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ASSESSMENT OF THE EFFECTIVENESS OF BIOSTABILIZATION IN IMPROVING THE GEOTECHNICAL PROPERTIES OF DEGRADED SOILS IN THE ARID REGIONS OF KAZAKHSTAN

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Abstract. The article presents an innovative approach to the restoration and stabilization of weak soils, using the example of the Turkestan region, characterized by an arid climate and degraded soil cover. The main goal of the study was to develop and experimentally validate a biostabilization technology aimed at improving the physico-chemical and engineering-geological properties of soils through environmentally safe compositions. This technology addresses challenges such as erosion, low bearing capacity, and land degradation, which are especially critical in arid regions. The research involved an engineering-

geological analysis of soils using laboratory and computational methods. Evaluated parameters included humus content, mobile phosphorus, nitrogen, exchangeable bases, water retention, and resistance to erosion. Experimental results showed that vermicompost significantly improves soil structure and geotechnical stability. Potassium polyacrylamide enhances water retention, reducing the risk of deformation and settlement. Lime-sulfur broth strengthens surface horizons and reduces wind erosion, although its impact on mechanical properties requires further study. The proposed biostabilization methods effectively improve the geotechnical characteristics of weak soils, increasing their resistance to erosion and enhancing their suitability for engineering applications such as foundation stabilization, slope reinforcement, and land restoration. These technologies are especially relevant in arid climates, where soil degradation is widespread. The study's findings can be applied in geotechnical engineering, engineering geology, and sustainable agriculture to support environmentally responsible land use and the restoration of degraded areas.

Keywords: resource efficiency, ecological safety, soil, biostabilization, germination technology, functional food products

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ҚАЗАҚСТАННЫҢ ШӨЛЕЙТТІ АУМАҚТАРЫНДАҒЫ ДЕГРАДАЦИЯҒА ҰШЫРАҒАН ТОПЫРАҚТАРДЫҢ ГЕОТЕХНИКАЛЫҚ ҚАСИЕТТЕРІН ЖАҚСАРТУДА БИОСТАБИЛИЗАЦИЯНЫҢ ТИІМДІЛІГІН БАҒАЛАУ

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Аннотация. Мақалада Түркістан өңірінің топырағы мысалында құнарсыз топырақтарды қалпына келтіру және тұрақтандыру бойынша инновациялық тәсіл ұсынылған. Бұл аймақтың климаты құрғақ және топырақ жамылғысы қатты деградацияға ұшыраған. Зерттеудің негізгі мақсаты — экологиялық қауіпсіз композицияларды қолдана отырып, топырақтың физико-химиялық және инженерлік-геологиялық сипаттамаларын жақсартуға бағытталған биостабилизация технологиясын әзірлеу және тәжірибе жүзінде тексеру болды. Бұл технология эрозия, төмен көтергіштік қабілет және жердің деградациясы сияқты мәселелерді шешуге бағытталған, бұл әсіресе құрғақ климаты бар аймақтар үшін өзекті. Зерттеу жұмысында зертханалық және есептеу әдістерінің кешенін қолдана отырып, топырақтың инженерлік-геологиялық талдаулары жүргізілді. Физико-химиялық және механикалық қасиеттер, соның ішінде гумустың мөлшері, жылжымалы фосфор, азот, алмастырғыш негіздер, су ұстау коэффициенті және эрозиялық процестерге төзімділік бағаланды. Эксперимент нәтижелері вермикомпостты қолдану топырақ құрылымын едәуір жақсартатынын және олардың геотехникалық тұрақтылығын арттыратынын көрсетті. Калий полиакриламиді су ұстау қасиеттерін күшейтіп, топырақтың деформациясы мен шөгу қаупін азайтады. Әк-күкіртті қайнатпа беткі қабаттарды нығайтуға оң әсер етеді және жел эрозиясының дамуын болдырмайды. Ұсынылған биостабилизация әдістері әлсіз топырақтардың геотехникалық сипаттамаларын жақсарту үшін үлкен әлеуетті көрсетеді. Олар топырақтың эрозиялық процестерге төзімділігін арттырып қана қоймай, сонымен қатар құрылысқа арналған тұрақты негіздер құру, беткейлерді нығайту және деградацияға ұшыраған жерлерді қалпына келтіру сияқты инженерлік шешімдерге жарамдылығын арттырады. Бұл технологияларды құрғақ климат жағдайында, топырақтар қарқынды деградацияға ұшыраған кезінде қолдану өзекті болып саналады. Алынған нәтижелер геотехникалық инженерияда, инженерлік геологияда және ауыл шаруашылығында қоршаған ортаны қорғауға және жер ресурстарын ұтымды пайдалануға бағытталған экологиялық тұрақты шешімдерді әзірлеу үшін пайдаланылуы мүмкін.

