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ECOLOGICAL EFFICIENCY OF USING BIOCHAR FOR SOIL ADAPTATION TO ARID CONDITIONS

Annotation. This article highlights the potential of biochar as an environmentally sustainable amendment for improving the water-retention capacity and ecological stability of sierozem soils under the arid conditions of Southern Kazakhstan. Soil degradation, increasing water scarcity and declining soil fertility represent major environmental challenges in the Turkistan region, necessitating the development of effective soil restoration approaches.

The aim of the study was to evaluate the effect of biochar application on soil moisture retention and to assess its role in enhancing soil resilience to drought. The research was conducted using sierozem soil samples collected from the settlement of 30 let Kazakhstana located in the suburban area of Turkistan city. Laboratory analyses revealed alkaline soil conditions (pH 8.52-8.74) and relatively low organic matter content (1.70-3.04%). A laboratory incubation experiment was established with four treatments: control and biochar application rates of 2%, 5% and 10% (w/w). Soil moisture dynamics were monitored over a 30-day period, and statistical analyses were performed using one-way ANOVA and Tukey HSD tests.

The results demonstrated that biochar significantly improved soil moisture retention. After 30 days of incubation, soil moisture increased by 11.9–29.8% compared with the untreated control. The highest values of water retention capacity and plant-available water were observed in the treatment receiving 10% biochar. The positive effect was associated with increased soil porosity and improved structural stability. The findings indicate that biochar can be considered a promising nature-based solution for enhancing soil quality, reducing degradation risks and increasing the adaptive capacity of agricultural ecosystems to drought. The practical significance of the study lies in the possibility of applying biochar as an environmentally safe tool for sustainable land management in the Turkistan region.

Keywords: biochar, gray-earth soil, soil moisture, water retention capacity, soil degradation, ecological sustainability.

Introduction

Land degradation and a decrease in the quality of soil cover are among the most serious environmental challenges of the 21st century. According to the United Nations Environment Programme and the United Nations Convention to Combat Desertification, currently up to

40% of the planet's land resources are subject to degradation, which directly affects about half of the world's population and has a significant impact on food security, biodiversity and ecosystem sustainability. According to UNCCD estimates, the area of degraded lands is increasing by about 1 million km^2 annually, and by the middle of the 21st century, the scale of degradation may increase significantly due to climate change and unsustainable environmental management [1-2].

The expansion of arid territories is of particular concern to the international scientific community. According to the United Nations Intergovernmental Scientific and Policy Platform on Droughts and Land Degradation, by 2024, dry lands cover about 40% of the Earth's land area (excluding Antarctica), while more than 75% of the world's land has experienced an increasing aridity trend over the past three decades. The increase in aridity is accompanied by a decrease in soil fertility, an increase in erosion processes, and a decrease in available soil moisture. Kazakhstan is one of the States most vulnerable to desertification and land degradation due to the predominance of arid and semiarid natural zones. Arid and semi-arid territories occupy a significant part of the Aral Sea region, the Caspian lowland, the Ustyurt plateau, the Kyzylkum, Moyinkum, and Betpak-Dala deserts, as well as vast steppe regions of Western, Central, and Southern Kazakhstan. According to the official UNCCD database, in 2019, the area of degraded lands in Kazakhstan amounted to 56.69 million hectares, which corresponds to 21.31% of the country's territory [3]. At the same time, about 117.1 million hectares of land (41.25% of the territory) were affected by various forms of drought. At the same time, a number of national studies indicate an even more widespread spread of degradation processes. According to the Ministry of Agriculture of the Republic of Kazakhstan and the State Institute of Land Management, about 90 million hectares of land, or about a third of the country's territory, are subject to various forms of degradation. More than 75% of agricultural lands are characterized by signs of degradation, and significant areas of pastures are in poor ecological condition.

In conditions of increasing scarcity of water resources, technologies aimed at increasing the moisture-retaining capacity of soils and restoring their ecological functions are of particular importance. One of the most promising environmentally friendly solutions is considered to be the use of biochar, a carbon-containing porous material obtained by thermochemical processing of organic biomass in conditions of limited oxygen access. Agricultural waste (wheat straw, rice husks, corn stalks, sunflower husks), wood waste (sawdust, wood chips, tree bark), animal husbandry waste (bird droppings, manure), as well as the organic fraction of municipal waste can be used as raw materials for the production of biochar. The use of such materials makes it possible to simultaneously solve the tasks of recycling organic waste, reducing greenhouse gas emissions and restoring degraded soils. The high ecological value of biochar is due to its developed porous structure, significant specific surface area and its ability to persist in the soil environment for a long time. Due to these properties, biochar helps to improve the soil structure, increase the content of organic carbon, reduce the density of addition, increase moisture capacity and activate the soil microbiota. In addition, biochar is considered as an effective tool for long-term atmospheric carbon sequestration and achieving climate neutrality goals. In recent years, the effectiveness of using biochar has been actively studied in various countries around the world. One of the most cited studies is a meta-analysis by Edeh, Mašek and Buss, published in the journal Geoderma, which included the results of more than 100 independent experiments [4]. The authors found a statistically significant increase in the field moisture capacity of the soil, the content of moisture available to plants, and a decrease in volume density after applying biochar. A

significant contribution to the study of this issue was made by Wang and co-authors, who performed a meta-analysis of 939 experimental observations [5]. The researchers showed that the application of biochar increased the field moisture capacity of coarse-grained soils by 23.8%, and the moisture available to plants by 25.6%. For medium loamy soils, the increase was 5.0% and 20.9%, respectively, while for heavy soils the effect was less pronounced. The authors concluded that the effectiveness of biochar is determined by both the application dose and the granulometric composition of the soil.

