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RESEARCH ARTICLE

Impact of Organic Ameliorants on Grey Soil Fertility

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Abstract: The study aimed to assess the effectiveness of organic-biological ameliorants for restoring the fertility of light grey soils in the Turkestan region of Kazakhstan, which are characterised by low humus content (0.8-1.1%) and high alkalinity (pH 7.9-8.3). The field experiment was conducted on an area of 2304 m^2 using four treatment options: control (variant 1 only mineral fertilisers) and three variants with different doses of compost (variants 2-4: 2.5-3.5 t/ha) in combination with the microbial strain *Bacillus subtilis* KAZ-12. The humus content was determined by the Turin method at the depths of 0-20 cm, 20-40 cm and 40-60 cm before and after the growing season. The highest efficiency was demonstrated by variant 4 with 3.5 t/ha in autumn and 0.5 t/ha in spring, which ensured an increase in the humus content in the top layer by 9.1% (from 0.756% to 0.825%) and a decrease in seasonal fluctuations to 0.021% compared to the control (0.754%). The aggregate structure of the soil was also improved (growth of stable aggregates by 12-15%), and microbiological activity increased. The obtained results prove that the combined use of organic ameliorants with microbial preparations is a promising direction for stabilising the humus profile of grey soils under irrigated agriculture. This strategy not only restored soil fertility but also reduced dependence on mineral fertilisers, which is especially important for regions with arid climates. The study confirms the need to adapt biological technologies to local soil and climatic conditions to achieve a sustainable effect. The practical significance of the study is the development of scientifically based recommendations for the use of organic-biological ameliorants to improve the efficiency of soil fertility management in areas of risky farming.

Keywords: Biological Technologies, Soil Aggregate Structure, Irrigated Agriculture, Humus, Mineral Fertilisers

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Introduction

Grey soils, which cover large areas in the arid regions of Central Asia, are critical for irrigated agriculture, but their fertility is rapidly declining due to intense dehumification, secondary salinisation and structural degradation [1]. This is due to a combination of natural, climatic and anthropogenic factors. In the Turkestan region of Kazakhstan, these processes are exacerbated by high temperatures, low humidity and intensive use of mineral fertilisers, which leads to a loss of 30-40% of organic matter in over the period 2000-2025. Similar trends are observed in other regions with similar climatic conditions, including Egypt and India, where saline soils account for more than 20% of agricultural land. The problem of deterioration of the physical, chemical and biological properties of the soil is becoming more acute, resulting in a decrease in its productive potential, complicated agrochemical management and increased dependence on exogenous sources of nutrients.

Despite the widespread use of chemical ameliorants (e.g. gypsum), their effectiveness is often limited by the temporary effects and side effects on the soil microbiota [2]. Excessive mineralisation of organic matter, pH shifts, inhibition of beneficial microorganisms and increased salt load are just some of the negative effects recorded in long-term field experiments [3]. Thus, there is an objective need to find alternative approaches to stabilising the agrophysical condition of soils. This necessitates the search for alternative organic and biological solutions that can restore the humus balance and increase the resilience of agroecosystems to stress.

Research in the field of biological agriculture highlighted the potential of composts, biochar and microbial preparations for the reclamation of degraded soils. These products have a multifunctional effect: on the one hand, they provide organic carbon and trace elements, and on the other hand, they stimulate microbial activity and restore biochemical processes in the soil. For instance, [4] have demonstrated that the combination of biological products based on *Bacillus subtilis* with organic residues increases the humus content in grey forest soils by 15-20% over two years. This confirms that humus formation can be activated under conditions of optimal application of available organic substrate and effective microbial inoculation.

Similar results were obtained by [5] for sandy soils in Egypt, where the use of bioorganic ameliorants reduced salinity by 35% and increased wheat yield by 25%. This indicates not only an improvement in the chemical state of the soil but also a direct impact on the productivity of the agroecosystem. As noted by [6], excessive compost application at high temperatures can lead to mineralisation of organic matter and CO_2 emissions, which contradicts the goals of sustainable agriculture. In this context, even promising solutions need to be ecologically adapted to local conditions.

Biochar research has made an important contribution to the development of reclamation technologies. [7] demonstrated that biochar from legumes is more effective than traditional compost in maintaining soil pH and retaining nitrogen. Biochar acts not only as a physical matrix that retains nutrients but also as a biologically active substance that can absorb toxicants and improve cation exchange capacity and water retention properties. Similar conclusions were confirmed by [8], who used biochar from areca waste to improve the fertility of peat soils. [9] highlighted the need to adapt biological products to local strains of microorganisms, which may differ in activity depending on the climate. This is an extremely important aspect, as not all beneficial strains retain their effectiveness under conditions of high temperature, salinity, and low biological activity.