Түйін сөздер: ресурстық тиімділік, экологиялық қауіпсіздік, топырақ, биостабилизация, өндіру технологиясы, функционалдық тағам өнімдері

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ОЦЕНКА ЭФФЕКТИВНОСТИ БИОСТАБИЛИЗАЦИИ В УЛУЧШЕНИИ ГЕОТЕХНИЧЕСКИХ ХАРАКТЕРИСТИК ДЕГРАДИРОВАННЫХ ПОЧВ АРИДНЫХ ТЕРРИТОРИЙ КАЗАХСТАНА

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Аннотация. В статье представлен инновационный подход к восстановлению и стабилизации слабых грунтов на примере почв Туркестанского региона, характеризующегося аридным климатом и деградированными почвенными покровами. Основной целью исследования являлась разработка и экспериментальная проверка технологии биостабилизации, направленной на улучшение физико-химических и инженерно-геологических характеристик почв с использованием экологически безопасных составов. Данная технология ориентирована на решение проблем, связанных с эрозией, низкой несущей способностью и деградацией земель, что особенно актуально для регионов с засушливым климатом. В работе проведён инженерно-геологический анализ почв с использованием комплекса лабораторных и вычислительных методов. Оценивались физико-химические и механические свойства, включая содержание гумуса, подвижного фосфора, азота, обменных оснований, коэффициент влагоудержания, а также устойчивость к эрозионным процессам.

По результатам экспериментов установлено, что применение вермикомпоста способствует существенному улучшению структуры почв и повышению их геотехнической стабильности. Полиакриламид калия усиливает водоудерживающие свойства, снижая риск деформаций и осадки грунта. Известково-серный отвар оказывает положительное влияние на укрепление поверхностных горизонтов и предотвращает развитие ветровой эрозии. Предложенные методы биостабилизации демонстрируют значительный потенциал для улучшения геотехнических характеристик слабых грунтов. Они позволяют не только повысить устойчивость почв к эрозионным процессам, но и увеличить их пригодность для инженерных решений, таких как создание устойчивых оснований для строительства, укрепление склонов и восстановление деградированных земель. Применение данных технологий особенно актуально в условиях аридного климата, где почвы подвержены интенсивной деградации. Полученные результаты могут быть использованы в геотехнической инженерии, инженерной геологии и сельском хозяйстве для разработки экологически устойчивых решений, направленных на защиту окружающей среды и рациональное использование земельных ресурсов.

Ключевые слова: ресурсоэффективность, экологическая безопасность, почва, биостабилизация, технология проращивания, функциональные продукты питания

Introduction. Modern geotechnical engineering and engineering geology are facing increasing demands for the development of environmentally sustainable and safe soil management methods for agricultural production. In recent years, there has been growing attention to issues of soil degradation, fertility, and minimizing environmental impact. In response to these challenges, interest is increasing in biotechnologies that contribute to improving the physical and chemical properties of soils and enhancing their agronomic value. One promising area is the use of sprouted grains of agricultural crops such as wheat, mung bean, and black-eyed pea, in combination with environmentally friendly soil treatment methods that not only improve soil structure but also ensure the production of nutritionally rich products (Wang et al., 2021; Mahmud et al., 2024).