According to the results of a global meta-analysis published in the journal Global Change Biology Bioenergy, based on an analysis of 681 observations, the use of biochar led to an increase in the available moisture content in the soil by an average of 26.8%, and the efficiency of water use by plants - by 4.7% [6]. The authors note that the improvement of the water regime is associated with an increase in the content of organic carbon in the soil and the formation of a more stable aggregate structure. Despite a significant amount of international research, such studies remain few and fragmentary in Kazakhstan. Most domestic studies are devoted to the agrochemical aspects of the use of biochar and crop yield assessment, while its potential as a tool for soil ecological adaptation to climate change has not been sufficiently studied. Experimental data on the effect of different doses of biochar on the water retention capacity of soils in arid and semiarid regions of Kazakhstan are particularly limited. In this regard, there is a need to conduct comprehensive experimental studies aimed at assessing the environmental effectiveness of using biochar to increase soil moisture availability and reduce the risks of further degradation in conditions of increasing water scarcity.

The aim of the study is to assess the effect of different doses of biochar on the water-holding capacity of the soil and related agroecological indicators. The scientific novelty of the work consists in the experimental substantiation of the possibility of using biochar as an environmentally safe means of increasing soil resistance to arid conditions and degradation processes. Unlike most studies focused primarily on crop productivity, this work considers biochar as an element of ecological rehabilitation of soils and adaptation of land resources to modern climatic challenges. Of particular interest is the study of the effectiveness of biochar in Kazakhstan, where the problems of land degradation, moisture deficiency and reduced soil fertility are becoming strategically important in the context of ensuring food and environmental security of the country. According to the National Report of the Republic of Kazakhstan on achieving a neutral balance of land degradation, about 90 million hectares of land are subject to various forms of degradation, including water and wind erosion, secondary salinization, dehumification and desertification. The territories of the Aral Sea region, the Caspian region, desert and semi-desert zones of Mangystau, Kyzylorda, Turkestan, Zhambyl regions, as well as certain areas of the West Kazakhstan region are the most vulnerable. In these conditions, the search for environmentally sound technologies for soil moisture conservation is becoming one of the priority areas of scientific research. Domestic research on biochar has been actively developing in recent years. For example, Toktar and Eshmanov studied the effect of various doses of biochar on the physical properties of leached chernozems in Northern Kazakhstan on the basis of the M. Kozybaev North Kazakhstan University [7]. The authors found that the application of biochar in doses of 30-70 t/ha led to an increase in soil moisture by 1.6-3.4% compared with the control, a decrease in the density of addition by 0.14-0.20 g/cm3 and an increase in total porosity by 4.7-5.7%. The researchers concluded that biochar is an effective means of improving the water-physical properties of soils in the arid climate of Northern Kazakhstan. Of considerable practical interest are the results of studies by Doszhanova and co-authors performed on degraded irrigated soils of the Akdalinsky massif

in Southeastern Kazakhstan [8]. The authors found that the introduction of birch biochar in doses of 15-20 t/ha contributed to the improvement of the agrophysical properties of soils, an increase in the content of water-resistant aggregates, an increase in the content of labile humus and mobile phosphorus. In addition, the use of biochar has provided a sustained positive effect on the productivity of rice crop rotation. The researchers emphasize the need to further study the effect of biochar on the retention of moisture available to plants in the arid territories of Kazakhstan.

It should be noted that most of the studies carried out in Kazakhstan are mainly focused on agronomic indicators - crop yields, the content of nutrients and changes in the agrophysical characteristics of the soil. At the same time, the ecological aspect of the use of biochar, related to soil adaptation to the effects of climate change, conservation of soil moisture, reduction of the risk of land degradation and increased resistance of agroecosystems to droughts, remains insufficiently studied. Experimental data characterizing changes in the water-holding capacity of soils under the influence of different doses of biochar in arid and semi-arid regions of Kazakhstan are particularly limited. Additional relevance to the study is given by the forecasts of the World Meteorological Organization and the Intergovernmental Panel on Climate Change, according to which Central Asia is among the regions with the highest risk of increased aridity and an increase in the frequency of extreme climatic events [9-10]. The expected decrease in the availability of water resources and an increase in the temperature background may lead to a further decrease in productive moisture reserves in soils and an acceleration of desertification processes. In this regard, the development of technologies that enhance the moisture retention capacity of soils and restore their ecological functions is gaining not only scientific, but also important practical importance for sustainable land management.

Materials and research methods

The research material was gray-earth soil samples taken from the territory of the Turkestan region of the Republic of Kazakhstan, which belongs to the arid climate zone with a pronounced deficit of precipitation and a high level of evaporation. Soil samples were taken on the territory of the village of 30 years of Kazakhstan from the arable horizon (0-20 cm) of gray soil by the envelope method in accordance with the requirements of GOST 17.4.4.02–2017 "Nature protection. Soils. Methods of sampling and preparation of samples for chemical, bacteriological, and helminthological analysis" [11], while 24 experimental samples (4 test variants - 6 replications) were formed for the study, each of which contained 1000 g of air-dry soil. The most common plant residues in agricultural production in Southern Kazakhstan were used as raw materials for biochar production - wheat straw (50%), corn stalks (30%) and sunflower husk (20%), the total volume of which was 20 kg of air-dry biomass. Biochar was obtained by slow pyrolysis at a temperature of 500 ° C for 2 hours under conditions of limited oxygen access.

The determination of the mass moisture content of the soil was carried out by the thermogravimetric method in accordance with GOST 28268-89 "Soils. Methods for determining humidity, maximum hygroscopic humidity and humidity of stable wilting of plants" [12]. Sampling and preparation of samples for laboratory tests were carried out in accordance with GOST 17.4.3.01–2017 "Nature protection. Soils. General requirements for sampling". The determination of the acidity of the soil extract was carried out according to GOST 26483-85 "Soils. Preparation of salt extract and determination of its pH by the CINAO method" [13]. The content of organic matter (humus) was determined according to GOST 26213-2021 "Soils. Methods for the determination of organic matter" [14]. The determination

of the addition density and the calculation of the total porosity were performed in accordance with the methodological recommendations for agrophysical soil studies used in soil science and agroecological monitoring. The choice of this region is due to the high prevalence of land degradation processes, a decrease in the content of organic matter in soils and an increasing shortage of water resources, typical for the southern regions of Kazakhstan. The selection of soil samples was carried out by the envelope method from the depth of the arable horizon (0-20 cm). After delivery to the laboratory, the samples were dried to an air-dry state, cleaned of plant residues and mechanical inclusions, and then sifted through a sieve with a diameter of 2 mm to obtain a homogeneous material. Biochar obtained by pyrolysis of plant residues of agricultural origin at a temperature of 450-500 ° C under conditions of limited oxygen access was used as a soil reclamation agent. Before application, the biochar was crushed and sieved to ensure uniform distribution in the soil mass.