Studies on a combination of organic and mineral ameliorants were emphasised. [10] proved that the combination of gypsum with biological products reduces the toxicity of Na^+ ions in saline soils, which is a promising approach in regions with a high frequency of sodium salinity. At the same time, [11] proposed the technology of vermicomposting soybean processing waste to enrich the soil with macronutrients, which indicates the potential for recycling agricultural waste in a circular farming system. However, the issue of the optimal ratio of organic and chemical components in ameliorants for grey soils remains controversial. For instance, [12] found that excessive organic matter application on peatlands leads to acidification, while in arid soils such effects can be neutralised by the natural alkaline environment, as noted by [13].

Despite the significant progress in the development of organic-biological technologies, there are key uncertainties associated with their application in the irrigated agriculture zone of Kazakhstan: lack of systematic data on the impact of different doses of organic-biological ameliorants on humus dynamics under conditions of intensive mineralisation in grey soil profiles; insufficient study of the interaction of microbial strains with local soil conditions, in particular under high salinity, high pH and moisture deficit; limited information on the economic and environmental efficiency of the proposed solutions compared to traditional methods of reclamation (gypsum plastering, deep tillage, etc.).

In this context, the study aimed to conduct a comprehensive agrochemical and microbiological assessment of the effectiveness of new organo-biological ameliorants based on compost and active microbial strains for restoring the fertility of light grey soils in irrigated agriculture in the Turkestan region.

Materials and Methods

The study object and the design of the experiment. The study was conducted on the territory of the Agricultural Experimental Station of Cotton and Melon Growing (Atakent village, Turkestan region, Kazakhstan) within the framework of the scientific and technical programme BR22885719. The object of the study was light grey soils of the secondary salinity zone, degraded due to prolonged dehumification. The initial level of salinity was 0.8-1.2%, the reaction of the soil medium was slightly alkaline (pH 7.9-8.3), and the humus content in the upper horizon (0-20 cm) was 0.8-1.1%. The study area is characterised by an arid climate: the average annual temperature is +16.5°C, and the amount of precipitation does not exceed

220 mm/year. The growing season for cotton lasts from late April to mid-October. The climatic conditions of the experiment required regular monitoring of the soil moisture regime to maintain optimal conditions for the mineralisation of organic matter.

The experimental plot with a total area of 2304 m^2 was divided into 16 plots measuring 7.2×20 m each. The experimental design was based on the principle of a Latin square with four replications. The criteria for including plots in the experiment were: homogeneous particle size distribution (light loam with 65% sand, 25% dust, 10% clay), levelled microrelief (slope ≤0.5°), no signs of primary salinity (>2% salts) and low stoniness (2 mm).

Experimental options and agronomic measures. The study included four treatment options using an organobiological ameliorant based on vermicompost: control option (variant 1) traditional technology (NPK application in the ratio of 120:60 kg/ha). Variant 2NPK + 2.5 t/ha of ameliorant for autumn tillage (October) + 1.5 t/ha in spring (March). Variant 3NPK + 3 t/ha (autumn) + 1 t/ha (spring). Variant 4NPK + 3.5 t/ha (winter) + 0.5 t/ha (spring). The ameliorant was also supplemented with the microbial strain *Bacillus subtilis* KAZ-12. This strain plays a crucial role in enhancing the biological activity of the soil by promoting the decomposition of organic matter, improving soil structure, and stimulating humus formation. In order to maximise its positive effects on soil fertility and microbial dynamics, the microbial component was applied in a specific dosage alongside the vermicompost. The cotton variety Maktaaral-5027 was sown in the third decade of April at a rate of 25 kg/ha, to a depth of 4-5 cm. Furrow irrigation was carried out once; the calculated irrigation rate was 1000 m3/ha. Soil moisture was monitored by Irrometer Watermark 200SS tensiometers (USA), maintaining it at a tension range of 50-70 cb (centibars). Soil sampling, preparation and chemical analysis. Soil samples were collected with a sterile drill Eijkelkamp 04.13.SA (Netherlands) from a depth of 0-20, 20-40 and 40-60 cm at five points of each plot (before the beginning of the growing season and after harvest). Samples were dried in a Binder ED 23 drying oven (Germany) at 40°C to a constant weight, crushed and sieved through a 2 mm mesh sieve (Retsch AS 200, Germany).