The germination process is a natural biochemical mechanism that activates enzymatic reactions, contributing to the breakdown of complex carbohydrates, fats, and proteins, thereby improving their digestibility. This process enhances the content of vitamins, minerals, and antioxidants in plants, positively affecting the quality of the soils used for their cultivation (Barakat et al., 2024; Hoehnel et al., 2022). However, traditional soil treatment methods, which include the use of chemical fertilizers and pesticides, can lead to the accumulation of toxic substances in soils, degradation of soil structure, and reduced fertility, creating risks for the sustainability of agroecosystems (Hertzler et al., 2020; Gamage et al., 2023).

In recent decades, there has been a surge in interest toward environmentally

safe technologies aimed at minimizing the chemical impact on soils. In particular, geotechnical engineering and engineering geology are tasked with developing methods that ensure the regeneration of degraded soils and improve their water retention capacity while maintaining a minimal environmental footprint (Hassan et al., 2022; Reed et al., 2022). The implementation of biotechnologies such as the use of vermicompost, potassium polyacrylamide, and natural growth stimulants represents an important step toward sustainable soil management and increased resistance to erosion (Rehman et al., 2023; Pereira et al., 2023).

Research shows that germinating grains in combination with the application of organic additives enhances the bioactive properties of plants and increases the nutrient content of soils, which is especially important for regions with low humus content and moisture deficiency (Gunathunga et al., 2024; Navarro-Vozmediano et al., 2025). These technologies not only improve the agronomic characteristics of soils but also contribute to the production of eco-friendly products that support human health and reduce the risks of micronutrient deficiencies (Gunathunga, et al., 2024).

Many studies confirm that the use of sprouted grains and environmentally safe soil treatment methods can play a key role in increasing soil resilience, preventing erosion, and improving their physical and chemical properties, thereby supporting the sustainable development of agriculture (Al-Taher et al., 2025). Moreover, such approaches minimize negative environmental impacts, making them an important tool in geotechnical engineering and engineering geology (Danciu et al., 2023; Demirel et al., 2024).

The aim of this study is to develop and optimize a technology for sprouting grain crops (wheat, mung bean, and black-eyed pea) using environmentally safe methods aimed at improving the physical and chemical properties of soils in the Turkestan region. The study proposes various compositions (vermicompost, potassium polyacrylamide, lime-sulfur decoction) for seed and soil treatment, taking into account the biochemical characteristics of the grain crops and the geological features of the region's soils. The proposed technology is expected to increase soil fertility, improve water retention capacity and erosion resistance, and ensure the production of eco-friendly, nutrient-rich products. The application of these methods will reduce the environmental footprint of agricultural production and contribute to the regeneration of degraded soils.

The results of this research may serve as a foundation for developing new standards for environmentally sustainable soil management in geotechnical engineering and engineering geology, and may stimulate the adoption of biotechnologies in agriculture to enhance the agronomic value of soils and meet the growing demand for eco-friendly food products.

Objects and Methods of Research. The objects of the study are the soils of the Turkestan region, grain and legume crops (wheat, black-eyed pea, mung bean), drinking water, vermicompost, potassium polyacrylamide, and lime-sulfur

decoction (LSD). The primary focus is on the engineering-geological properties of the soils, their composition, structure, and potential for improvement for agricultural use and geotechnical purposes.

The research was conducted using a combination of methods, including visual inspection (photographic documentation), laboratory analyses, and computational techniques. The analysis of the composition and properties of soils and other materials was carried out at the "Environmental Monitoring and Chemical Analysis" laboratory of the "Ecology" Research Institute at Khoja Akhmet Yassawi International Kazakh-Turkish University.