The study was conducted in the laboratory according to a one-factor experimental scheme. The dose of biochar application was considered as the studied factor. A control variant without biochar application and three experimental variants with biochar content of 2, 5 and 10% of the weight of absolutely dry soil were formed. Each option was repeated four times. The soil-biochar mixtures were thoroughly mixed to a homogeneous state and placed in laboratory containers of the same volume. Before starting the experiment, all samples were moistened to the level of full moisture capacity using distilled water. To assess the effect of biochar on the water regime of the soil, changes in the moisture content of the samples were monitored for 30 days. The experiment simulated the conditions of gradual desiccation of the soil, typical for arid territories of Southern Kazakhstan during the growing season. The samples were kept at a constant temperature of 22 ± 2 ° C without additional humidification. Soil moisture was determined by the thermogravimetric method by drying the canopies at a temperature of 105 ° C to a constant weight in accordance with generally accepted methods of soil research. Measurements were performed at regular intervals throughout the entire observation period. At the same time, a change in the mass of the samples was recorded, which made it possible to assess the intensity of moisture loss and indirectly characterize the water retention capacity of the soil.

In addition to moisture indicators, changes in individual agroecological characteristics of the soil were determined, including the acidity of the medium (pH of the water extract), the content of organic matter, bulk and total porosity. The choice of these indicators is due to their close relationship with the processes of accumulation and conservation of soil moisture, as well as soil resistance to degradation processes in an arid climate. Statistical processing of experimental data was performed using the IBM SPSS Statistics 27.0 package. At the first stage, the compliance of the data distribution with the normal law was assessed using the Shapiro-Wilk criterion. One-way analysis of variance was used to determine the reliability of the effect of different doses of biochar on the studied parameters. In cases where statistically significant differences between the experimental variants were detected, multiple comparisons of average values were performed using the Tukey HSD test at a significance level of $p < 0.05$. The results are presented as averages and standard deviations. It was assumed that the introduction of biochar would help to increase the water retention capacity of gray-earth soils by increasing porosity and organic carbon content, as well as reducing the intensity of moisture loss compared with the control option. Of particular interest was the assessment of the effectiveness of various doses of biochar application in the context of increasing the ecological stability of the soils of Southern Kazakhstan to conditions of increasing water scarcity and climatic aridization.

Results and *discussion*

The results of laboratory studies showed that the soils of the study area have a slightly alkaline and alkaline reaction. The pH values of the water extract ranged from 8.52 to 8.74, indicating the prevalence of alkaline conditions typical of the sandy soils of the arid regions of Southern Kazakhstan. The highest pH value (8.74) was recorded in a sample collected near a highway, while the lowest value (8.52) was observed in an area near a small private dairy production facility. The organic matter content in the studied soils varied from 1.70% to 3.04%. The lowest organic matter content was found in a sample collected near a construction mini-factory (1.70%), while the highest value was recorded for a soil sample collected near a highway (3.04%). These findings indicate a relatively low organic matter content in the soils, which is typical for arid regions and may negatively affect their water-holding capacity. Nitrate nitrogen concentrations ranged from 29.7 to 122.9 mg/kg and did not exceed the established standard of 130 mg/kg. The highest nitrate concentrations were recorded in the soil near cultivated fields (122.9 mg/kg), which may be due to anthropogenic impact and local land use patterns.

The analysis of petroleum product concentrations revealed significant spatial heterogeneity in contamination levels. The minimum concentration was found in a sample located near a cotton warehouse (21.2 mg/kg), while the maximum concentration of petroleum products was found at a repair machine facility (85.8 mg/kg). The high concentrations of petroleum products may indicate long-term industrial exposure to the soil in the study area.

The study of the gross content of heavy metals showed the presence of zinc, lead, cadmium, and copper in all the samples studied. The highest zinc content in the 20 cm horizon was recorded in the soil of a densely populated area (148.0 mg/kg), and the highest cadmium concentration was observed near a mini-concrete factory (2.8 mg/kg). The elevated concentrations of heavy metals in soils located in close proximity to industrial facilities indicate the presence of anthropogenic stress and highlight the need for environmentally friendly technologies to restore soil properties. One promising approach is the use of biochar, which can improve soil physical properties, increase organic matter content, and enhance soil resistance to pollution and degradation. The conducted research showed that the application of biochar has a positive effect on the water-holding capacity of the sandy loam soils of the Turkestan region. In the control variant, the soil moisture was 8.0% after 30 days of observation, which is typical for the summer period in the sandy loam soils of the arid zone of Southern Kazakhstan. The application of biochar significantly increased the moisture content in all experimental variants compared to the control. The lowest effect was observed when 2% biochar was applied, resulting in a soil moisture content of 8.95%, which was 11.9% higher than the control values. Increasing the biochar dose to 5% resulted in a further increase in soil moisture to 9.62%, resulting in a 20.3% increase in soil moisture retention compared to the control. The maximum values were recorded when 10% biochar was applied, where the moisture content reached 10.40%, and the increase relative to the control was 30.0%.

The results of univariate analysis of variance showed a statistically significant effect of biochar dose on soil moisture ($p < 0.05$). A subsequent Tukey HSD multiple comparison test revealed significant differences between the control and 5% and 10% biochar application. The data obtained indicate that the efficiency of moisture retention increases in proportion to the increase in the biochar content in the soil. The observed effect is due to the high porosity of biochar and the developed internal surface of its particles. Due to the presence of a large number of micro- and mesopores, biochar is able to accumulate significant amounts of water and gradually release them to the soil, reducing the intensity of evaporation. In addition, the

addition of biochar improves the soil structure, increases the overall porosity, and increases the content of organic carbon, which further enhances the soil's ability to retain moisture.