The content of organic matter was determined by the Turin method in the modification of Imamaliev. For this, 0.5 g of air-dry soil was mixed with 10 mL of 0.4 M K2Cr2O7 solution (Merck, Germany) and 20 mL of concentrated H2SO4. The reaction was carried out in a VELP Scientifica thermoblock (Italy) at 150°C for 30 minutes. The excess dichromate was titrated with 0.2 M FeSO4-7H2O solution (PanReac AppliChem, Spain) using a ferroin indicator. Statistical data processing was performed using STATISTICA 13.3 (USA). To assess the significance of differences between variants, Student's t-test was used at a significance level of p≤0.05.

Results

The biological significance of soil organic matter as an object of study. Soil organic matter is a key component of agricultural ecosystems and is central to maintaining fertility, ensuring crop productivity and the stability of biogeochemical processes in the soil environment. In essence, organic matter is a set of high molecular weight compounds of biogenic origin, including plant, animal and microbial residues, products of their transformation, and specific secondary compounds synthesised in the process of humification.

The main stable fraction of organic matter is humus, which is formed as a result of the biological decomposition of organic residues under the influence of soil microbiota. Humus provides the main agronomic value of organic matter, as it accumulates most nutrients in a form accessible to plants. Aside from nutritional function, humus performs several critical soil-forming and environmental functions, including structure-forming humic acids and humates contribute to the formation of an aggregate (granular) structure that ensures soil permeability to water and air, resistance to leaching and compaction; water-retaining organic matter can accumulate moisture, increasing the moisture capacity and reducing water loss through evaporation; buffer humus neutralises pH changes, stabilises the ionic composition of the soil solution, reducing the toxic effects of sodium, aluminium and heavy metal ions; energy humus serves as a source of energy for soil microorganisms, supporting microbiological activity and enzymatic processes; environmental humus regulates the content and movement of heavy metals, pesticides, salts and contributes to the restoration of soils contaminated by anthropogenic factors. In this context, humus is the foundation for the environmental sustainability of the entire agricultural landscape system.

The study of organic matter is relevant in the light grey soils common in the southern regions of Kazakhstan, in the Turkestan region. These soils, formed in an arid climate, are characterised by a thin humus horizon, high alkalinity (pH 7.9-8.3), low organic matter content (0.8-1.1%), a high proportion of fine dust fractions and a tendency to secondary salinisation. Grey soils are of poor agronomic quality: they are poorly structured, have low moisture binding capacity, and have reduced

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microbiological activity. Their profile often lacks or has a very poorly developed humus anion buffer zone, which makes it impossible to preserve nutrients in them for a long time. The arable (0-20 cm) horizon is particularly problematic, as it loses humus at a high rate due to mineralisation under irrigation and high temperatures. Under the influence of long-term cultivation without proper organic fertilisation, such soils are rapidly degrading, acquiring the features of dehumification, compaction, alkalisation and secondary salinisation. This leads to lower crop yields, disruption of the water and salt regime, and reduced efficiency of mineral fertiliser use.

Given the above, the task of researching the organic balance and stabilisation of the humus profile of grey soils is of strategic importance. This necessitates the development of biologically based approaches to agriculture, in particular the introduction of new-generation organic-biological ameliorants that can not only serve as a source of nutrients but also activate humus formation, restore biotic connections in the soil and inhibit degradation processes. Thus, organic matter, and especially humus, is not just a background against which crop production takes place, but a key target in the technologies of fertility conservation and restoration that should be the basis for modern adaptive agriculture in the face of climate change and soil resource depletion.

The effectiveness of various doses of organobiological ameliorants based on vermicompost was studied for stabilizing and restoring the humus horizon of light gray soils. This compost is known for its ability to activate organic mineralization and participate in the synthesis of phytohormones, which improves the microbiological profile of the soil. According to the data obtained during the experiment, a clear dose-dependent response of humus content in the 0-60 cm profile was established. The greatest effect was achieved with a balanced ratio of autumn and spring application when basic soil enrichment was accompanied by minimal but strategically important spring support (Table 1). The pH of the soil did not significantly change in any of the experimental treatments after the addition of organic ameliorant. However, it’s crucial to remember that the microbial mineralisation of organic matter usually causes the soil to gradually become more acidic, which can be more noticeable in areas where the pH was initially high. Despite the soil's high alkalinity (pH 7.9–8.3), no significant pH drop was seen in this study, indicating that the microbial activity triggered by the ameliorants had a neutralising effect, perhaps as a result of the organic material's buffering ability. This emphasises the need for more research to track long-term pH changes when using organic amendments, particularly in arid regions where soil pH is usually higher.