The titrimetric method was used to determine nitrogen content in the soils.

The Machigin method was applied to analyze the mobile form of phosphorus.

The Tyurin method was used to determine humus content.

The Kappen-Gilkovich method allowed for the assessment of exchangeable base content (Sainova et al., 2023).

The physical and mechanical properties of the soils were studied to evaluate their bearing capacity, water permeability, and resistance to deformation.

Soil Characteristics of the Turkestan Region

The soils of the Turkestan region, predominantly gray or gray-brown in color, are characterized by the following parameters:

• Humus content: approximately 1.2%, indicating a low organic component and limited fertility.

• Total nitrogen: about 0.16%, suggesting a deficiency in essential nutrients.

• Available phosphorus: ranges from 11.2 to 26.4 mg/kg, reflecting the heterogeneity of the soil cover.

• Exchangeable bases: between 21.6 and 24.9 mg/100 g, which influences the soil's cation exchange capacity.

• Moisture content: low, indicating a water deficit and the need to improve water retention properties.

From an engineering geology perspective, the low levels of humus and moisture make the region's soils vulnerable to erosion, compaction, and degradation. This presents challenges for geotechnical projects such as the construction of agricultural infrastructure or irrigation systems, which require stable soils.

Vermicompost as a Means of Improving the Geotechnical Properties of Soils

Vermicompost is an organic fertilizer produced through the decomposition of agricultural waste (both plant- and animal-based) using red Californian worms (Eisenia fetida) (Fig. 1). The vermicomposting process enhances soil structure, water retention capacity, and microbiological activity, which is directly relevant to geotechnical engineering.

Table 1 presents the chemical composition of vermicompost obtained from the recycling of livestock and crop production waste. The vermicompost was produced at the production facility of the "Ecology" Research Institute at Khoja Akhmet Yassawi International Kazakh-Turkish University.

The vermicompost production process at the "Ecology" Research Institute was carefully monitored, and the final product meets all required standards and regulations applicable to organic fertilizers.

Table 1 – Chemical composition of vermicompost

№	Indicators of composition	Content, %
1	Dry matter	51-58
2	pH	6.7-7.3
3	Moisture	40-44
4	Humus substances	27-33
5	Total phosphorus (P_2O_5)	1.5-2.4
6	Total nitrogen	2.3-3.2
7	Total potassium (K_2O)	1.1-1.8
8	Magnesium	0.6-1.0
9	Calcium	6.0-7.8
10	Helminth eggs	not detected

Vermicompost improves the physical and mechanical properties of soils by increasing their porosity, permeability, and resistance to erosion. This is particularly important for geotechnical applications, such as soil stabilization for the foundations of agricultural structures or irrigation channels. The high content of humic substances (27–33%) enhances the soil's cation exchange capacity, which improves soil cohesion and its ability to retain moisture, thereby reducing the risk of settlement and deformation.

Figure 1. Vermicompost – an organic fertilizer obtained using red California earthworms *(Eisenia fetida)*

Lime-Sulfur Decoction and Its Geotechnical Significance

Lime-sulfur decoction (LSD) is an aqueous solution of calcium polysulfides used primarily for protecting plants against pests and diseases. From a geotechnical perspective, LSD can be utilized for soil stabilization, particularly under low-moisture conditions. Its components such as calcium polysulfides (CaS_n) and

calcium hydroxide possess binding properties that can enhance the strength characteristics of soils.

Preparation of LSD:

To prepare 17 liters of solution, 2 kg of sulfur powder, 1 kg of slaked lime, and 17 liters of water are required.

The process involves boiling the mixture with the addition of a surfactant to improve dispersion.

The application of LSD to soils in the Turkestan region may help reduce dust formation and increase the resistance of the surface layer to wind erosion factors that are crucial under the engineering-geological conditions of the region.