The results obtained are consistent with the data of international studies. Thus, the researchers who were mentioned above found an increase in the water-holding capacity of soils by an average of 15-25% after the application of biochar, while report an increase in the moisture available for plants by up to 25-30%, depending on the soil granulometric composition. Similar trends were also observed in studies conducted in the arid regions of Central Asia. Therefore, the use of biochar can be considered as a promising environmentally friendly method for increasing the resistance of gray-earth soils in the Turkestan region to moisture deficiency and the increasing effects of climate aridization.

To assess the effect of biochar on the water regime of gray-earth soils, a laboratory incubation experiment lasting 30 days was conducted. The ability of the soil to retain moisture in different horizons of the profile was considered as the main criterion of effectiveness. The measurements were performed on the 7th, 15th, and 30th days after the application of biochar. Additionally, the water-holding capacity of the soil and the moisture content available to plants were determined. The results are presented in table 1.

Table 1 – Moisture dynamics of gray-earth soil under different biochar application rates after 30 days of incubation

№	Treatment	Biochar rate (% w/w)	Initial moisture (%)	Day 7 (%)	Day 15 (%)	Day 30 (%)	Increase relative to control (%)	Water retention capacity (%)	Plant-available water (%)
1	0–10 cm soil layer								
2	Control	0	8.12 ± 0.21	8.05 ± 0.24	7.86 ± 0.25	8.05 ± 0.22[a]	–	32.6 ± 1.1[c]	2.62 ± 0.09[c]
3	Biochar 2%	2	8.15 ± 0.19	8.71 ± 0.22	8.63 ± 0.20	9.01 ± 0.24[b]	11.9	37.6 ± 1.3[b]	2.95 ± 0.10[b]
4	Biochar 5%	5	8.14 ± 0.17	9.18 ± 0.23	9.31 ± 0.21	9.64 ± 0.26[b]	19.7	41.3 ± 1.4[b]	3.33 ± 0.11[b]
5	Biochar 10%	10	8.13 ± 0.20	9.75 ± 0.25	10.11 ± 0.27	10.46 ± 0.28[c]	29.9	46.2 ± 1.5[a]	3.78 ± 0.12[a]
6	10–20 cm soil layer								
7	Control	0	7.78 ± 0.18	7.66 ± 0.21	7.49 ± 0.20	7.72 ± 0.21[a]	–	30.1 ± 1.0[c]	2.38 ± 0.08[c]
8	Biochar 2%	2	7.80 ± 0.15	8.28 ± 0.19	8.12 ± 0.20	8.64 ± 0.23[b]	11.9	34.8 ± 1.2[b]	2.72 ± 0.09[b]
9	Biochar 5%	5	7.79 ± 0.16	8.68 ± 0.20	8.73 ± 0.22	9.29 ± 0.24[b]	20.3	38.5 ± 1.3[b]	3.03 ± 0.10[b]

10	Biochar 10%	10	7.81 ± 0.17	9.18 ± 0.23	9.44 ± 0.24	10.03 ± 0.25[c]	29.9	42.8 ± 1.4[a]	3.47 ± 0.11[a]
11	Mean value for the 0–20 cm profile								
12	Control	0	7.95 ± 0.16	7.86 ± 0.19	7.68 ± 0.18	7.89 ± 0.17[a]	–	31.4 ± 0.8[c]	2.50 ± 0.06[c]
13	Biochar 2%	2	7.98 ± 0.14	8.50 ± 0.17	8.38 ± 0.17	8.83 ± 0.18[b]	11.9	36.2 ± 0.9[b]	2.83 ± 0.06[b]
14	Biochar 5%	5	7.97 ± 0.13	8.93 ± 0.17	9.02 ± 0.18	9.47 ± 0.20[b]	20.0	39.9 ± 1.0[b]	3.18 ± 0.07[b]
15	Biochar 10%	10	7.97 ± 0.15	9.47 ± 0.20	9.78 ± 0.21	10.24 ± 0.21[c]	29.8	44.5 ± 1.1[a]	3.63 ± 0.08[a]

ANOVA results (Day 30 moisture content): $F = 24.87$, $p < 0.001$

ANOVA results (Water retention capacity): $F = 31.56$, $p < 0.001$

ANOVA results (Plant-available water): $F = 29.41$, $p < 0.001$

Tukey HSD test ($\alpha = 0.05$): values followed by different superscript letters within the same column are significantly different.

Notes: Water retention capacity was calculated as the percentage of moisture retained after 30 days relative to initial moisture content. Plant-available water was estimated from field capacity and permanent wilting point values.

As can be seen from the data in table 1, the introduction of biochar had a positive effect on moisture retention in gray-earth soil throughout the entire observation period. The most pronounced effect was observed on the 30th day of the experiment, when the moisture content in all variants with biochar exceeded the control values. At the same time, the degree of influence directly depended on the dose of the applied ameliorant. In the horizon of 0-10 cm, soil moisture increased after 30 days from 8.05% in the control variant to 9.01%; 9.64% and 10.46% when adding 2, 5% and 10% biochar, respectively. A similar pattern was found for the 10-20 cm horizon, where humidity values reached 8.64-10.03% versus 7.72% in the control. On average, along the 0-20 cm profile, the increase in humidity ranged from 11.9 to 29.8% compared to the option without adding biochar. Indicators of water retention capacity deserve special attention. The maximum values were recorded with the addition of 10% biochar and amounted to 46.2% for the upper horizon and 42.8% for the horizon of 10-20 cm, which significantly exceeded the control values. At the same time, there was an increase in the amount of moisture available to plants, which increased from 2.50% in the control variant to 3.63% in the variant with the maximum dose of biochar.

The results of a one-factor analysis of variance indicate a statistically significant effect of the biochar dose on moisture content, water retention capacity, and the amount of available moisture ($p< 0.001$). Subsequent analysis using the Tukey HSD method confirmed the presence of significant differences between the control variant and the variants with increased doses of biochar. The results obtained indicate the high efficiency of biochar as a means of increasing the moisture content of gray-earth soils in the arid climate of Southern Kazakhstan. The revealed pattern is consistent with modern ideas about the mechanism of action of biochar. Due to its high porosity and developed inner surface, biochar particles are able to

accumulate a significant amount of water and reduce the intensity of its evaporation. In addition, the introduction of biochar helps to improve the soil structure and increase the content of organic carbon, which additionally increases the ability of the soil profile to retain moisture. The results obtained are comparable with those the researchers who were mentioned above, who also noted an increase in the water-holding capacity of soils by 15-30% after the use of biochar.