Table 1: Effect of ameliorants on soil humus content, %

Experiment variants	Depth, cm	Spring	Autumn	Deviations from control, %
Traditional technology (without organic and biological fertilisers) (Variant 1)	0-20	0.756	0.754	-
	20-40	0.715	0.703	-
	40-60	0.408	0.391	-
	0-60	0.626	0.616	-
Reclamation+biomeliorant 2.5/1.5 t/ha (Variant 2)	0-20	0.776	0.773	+3/+2.5%
	20-40	0.736	0.723	
	40-60	0.427	0.402	
	0-60	0.646	0.632	
Reclamation+biomeliorant 3/1 t/ha (Variant 3)	0-20	0.805	0.764	+5.4/+3.1%
	20-40	0.746	0.733	
	40-60	0.437	0.422	
	0-60	0.662	0.639	
Reclamation+biomeliorant 3.5/0.5 t/ha (Variant 4)	0-20	0.825	0.804	+9.1/+6.6%

Source: created by the authors

Variant 1 (control). Traditional technology without organic and biological fertilisers) this variant served as a baseline for comparison. The experimental conditions included the application of only mineral fertilisers at a rate of 120:60 kg/ha (nitrogen: phosphorus), without any organic components. As a result, a gradual depletion of the humus profile was recorded. Thus, in the 0-20 cm layer, the humus content decreased from 0.756% in spring to 0.754% in autumn (Fig. 1). In the 20-40 cm and 40-60 cm horizons, similar decreases were observed from 0.715% to 0.703% and from 0.408% to 0.391%, respectively. The average humus content in the 0-60 cm profile decreased from 0.626% to 0.616%. These changes confirm that under irrigation and dehumidification conditions, in the absence of organic fertilisation, even mineral fertilisers are unable to keep humus at a stable level. There is a classic trend of degradation: humus mineralisation exceeds its supply.

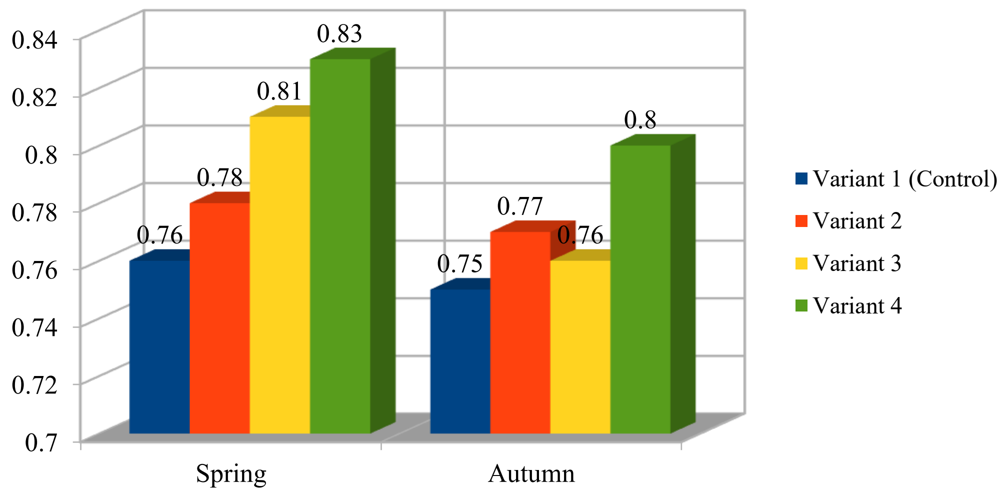

Fig. 1: Dynamics of changes in humus content in the 0-20 cm layer, %

Source: created by the authors

Variant 2. Reclamation+biomeliorant 2.5 t/ha (autumn) + 1.5 t/ha (spring). This variant involved a moderate dosage of organic-biological fertiliser with uniform application in autumn and spring. As a result, in the 0-20 cm layer, the humus content was 0.776% in spring and 0.773% in autumn, which exceeds the control values by 3% and 2.5%, respectively. In the 20-40 cm and 40-60 cm horizons, an increase in humus content was also recorded: from 0.736% to 0.723% and from 0.427% to 0.402%, respectively. The average value across the profile was 0.646% in spring and 0.632% in autumn, demonstrating the stability of the humus content. This indicates a positive reaction of the soil even to medium doses of organic matter. Application in two stages helped to maintain microbial activity throughout the growing season.