Experimental Study of the Effects on Soils and Crops

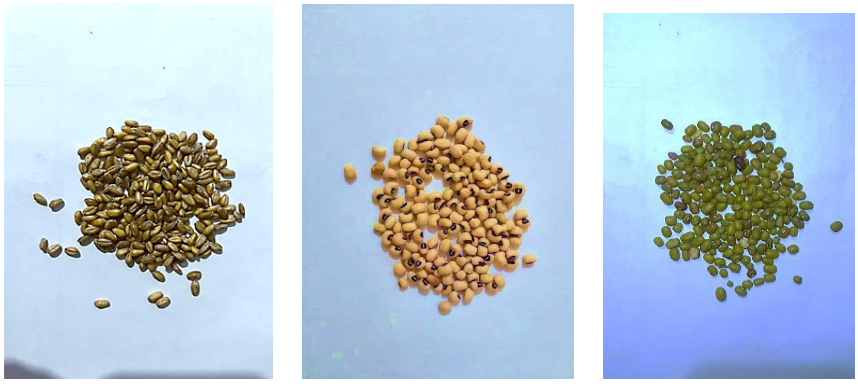
To investigate the impact of various formulations on the germination of agricultural crops (wheat, black-eyed pea, mung bean) (Fig. 2) and the improvement of soil properties, experiments were conducted using the following solutions:

Natural water (control);

Vermicompost solution (1:10, 500 ml of vermicompost per 5 liters of water);

Mixture of vermicompost and potassium polyacrylamide (500 ml of vermicompost + 500 ml of 0.5% potassium polyacrylamide solution);

Mixture of vermicompost, potassium polyacrylamide, and LSD (500 ml of vermicompost + 500 ml of 0.5% potassium polyacrylamide solution + 50 ml of 5% lime-sulfur decoction).



a) b) c)

Figure 2. Agricultural crops used to study the effects on the physico-chemical and geotechnical properties of soils (a: wheat, b: black-eyed peas, c: mung beans)

The seeds were soaked in the solutions for 2-3 hours, after which they were placed on cotton pads in Petri dishes for germination observation. Each dish contained 50 seeds of wheat and mung bean, and 25 seeds of black-eyed pea. 50 ml of solution was added to each Petri dish, and the germination dates and growth intensity of the plants were recorded (Fig. 3).

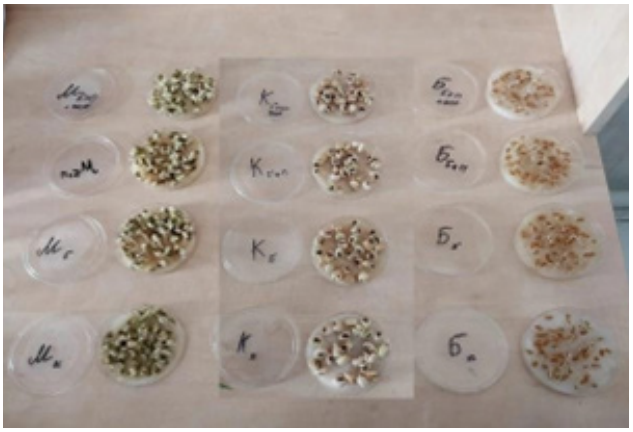


Figure 3. Appearance of seeds placed in a Petri dish

Results and Discussion

Results of Growth Intensity Measurements for Grain Crops (Wheat, Black-Eyed Pea, Mung Bean)

According to the study results, black-eyed pea demonstrated the highest growth intensity across all four formulations, confirming its strong adaptability to various substrate conditions (Fig. 4).

Figure 4. Growth of black-eyed peas.

Wheat and mung bean also showed a positive response to the application of moisturizing formulations, especially those containing vermicompost, which improves the structure and water retention capacity of the substrate (Fig. 5).

a) b)

Figure 5. Manifestations of growth intensity of wheat (a) and mung beans (b)

The experimental results show significant differences in the growth intensity of cereal crops depending on the moisturizing compositions used. Four compositions were applied during the study: natural water, vermicompost, vermicompost with potassium polyacrylamide, and vermicompost with potassium polyacrylamide and lime-sulfur decoction. These compositions made it possible to assess the effect of each component on the growth of wheat, mung bean, and black-eyed pea seeds.