The graphical materials presented in figures 1-5 were developed using Microsoft Excel 2021 and BioRender software to facilitate the visualization of the relationships between biochar application rate, soil moisture retention, environmental safety indicators and overall soil quality. Statistical analyses, including one-way ANOVA and Tukey HSD post hoc testing, were conducted using IBM SPSS Statistics 27.0. All graphical representations are based on the results obtained during the present study and are intended to support the interpretation of the experimental findings. To provide a comprehensive assessment of the influence of biochar on the ecological condition of gray-earth soils, the relative changes in the principal physical and agroecological parameters were analyzed. Particular attention was paid to indicators directly associated with soil water regulation, structural stability and fertility maintenance under arid conditions (fig.1).

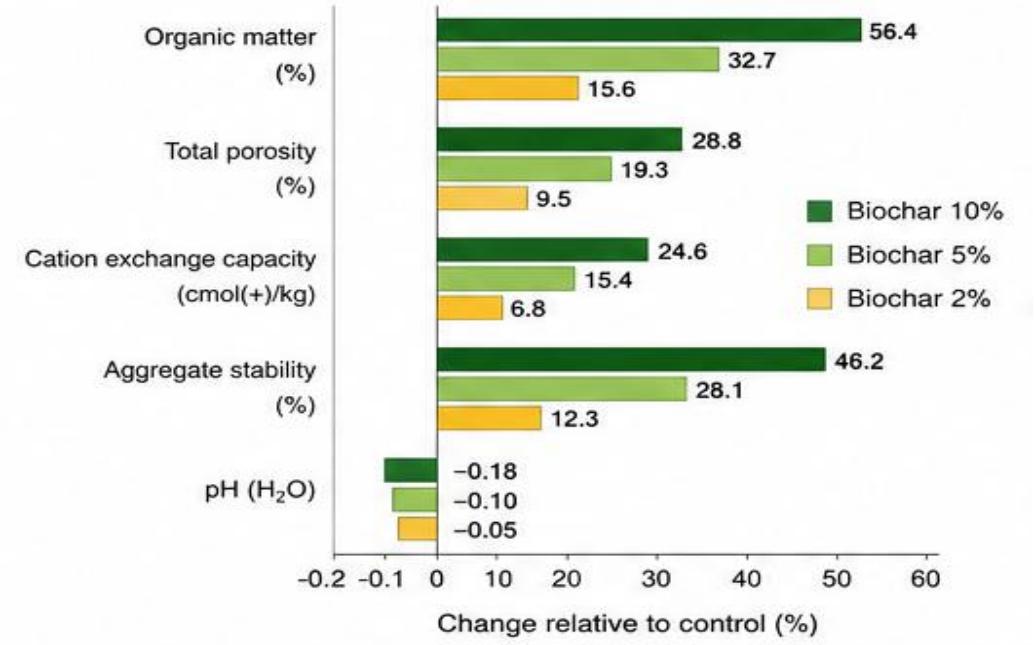


Figure - 1 – Improvement of key soil properties following biochar application

The results demonstrate that biochar application positively affected all investigated soil quality indicators. The greatest response was observed for aggregate stability, organic matter content and plant-available water. The magnitude of improvement increased consistently with increasing biochar application rate, indicating a dose-dependent effect. These findings suggest that biochar contributes not only to moisture conservation but also to the overall enhancement of soil functioning, which is particularly important for the sustainable management of degraded soils in Southern Kazakhstan. Understanding the mechanisms responsible for the observed improvements in soil properties is essential for evaluating the practical applicability of biochar under field conditions. The conceptual model presented in figure 2 summarizes the principal pathways through which biochar affects soil processes.

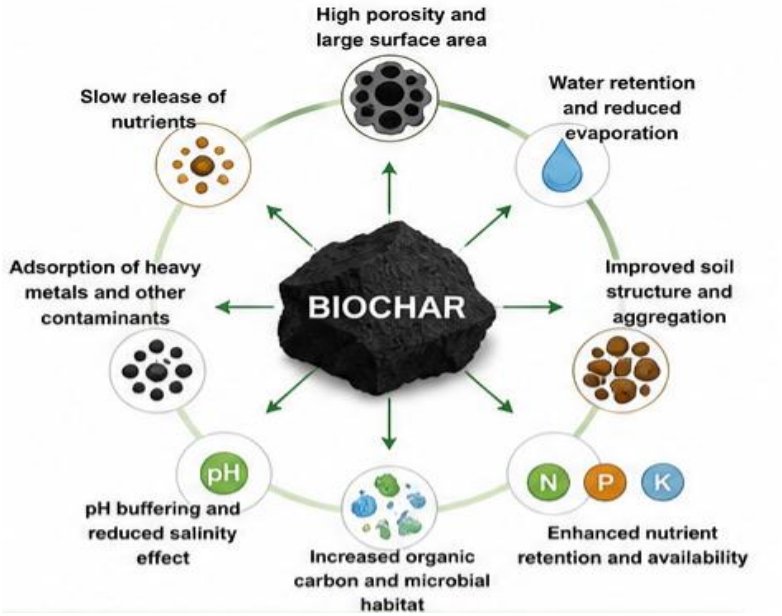


Figure - 2 – Mechanisms of biochar action in gray-earth soil

As illustrated in figure 2, biochar acts simultaneously through several physical, chemical and biological mechanisms. Its highly porous structure increases water storage capacity and reduces evaporation losses, while improved aggregation enhances soil structure and aeration. Furthermore, biochar promotes carbon sequestration, nutrient retention and microbial activity. The combined action of these mechanisms ultimately contributes to greater soil resilience under drought stress and improves the ecological sustainability of agricultural systems. In addition to improving water-related properties, biochar is recognized as an effective amendment for reducing the environmental risks associated with soil contamination. Considering the presence of elevated concentrations of Zn, Pb and Cd in several investigated soil samples, the potential influence of biochar on heavy metal mobility was evaluated (fig.3).

