11	204 ± 15	1.78 ± 0.10	1.50 ± 0.10	46 ± 3	35 ± 3	30.9 ± 1.0	33.3 ± 1.0
10	143 ± 9	177 ± 12	1.88 ± 0.09	1.63 ± 0.11	49 ± 3	39 ± 4	34.2 ± 1.5	34.0 ± 1.3
15	160 ± 10	196 ± 12	2.01 ± 1.11	1.77 ± 0.11	43 ± 2	39 ± 3	37.8 ± 1.7	34.9 ± 1.3
20	158 ± 7	188 ± 12	1.82 ± 0.09	1.64 ± 0.08	41 ± 2	40 ± 5	40.0 ± 1.9	34.5 ± 1.5

CONCLUSION

Applying biochar at rates of 15-20 ton ha^{-1} during the primary soil treatment improves bulk density. It increases the content of agronomically valuable and water-resistant soil aggregates in the plow layer. There is a significant increase in the levels of labile humus and available phosphorus. The enhancement of agrophysical and agrochemical properties of degraded takyr-like soils ultimately leads to increased productivity of rice rotation crops due to the action and residual effects of the applied biochar during moldboard plowing. Rice and spring wheat yields are primarily boosted by improved tillering productivity, while soybean yields increase due to additional pod formation. Further research is needed to study the impact of different biochar amendments on soil quality and the retention of available water for plants in arid agricultural soils. In arid regions, trials should include the effects of various biochar particle sizes and application rates to balance the benefits of this potential soil organic matter source while avoiding adverse side effects such as increased soil salinity.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Ethical approval

The conducted research is not related to either human or animal use.

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