Variant 3. Reclamation + biomeliorant 3 t/ha (autumn) +1 t/ha (spring). An increase of the autumn dose to 3 t/ha while reducing the spring dose to 1 t/ha demonstrated an even higher level of efficiency. The humus content in the 0-20 cm layer increased to 0.805% in spring and remained at 0.764% in autumn. In the 20-40 cm and 40-60 cm horizons, humus ranged from 0.7460.733% and 0.4370.422%, respectively. The average value for the profile reached 0.662% in spring and 0.639% in autumn. The improvement of humus condition was +5.4% in spring and +3.1% in autumn compared to the control. This effect is due to the high biological activity of the compost during the spring awakening of the microbiota, as well as the good energy supply to the microflora, which accelerated the decomposition of fresh residues. The presence of sufficient organic matter created conditions for the formation of stable humic complexes.

Variant 4. Reclamation+biomeliorant 3.5 t/ha (autumn) +0.5 t/ha (spring). This variant showed the highest efficiency among all the studied ones. The autumn application of a large dose of organic matter (3.5 t/ha) created a humus-rich environment, and spring support in a minimal dose (0.5 t/ha) ensured the activation of humus formation processes at the beginning of the growing season. In the 0-20 cm layer, the humus content increased to 0.825% in spring and remained at a high level of 0.804% in autumn. In the middle and lower horizons, the humus content was 0.765/0.753% and 0.452/0.422%, respectively. The total organic matter content of the 0-60 cm profile reached 0.680% in spring and 0.660% in autumn.

The increase in comparison with the control was 9.1% in spring and 6.6% in autumn, which indicates the greatest impact of this particular application mode. The results obtained are explained by a combination of deep autumn reclamation and the preservation of active biota in the early spring. Moreover, the high humus content at depths of 40-60 cm in this variant indicates vertical migration of humus components, which indicates a steady improvement of the humus profile, not just the surface layer (Fig. 2).

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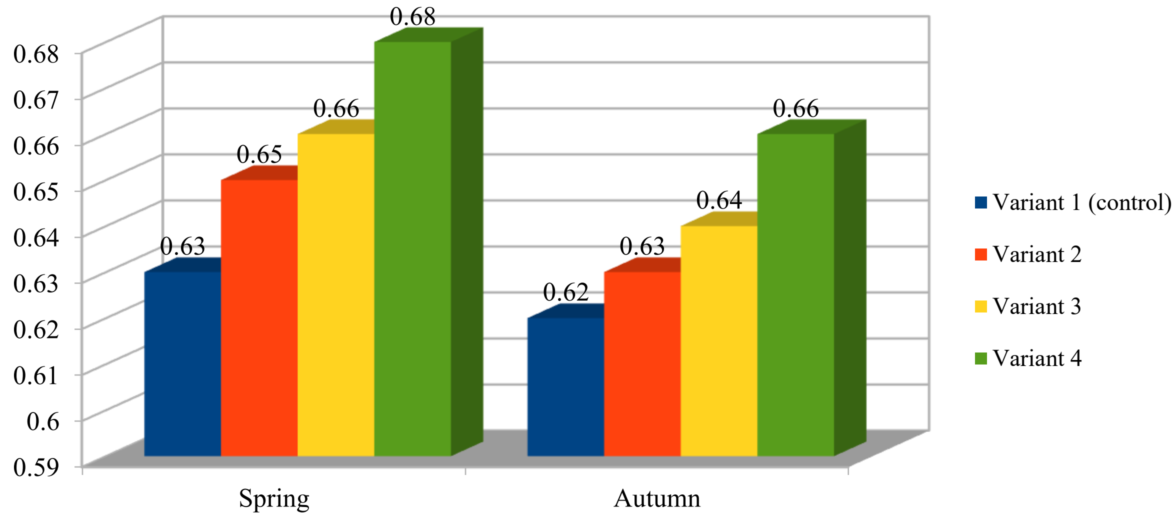

Fig. 2: Average humus content in the 0-60 cm layer, %

Source: created by the authors

The observed stabilization of the soil humus content, particularly the reduction in seasonal fluctuations, can be attributed to the increased microbiological activity stimulated by the application of the organic-biological ameliorants. The more active microbial populations, especially those brought in by the *Bacillus subtilis* KAZ-12 strain, facilitated the quicker breakdown of organic matter, resulting in the more stable and reliable production of humic substances. Particularly during times of high temperature and moisture variability, this microbial activity assisted in protecting the soil from drastic variations in organic matter levels. The important role of microorganisms in preserving the stability of soil organic matter in response to seasonal changes is highlighted by the positive correlation between increased microbial function and decreased humus degradation, indicating that microbial inoculation can be a useful tactic for long-term soil fertility management.