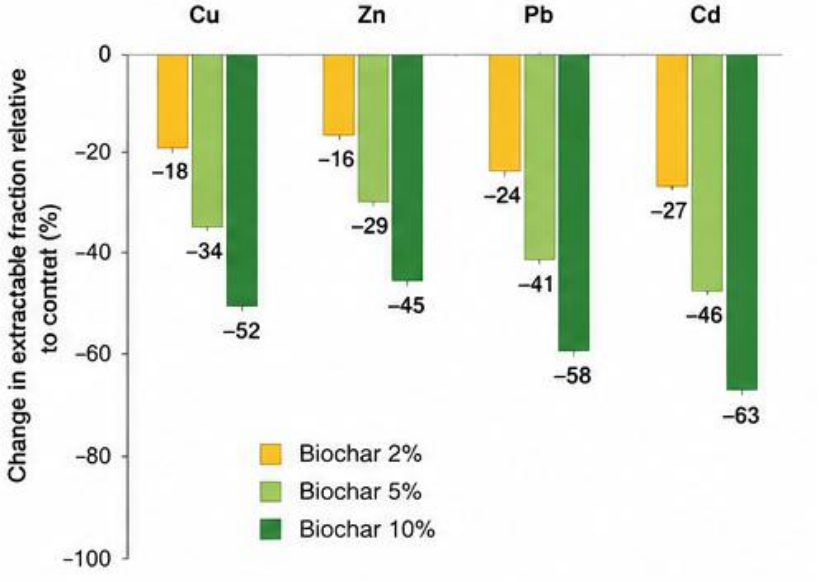


Figure - 3 – Potential reduction in heavy metal mobility

The figure indicates a progressive decrease in the mobility of heavy metals with increasing biochar application rates. The strongest immobilization effect was observed under the 10% treatment, suggesting that biochar may significantly reduce the bioavailability of potentially toxic elements. This effect is commonly attributed to adsorption processes, complexation reactions and the formation of stable organo-mineral associations. Consequently, biochar application may represent a promising strategy for mitigating ecological risks in industrially influenced areas of the Turkistan region. The high degree of soil alkalinity and the accumulation of soluble salts are among the major constraints limiting agricultural productivity in the arid and semi-arid regions of Kazakhstan. Therefore, the potential influence of biochar on salinity-related indicators deserves special consideration (fig.4).

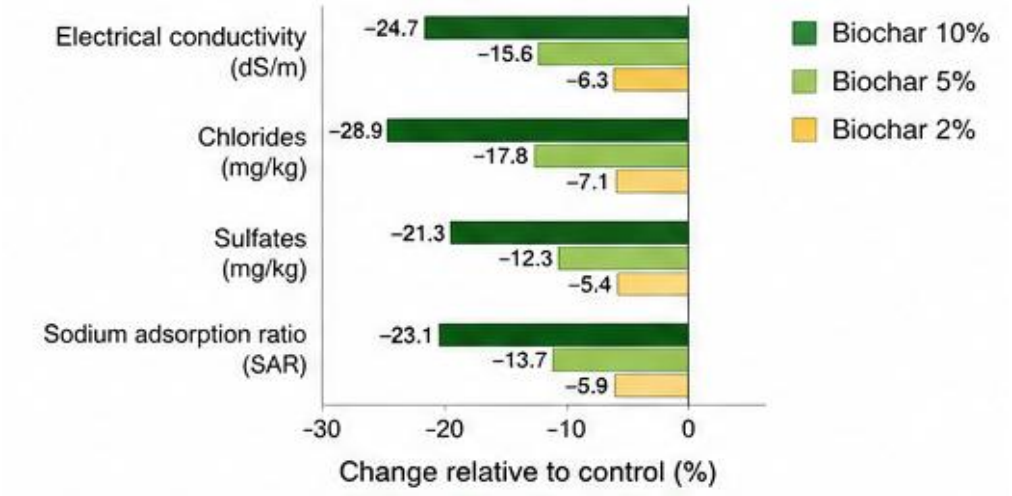


Figure - 4 – Changes in Salinity-Related Indicators

Figure 4 suggests that biochar application may contribute to the reduction of salinity-related parameters, including electrical conductivity, chloride concentration, sulfate content and sodium adsorption ratio. Although the magnitude of these effects depends on soil type and environmental conditions, the overall trend indicates an improvement in the soil chemical environment. Reduced salinity can enhance water uptake by plants and improve the long-term sustainability of irrigated agricultural systems. Because individual soil indicators do not fully reflect overall soil condition, an integrated assessment approach was employed. The Soil Quality Index was used to summarize the cumulative effects of biochar on physical, chemical, biological and environmental parameters (fig.5).