The data on the growth intensity of wheat, mung bean, and black-eyed pea seeds after treatment with various moisturizing compositions are presented in Tables 2, 3, and 4.

Table 2. Growth intensity of wheat seeds after treatment with four different moisturizing compositions, cm

Moisturizing compositions	22.03. 2024	25.03. 2024	27.03. 2024	29.03. 2024	01.04. 2024	03.04. 2024	05.04. 2024	08.04. 2024	10.04. 2024
Natural water	1.1	2.6	3.5	6.6	12.0	14.7	20.2	27.9	29.7
Vermicompost	1.6	3.1	5.4	9.5	14.6	18.2	22.5	30.2	33.0
Vermicompost + potassium polyacrylamide	1.4	2.9	4.3	8.2	13.2	16.4	21.6	29.4	31.8
Vermicompost + potassium polyacrylamide + lime-sulfur solution	1.2	2.7	3.8	7.2	12.6	15.1	20.8	28.3	30.4

According to Table 2, it is evident that wheat showed the highest growth intensity when treated with vermicompost. Specifically, the growth intensity of the seeds treated with vermicompost increased from 1.6 cm to 33.0 cm between March 22 and April 10. This exceeds the growth of seeds moistened with natural water (29.7 cm), indicating a positive effect of vermicompost on wheat germination and growth.

In addition, the combination of potassium polyacrylamide with vermicompost

(31.8 cm) produced good results, although it was slightly less effective than pure vermicompost. This may be due to the fact that potassium polyacrylamide helps improve soil structure and increases its water retention capacity, which is especially important for the arid soils of the Turkestan region, where low moisture limits plant growth. However, the combination with the lime-sulfur decoction (30.4 cm) showed less pronounced growth, indicating a possible inhibitory effect of the lime-sulfur decoction.

Thus, it can be concluded that the optimal conditions for wheat involve the use of vermicompost, and the addition of potassium polyacrylamide and lime-sulfur solution has an additional effect, but it is not as pronounced as in the case of pure vermicompost.

Table 3. Growth intensity of black-eyed pea seeds after treatment with four different moisturizing compositions, cm

Moisturizing compositions	22.03. 2024	25.03. 2024	27.03. 2024	29.03. 2024	01.04. 2024	03.04. 2024	05.04. 2024	08.04. 2024	10.04. 2024
Natural water	1.8	2.9	4.2	7.7	13.4	15.5	21.6	28.7	30.9
Vermicompost	2.4	3.8	5.7	9.7	15.5	17.4	23.8	31.0	34.2
Vermicompost + potassium polyacrylamide	2.2	3.5	5.0	8.9	14.8	16.7	22.9	30.1	32.6
Vermicompost + potassium polyacrylamide + lime-sulfur solution	2.0	3.1	4.6	8.0	13.8	15.9	22.1	29.2	31.5

The black-eyed pea showed the most significant growth among all the crops. It demonstrated good results both when treated with vermicompost and when combined with potassium polyacrylamide and lime-sulfur solution. The greatest growth of the peas was recorded in the group using only vermicompost (34.2 cm), which confirms its high biological activity and ability to stimulate growth even under limited water supply conditions. Interestingly, the addition of potassium polyacrylamide in combination with vermicompost also yielded good results (32.6 cm), which may suggest that polyacrylamide improves the water-retaining properties of the substrate and enhances growth conditions. The composition with lime-sulfur solution (31.5 cm) also showed good results, although slightly lower, which may be related to the chemical composition of the lime-sulfur solution, which could interact with plants within a certain range. The minimum growth was recorded in the group treated with natural water (30.9 cm), highlighting the importance of using additional fertilizers to stimulate plant growth, especially in laboratory experiments.