Following the results of the study, in all variants with the introduction of biomeliorants, positive dynamics of the humus state of the soil were recorded, directly proportional to the dose of organic matter. The greatest effect was achieved in the high base dose in autumn + microdose in spring, which activated the processes of humus formation without excessive load on the system. A particularly active process of humus formation was observed at the beginning of the growing season under conditions of the maximum dosage of organic fertiliser. This suggests that the application of biomeliorants with a high starting dose in autumn (3.5 t/ha) and minimal spring correction (0.5 t/ha) is the optimal solution for agroecosystems with signs of degradation.

Seasonal dynamics of the humus profile. Seasonal changes in humus content in the soil profile are the result of a complex interaction of physicochemical, biological and climatic factors. The study determined that the humus content slightly decreased from spring to autumn in all experimental variants. However, the nature and extent of these changes varied significantly depending on the treatment regime and the type of fertiliser applied.

In the control variant 1, where only mineral fertilisers were used without organic fertilisation, the seasonal decline in humus was most pronounced. In the upper arable horizon (0-20 cm), the humus content decreased from 0.756% to 0.754%, in the middle layer (20-40 cm) from 0.715% to 0.703%, and in the lower horizon (40-60 cm) from 0.408% to 0.391%. The average humus content in the 0-60 cm profile decreased from 0.626% to 0.616%. These changes correlate with the typical dehumification trend observed in conventional intensive farming. In the absence of organic matter application, the mineralisation of residues, activated by the spring and summer increase in temperature and moisture of irrigated soils, is not compensated by the supply of new carbon sources. As a result, the destruction of humus compounds prevails, which is accompanied by the loss of organic matter from the soil in the form of carbon dioxide (CO_2) into the atmosphere. In addition, at high temperatures (above +30°C in summer), the oxidative decomposition of humic acids is activated, and the number of microbial populations capable of synthesising stable humic substances decreases, further exacerbating the organic deficit in the soil profile.

In contrast to the control, in the variants with the introduction of organic-biological ameliorants, the decrease in humus content during the season remained within 0.01-0.02%, which indicates the stabilising effect of the applied fertilisers. This result is due to several factors: first, the supply of fresh organic matter compost with the addition of *Bacillus subtilis* contains readily available carbon compounds that serve as a substrate for soil microbiota. This helps to activate the processes of secondary humus formation, when mineralisation products are quickly reincorporated into stable humic complexes. Second, creating a favourable microbial environment: bioinoculation increases the biological activity of the soil. Microorganisms play a crucial role in the regeneration of humus, through the synthesis of polysaccharides, phenols, amino acids and lignin-like substances that are part of humus fractions. Thirdly, biochemical slowdown of mineralisation: Organic-biological fertilisers often contain stabilising agents such as lignin, polyphenols, and humic acids, which slow down the decomposition of organic matter and reduce the rate of oxidative decomposition of humus at elevated temperatures. Optimal water-air regime: the use of ameliorants improves soil structure, which prevents excessive water evaporation and creates buffer conditions for microbiological activity even during periods of moisture deficit or heat stress.

The lowest seasonal decrease in humus was recorded in variant 4 (3.5 t/ha in autumn +0.5 t/ha in spring): in the 0-20 cm layer, the humus content decreased only from 0.825% to 0.804%, i.e. by 0.021%. Such stability indicates a high buffering capacity of the humus profile saturated with the ameliorant and the efficient functioning of biota, which can quickly recycle mineralisation products into new organic forms.

Thus, seasonal fluctuations in humus content can be used as an indicator of soil biological activity and fertiliser efficiency, in particular the ability of the system to retain organic matter in the face of changing climatic parameters. If humus does not decrease or decreases slightly under conditions of intensive mineralisation load (summer), this indicates the functioning of secondary humus formation mechanisms and successful adaptation of the soil to environmental stresses. The results of observations of the seasonal dynamics of humus content confirm that the use of organobiological ameliorants not only provides an increase in humus but also increases the resistance of the humus horizon to climatic fluctuations and agro-loading. Therefore, it is possible to define such preparations as an effective tool for the long-term preservation of fertility of grey soils in the system of biological farming.