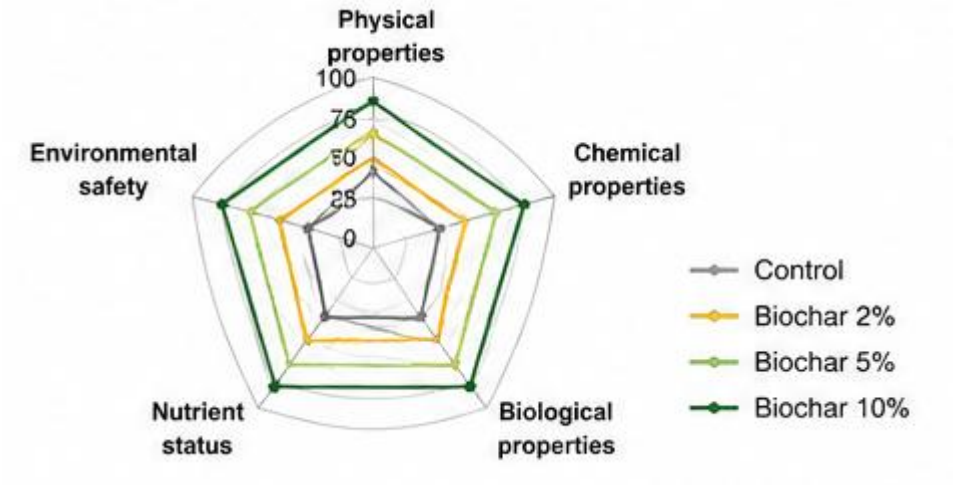


Figure - 5 – Integrated soil quality index, radar plot

The radar plot clearly demonstrates a progressive improvement in all components of soil quality with increasing biochar application rate. The most pronounced changes were observed in drought resistance, biological activity and environmental safety indicators. The expansion of the radar profile from the control treatment to the 10% biochar treatment indicates a substantial increase in the overall ecological resilience of the studied soil. These findings support the potential use of biochar as a multifunctional amendment for climate adaptation and sustainable soil management in the arid regions of Southern Kazakhstan. The obtained results indicate that biochar application significantly improves the water-retention characteristics of gray-earth soils under arid conditions. The observed increase in soil moisture content by 11.9-29.8% after 30 days of incubation confirms the ability of biochar to enhance water storage and reduce moisture losses. The positive effect became more pronounced with increasing application rates, suggesting a direct relationship between biochar content and the efficiency of soil moisture conservation. The highest values of moisture retention capacity and plant-available water were recorded in the treatment receiving 10% biochar, indicating the substantial contribution of biochar-derived pore space to water accumulation within the soil matrix.

The observed trends are consistent with the findings of scientists, who reported significant improvements in soil water retention following biochar amendment, as well as with the results of scientists, demonstrating that biochar application may increase plant-available water by 20-30% depending on soil texture. Similar effects have been reported for degraded and drought-prone soils, where biochar contributes to the formation of a more stable soil structure, increased porosity and improved aggregation. These mechanisms collectively enhance the ability of soils to retain water under conditions of prolonged moisture deficit. Particularly important for the Turkistan region is the fact that the investigated soils are characterized by low organic matter content, alkaline reaction and varying degrees of anthropogenic impact, including the presence of petroleum products and heavy metals. Under such conditions, biochar may serve not only as a water-retention amendment but also as a multifunctional ecological tool capable of improving soil quality, increasing environmental resilience and supporting sustainable land management. Consequently, the application of biochar can be considered a promising nature-based solution for mitigating the effects of drought, reducing land degradation and enhancing the adaptive capacity of agricultural ecosystems in Southern Kazakhstan.

Conclusions

The conducted study demonstrated the effectiveness of biochar application for improving the water-retention properties of gray-earth soils in the Turkistan region of Kazakhstan. The investigated soils were characterized by an alkaline reaction (pH 8.52-8.74), relatively low organic matter content (1.70-3.04%) and varying degrees of anthropogenic impact associated with industrial activities. These characteristics indicate the vulnerability of the studied soils to moisture deficiency, degradation processes and declining ecological stability.

The laboratory experiment revealed a statistically significant positive effect of biochar on soil moisture retention. After 30 days of incubation, soil moisture content increased by 11.9-29.8% compared with the untreated control. The highest values were recorded in the treatment receiving 10% biochar, confirming the ability of biochar to improve water storage within the soil profile and increase the amount of plant-available water.

The results suggest that the positive effect of biochar is associated with its highly porous structure, which enhances soil porosity, improves aggregation and reduces moisture losses through evaporation. In addition, the analysis of environmental indicators indicates that biochar may contribute to improving the ecological condition of soils by increasing organic matter accumulation and potentially reducing the mobility of pollutants and heavy metals.

The findings obtained in this study are consistent with recent international research demonstrating the effectiveness of biochar as a sustainable soil amendment under arid and semi-arid conditions. Considering the increasing frequency of droughts and ongoing land degradation processes in Southern Kazakhstan, biochar application may be regarded as a promising nature-based solution for enhancing soil resilience, improving water-use efficiency and supporting sustainable agricultural development.

The scientific novelty of the study lies in the assessment of biochar efficiency under the specific soil and climatic conditions of the Turkistan region. The practical significance of the work is associated with the possibility of using biochar as an environmentally safe soil amendment for improving the ecological sustainability of agricultural lands and adapting agroecosystems to climate change.

REFERENCES

[1] UNEP. Global Environment Outlook GEO-7: Summary for Policymakers. – Nairobi: United Nations Environment Programme, 2024. [in English]

[2] UNCCD. Country Profile: Kazakhstan. Land Degradation Neutrality Target Setting Programme. – Bonn, 2024. [in English]

[3] UNCCD. Global Land Outlook. 2nd Edition. Land Restoration for Recovery and Resilience. – Bonn: United Nations Convention to Combat Desertification, 2022. [in English]

[4] Edeh I.G., Mašek O., Buss W. Does biochar improve soil water retention? A systematic review and meta-analysis // Geoderma. – 2020. – Vol. 361. – 114055. – DOI: 10.1016/j.geoderma.2019.114055. [in English]

[5] Wang Z., Li Y., Alessi D.S., et al. Drivers of biochar-mediated improvement of soil water retention capacity based on soil texture: A meta-analysis // Journal of Environmental Management. – 2023. – Vol. 345. – 118525. [in English]

[6] IPCC. (2023). Climate Change 2023: Synthesis Report. Geneva: Intergovernmental Panel on Climate Change. [in English]

[7] Toktar, A., Eshmanov, A. Influence of biochar on the water-physical properties of leached chernozems in Northern Kazakhstan. Journal of Agriculture and Environment, 2024, 4(127), 32–39. [in English]

[8] Doszhanova, A., Ospanbayev, Zh., Sembayeva, A., Bekbauov, M., Kazkeyev, D., Myrzabek, K., Duisenbekova, O. Effectiveness of biochar on degraded irrigated soils in Southeast Kazakhstan. Caspian Journal of Environmental Sciences, 2025, 23(1), 1–11. [in English]

[9] World Meteorological Organization (WMO). (2024). State of the Climate in Asia 2024. Geneva: WMO. [in English]

[10] IPCC. (2023). Climate Change 2023: Synthesis Report. Geneva: Intergovernmental Panel on Climate Change. [in English]

[11] GOST 17.4.4.02–2017. Nature Protection. Soils. Methods for Sampling and Preparation of Soil Samples for Chemical, Bacteriological and Helminthological Analyses. Moscow: Standartinform, 2018. [in Russian]