Table 4. Growth intensity of mung bean seeds after treatment with four different moisturizing compositions, cm

Moisturizing compositions	22.03. 2024	25.03. 2024	27.03. 2024	29.03. 2024	01.04. 2024	03.04. 2024	05.04. 2024	08.04. 2024	10.04. 2024
Natural water	0.6	1.1	1.8	4.0	9.3	12.0	17.4	21.6	25.2
Vermicompost	1.1	2.3	3.4	6.2	11.8	14.2	19.7	23.8	27.5
Vermicompost + potassium polyacrylamide	0.9	1.9	2.8	5.7	11.0	13.4	18.9	23.0	26.7
Vermicompost + potassium polyacrylamide + lime-sulfur solution	0.8	1.4	2.1	4.9	10.2	12.8	18.1	22.3	26.0

Mung bean, like wheat, showed good results, but its growth was less pronounced compared to black-eyed peas and wheat. The greatest growth was recorded when using vermicompost, where the growth reached 27.5 cm. This suggests that although mung bean responds well to vermicompost, it is not as sensitive to germination conditions as other crops. The use of polyacrylamide in combination with vermicompost (26.7 cm) yielded good results, but not as pronounced as with pure vermicompost. This confirms that the addition of polyacrylamide helps improve the soil and water structure, but for mung beans, the effect of these additives is not as critical. The composition with lime-sulfur solution (26.0 cm) showed similar results, confirming the neutral effect of the lime-sulfur solution on mung bean growth. Natural water, as in other cases, showed the lowest result (25.2 cm), which confirms the slower and more limited seed growth without additional stimulation from fertilizers and additives.

Analysis from a Geotechnical and Engineering Geology Perspective

The experimental results demonstrate the impact of moisturizing compositions on the physico-chemical and geotechnical properties of the substrate, which is significant for engineering geology and geotechnical engineering:

Vermicompost increases humus content and microbiological activity, which improves soil structure, porosity, and water retention capacity. This reduces the risk of erosion and enhances soil resistance to deformation important factors for constructing irrigation systems and agricultural facilities in arid regions.

Potassium polyacrylamide enhances the soil's water-holding capacity, which is particularly important for the Turkestan region, where moisture levels are low (approximately 1.2% humus content). It contributes to soil stabilization, prevents subsidence, and improves the soil's bearing capacity.

Lime-sulfur decoction strengthens the soil's surface layer due to the binding properties of calcium polysulfides, reducing wind erosion and increasing resistance to external impacts. However, its weaker effect on plant growth may indicate the need to optimize its dosage to preserve microbiological activity.

The graphs of initial and total growth intensity (Figures 6-7) confirm that

vermicompost and its combinations with potassium polyacrylamide create optimal conditions for germination by improving the physical and mechanical properties of the substrate.