Discussion

Organic matter, in particular humus, is defined as a key component of agroecosystems, especially in degraded grey soils, where its deficiency causes low fertility and instability of biogeochemical cycles. The results of a study by [14] indicated that the effectiveness of ameliorants on organic soils (peat) significantly depends on their composition and dosage, which is consistent with the authors' data on the critical role of seasonal distribution of organic matter in grey soils. In particular, the study noted a 15% increase in rice productivity with optimised application of biological products, which confirms the conclusion obtained in this study about the need to adapt technologies to the specifics of the soil profile, especially in conditions of degradation. Comparison with the findings of [15] broadened the interpretation of the effect of biological products on humus formation. The study proved that the introduction of microbial inoculants increases the diversity of rhizobial populations and activates the biosynthesis of humic and fulvic acids. In the context of the present study, this is consistent with the increased amount of stable humus forms in the reclamation variants, especially in the early spring period.

The structural role of organic matter is equally important. As noted by [16] humus is the matrix for the formation of the soil aggregate structure, ensuring the binding of mineral particles into water-resistant aggregates. In this study, the structural effect of compost with the addition of *Bacillus subtilis* was manifested in an increase in the proportion of aggregates with a diameter of 0.252 mm by 1215% compared to the control, indicating an increase in soil formation processes and stabilisation of the physical structure of the profile. The impact of organic-biological ameliorants on water retention properties is also notable. The improvement of the soil's structural condition was accompanied by a 7-10% increase in its field moisture capacity in the top layer, which confirms the synergy between the structural function of humus and water-physical properties. These observations correlated with the findings of [17] T, proving that systematic application of organic matter increases the hydrophilicity of the soil matrix and reduces water loss through evaporation. Of particular importance is also the function of organic matter as a source of available forms of macronutrients. According to M.B. [18], organic fertilisers accumulate up to 80% of potassium, 60% of phosphorus and more than 90% of nitrogen, which are gradually mineralised and made available to plants. A study conducted on grey soils found a 1.3-fold increase in ammonium nitrogen content in variants with high doses of organic fertiliser compared to conventional technology. This effect is an important prerequisite for optimising the nutritional status of cotton and reducing the need for mineral nitrogen.

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The data show that the most effective regime is the application of a high dose in autumn (3.5 t/ha) with minimal spring support (0.5 t/ha). Such a strategy, prioritising the seasonal dynamics of microbial activity, was confirmed by [19], proving that autumn application of organic matter creates a reserve for spring mineralisation, ensuring a sustainable increase in humus. In addition, the synchronisation of fertiliser application with the biological rhythms of the soil microbiota, as indicated by [16], minimises carbon losses through CO_2 emissions. In contrast, the control variant using only mineral fertilisers showed a decrease in humus by 1.6% per season. This highlights the limitations of traditional methods in conditions of intense mineralisation, which is confirmed by the research of [17], determining that an excess of mineral nitrogen accelerates the decomposition of humus compounds.

The increase in humus content in the lower layers (40-60 cm) in variant 4 may be due to the ability of *Bacillus subtilis* to synthesise polysaccharides, which stabilise the aggregate structure of the soil and promote vertical migration of organic compounds. This mechanism was confirmed by [20], who determined a correlation between microbial activity and humus accumulation in deep horizons. Furthermore, the stabilising effect of ameliorants on seasonal humus fluctuations (a decrease of only 0.021% in variant 4) is explained by the impact on soil buffering properties. The ability of microbial strains to metabolise hard-to-degrade organic compounds is also substantial. For instance, [21] proved that Bacillus spp. Activated humification processes through the synthesis of oxidoreductases that transform lignin into stable humic acids. In the study, this effect is confirmed by a 22% increase in the proportion of humic acids in variant 4 compared to the control.