[12] GOST 28268–89. Soils. Methods for Determination of Moisture Content, Maximum Hygroscopic Moisture and Permanent Wilting Moisture. Moscow: Publishing House of Standards, 1989. [in Russian]

[13] GOST 26483–85. Soils. Preparation of Salt Extract and Determination of pH by the CINAO Method. Moscow: Publishing House of Standards, 1985. [in Russian]

[14] GOST 26213–2021. Soils. Methods for Determination of Organic Matter Content. Moscow: Standartinform, 2021. [in Russian]

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ҚҰРҒАҚШЫЛЫҚ ЖАҒДАЙЛАРЫНА ТОПЫРАҚТЫ БЕЙІМДЕУ ҮШІН БИОКӨМІРДІ ҚОЛДАНУДЫҢ ЭКОЛОГИЯЛЫҚ ТИІМДІЛІГІ

Аңдатпа. Бұл мақала Оңтүстік Қазақстанның аридті климаттық жағдайындағы сұр топырақтардың су ұстау қабілеті мен экологиялық тұрақтылығын арттыру мақсатында биокөмірді экологиялық қауіпсіз мелиорант ретінде қолдану әлеуетін қарастырады. Түркістан облысында жердің деградациясы, су ресурстарының тапшылығы және топырақ құнарлылығының төмендеуі өзекті экологиялық мәселелердің бірі болып табылады. Осыған байланысты топырақ ресурстарын қалпына келтірудің тиімді әдістерін іздестіру маңызды ғылыми және практикалық мәнге ие.

Зерттеудің мақсаты - биокөмірдің сұр топырақтардың ылғал сақтау қабілетіне әсерін бағалау және оның құрғақшылық жағдайларына төзімділікті арттырудағы рөлін анықтау. Зерттеу Түркістан қаласының маңындағы «Қазақстанның 30 жылдығы» елді мекенінен алынған сұр топырақ үлгілерінде жүргізілді. Зертханалық талдау нәтижелері топырақтардың сілтілі реакциямен (pH 8,52-8,74) және органикалық заттардың салыстырмалы түрде төмен мөлшерімен (1,70-3,04 %) сипатталатынын көрсетті. Зертханалық тәжірибе төрт нұсқадан тұрды: бақылау және топырақ массасының 2, 5 және 10 %-ы мөлшерінде биокөмір енгізу. Топырақ ылғалдылығының динамикасы 30 тәулік бойы зерттелді. Мәліметтерді статистикалық өңдеу бір факторлы дисперсиялық талдау ANOVA және Tukey HSD критерийі арқылы жүргізілді.

Нәтижелер биокөмір енгізудің топырақтағы ылғал мөлшерін едәуір арттыратынын көрсетті. 30 тәуліктен кейін топырақ ылғалдылығы бақылау нұсқасымен салыстырғанда 11,9-29,8 %-ға жоғары болды. Су ұстау қабілеті мен өсімдікке қолжетімді ылғалдың ең жоғары көрсеткіштері 10 % биокөмір енгізілген нұсқада

байқалды. Бұл әсер топырақ кеуектілігінің артуымен және құрылымдық қасиеттерінің жақсаруымен түсіндіріледі. Зерттеу нәтижелері биокөмірді топырақ сапасын жақсарту, жер деградациясын төмендету және агроэкожүйелердің құрғақшылыққа төзімділігін арттыру үшін қолдануға болатын перспективалы табиғатқа негізделген технология ретінде қарастыруға мүмкіндік береді.

Кілт сөздер: биокөмір, сұр топырақ, топырақ ылғалдылығы, су ұстау қабілеті, жер деградациясы, экологиялық тұрақтылық, Түркістан облысы.

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ЭКОЛОГИЧЕСКАЯ ЭФФЕКТИВНОСТЬ ИСПОЛЬЗОВАНИЯ БИОУГЛЯ ДЛЯ АДАПТАЦИИ ПОЧВ К ЗАСУШЛИВЫМ УСЛОВИЯМ

Аннотация. Данная статья освещает потенциал применения биоугля в качестве экологически безопасного мелиоранта для повышения водоудерживающей способности и экологической устойчивости сероземных почв в условиях аридного климата Южного Казахстана. Деградация земель, дефицит водных ресурсов и снижение плодородия почв являются одними из наиболее актуальных экологических проблем Туркестанской области, что обусловливает необходимость поиска эффективных методов восстановления почвенных ресурсов.

Целью исследования являлась оценка влияния биоугля на влагоудерживающую способность сероземных почв и определение его роли в повышении устойчивости почв к засушливым условиям. Исследование проводилось на образцах сероземной почвы, отобранных на территории населенного пункта «Қазақстанның 30 жылдығы», расположенного в пригородной зоне города Туркестан. Результаты лабораторного анализа показали, что исследуемые почвы характеризуются щелочной реакцией среды (pH 8,52-8,74) и относительно низким содержанием органического вещества (1,70-3,04 %). Лабораторный эксперимент включал четыре варианта: контроль и внесение биоугля в дозах 2, 5 и 10 % от массы почвы. Динамика влажности почвы изучалась в течение 30 суток. Статистическая обработка данных выполнялась с использованием однофакторного дисперсионного анализа ANOVA и критерия Tukey HSD.

Полученные результаты показали, что внесение биоугля способствует достоверному повышению влажности почвы. Через 30 суток содержание влаги увеличилось на 11,9-29,8 % по сравнению с контрольным вариантом. Наиболее высокие показатели водоудерживающей способности и содержания доступной для растений влаги были зафиксированы при внесении 10 % биоугля. Установлено, что положительный эффект связан с увеличением пористости и улучшением структурного состояния почвы. Результаты исследования свидетельствуют о перспективности использования биоугля в качестве природоподобной технологии для повышения качества почв, снижения рисков деградации земель и повышения устойчивости агроэкосистем к засухам в условиях Туркестанской области.

Ключевые слова: биоуголь, сероземная почва, влажность почвы, водоудерживающая способность, деградация земель, экологическая устойчивость, Туркестанская область.