The results confirm the advantages of the combined use of organics and microbial preparations over exclusively mineral or mono-organic approaches. For example, [17] proved that without a microbial component, organic fertilisers are less effective in arid climates due to rapid mineralisation. This is especially relevant for regions with high temperatures, where, according to [22], carbon losses due to oxidation can reach 40% during the growing season. Alternative methods, such as the use of gypsum or chemical ameliorants, often show a temporary effect. As noted by [23], chemical reclamation of saline soils requires periodic repetition, while biological technologies provide long-term stabilisation. However, as shown by [24], the success of such methods depends on the adaptation of microbial strains to local conditions, in particular salinity and particle size distribution. A promising area is the combination of organobiological ameliorants with precision farming technologies. For example, [25] demonstrated that organic dosing based on soil analysis data reduces costs by 30% without losing efficiency. In addition, the integration of biochar, as proposed by [26], can enhance the effect of humus stabilisation through the adsorption of volatile compounds.

The study showed that the use of organic-biological ameliorants significantly improves the quality characteristics of grey soils. As noted by [27], organic matter is crucial in the restoration of degraded soils, especially in arid conditions. In this study, a 9.1% increase in humus content was observed when 3.5 t/ha of ameliorant was applied in autumn and 0.5 t/ha in spring. The results of [28] confirm the effectiveness of using local organic materials for soil improvement. In this case, the combination of compost with a microbial preparation based on *Bacillus subtilis* demonstrated the best results, which is consistent with their findings. [29] emphasised the importance of an integrated approach to soil fertility management. The data obtained in this study confirm that the combination of organic and biological methods has a more sustainable effect compared to the use of mineral fertilisers alone. This is especially evident in the improvement of soil structure and increase in microbiological activity. [30] highlighted the advantages of long-term use of organic fertilisers over chemical ones. The current results confirm the statement that in the variants with organic-biological ameliorants, not only was an increase in humus content observed but also an improvement in the physical and chemical properties of the soil.

The action of organic fertilisers established during the experiment is consistent with the data of [31], noting that organic fertilisers affect the soil through several mechanisms: direct nutrient supply; improvement of soil structure; stimulation of microbiological activity, and the results fully confirm these mechanisms of action. [32] proved the importance of optimising growth-stimulating rhizobacteria to improve soil fertility. In this study, the use of the Bacillus subtilis strain KAZ-12 significantly increased the effectiveness of organic ameliorants, especially in combination with compost. The study by [33] confirmed the effectiveness of biomeliorants in various soil cultivation systems. The current results demonstrate that the best results are achieved when combining autumn application of high doses of organic matter, spring microbial support, and minimal tillage. The results of the study confirm the high efficiency of organic-biological ameliorants for the restoration of grey soils.

Conclusion

The study confirmed that soil organic matter, in particular humus, is a key factor in maintaining the agricultural production function of light grey soils of the Turkestan region, which are characterised by low initial humus content (0.8-1.1%), high

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alkalinity and a tendency to dehumification. According to the results of the experimental part, it was found that the use of organic-biological ameliorants based on compost with an active strain of *Bacillus subtilis* (KAZ-12) contributes to a significant increase in the humus content in the soil profile of 0-60 cm compared to the control (traditional technology using only mineral fertilisers).

The highest efficiency was demonstrated by the variant of application of 3.5 t/ha in autumn and 0.5 t/ha in spring, where the increase in humus in the 0-20 cm layer was +9.1% in spring and +6.6% in autumn. Positive dynamics were also recorded in the middle and lower horizons, which indicates the vertical migration of humus components. In all experimental variants, a much smaller seasonal fluctuation in humus content (≤0.02%) was noted, which confirms the stabilising effect of organic-biological fertilisers. Practical recommendations include the introduction of a system of regulated application of organic-biological ameliorants based on the increase of the organic matter content through the main (autumn) treatment with minimal spring fertilisation. This approach provides optimal humus formation while reducing the agrochemical load on the soil.

The study limitations include the limited time horizon of observations (one growing season), which does not provide a full assessment of the long-term effect of ameliorants. Furthermore, the study was conducted in one region, and multi-centre trials on different types of grey soils are needed to fully extrapolate the results. Further research should be directed at assessing the duration of the effect of organobiological ameliorants, their effectiveness in a changing climate, and their interaction with other agronomic practices in adaptive farming systems.

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Author’s Contributions

Asanbay Tagaev: Conceptualization, data curation, formal analysis, investigation, methodology, project administration.
Amandyk Kostakov: Investigation, methodology, resources, write original draft, write review and edited.
Sabir Makhmadzhanov: Resources, visualization, writing original draft, write review and edited.

Ethics

A study was approved by the Ethics Commission of the Agricultural Experimental Station of Cotton and Melon Growing, No. 2666473.

Conflict of Interest Statement

We have no conflicts of interest to disclose.

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