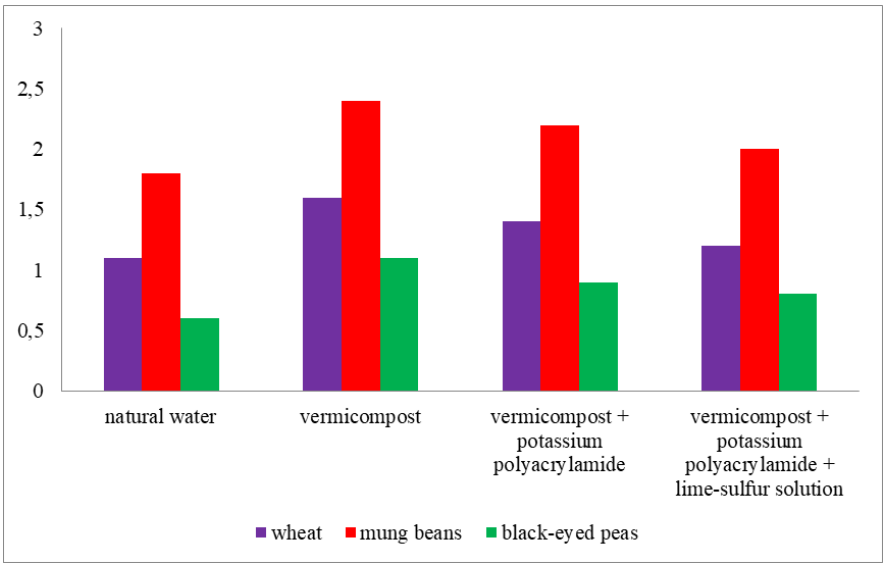


Figure 6. Initial growth intensity of cereal crops during the growing season, cm

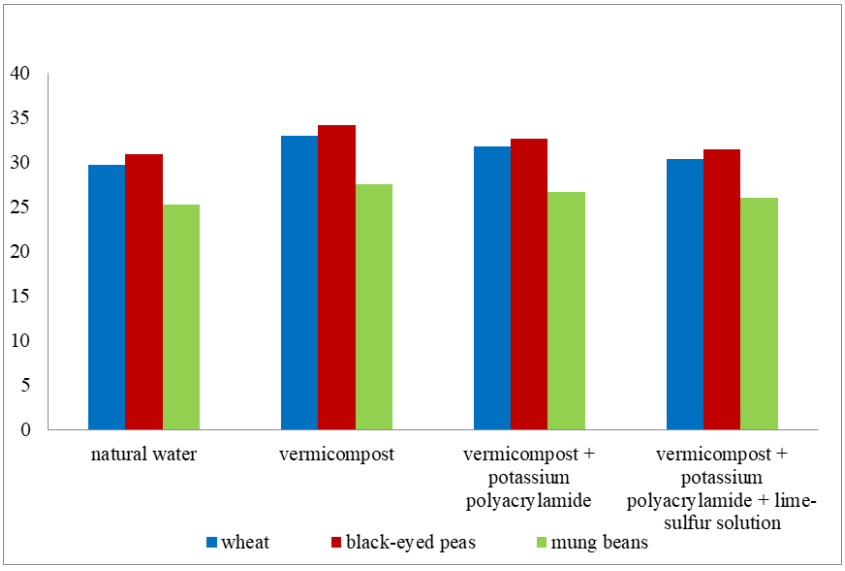


Figure 7. Growth intensity of cereal crops during the growing season (22.03.2024-10.04.2024), cm

The results confirm that vermicompost is a key factor in improving the geotechnical properties of soils in the Turkestan region. Its application increases the content of organic matter, improves soil structure, and enhances its water

retention capacity, which is critical for arid soils with low humus content (1.2%) and moisture levels. Potassium polyacrylamide further enhances the water-holding properties, reducing the risk of soil degradation and improving its suitability for agricultural and engineering purposes. Although lime-sulfur decoction has a lesser effect on plant growth, it contributes to strengthening the soil surface layer, which is important for preventing erosion under wind exposure conditions.

Natural water showed the lowest effectiveness, emphasizing the need to use organic and synthetic additives to improve the properties of arid soils. These findings can be applied in geotechnical engineering for designing sustainable agroecosystems, reinforcing soils under irrigation systems, and preventing erosion in the conditions of the Turkestan region.

Conclusion. Based on the conducted study on the effects of various moisturizing compositions on the physico-chemical and engineering properties of soils, the following conclusions can be formulated from the perspective of geological and geotechnical engineering:

1. The application of vermicompost significantly improves the physico-chemical characteristics of soil: it increases the content of organic matter, enhances structure and water retention capacity, and boosts microbiological activity. This makes vermicompost an effective means for soil stabilization and the rehabilitation of degraded areas within geotechnical systems.

2. The combination of vermicompost with potassium polyacrylamide enhances the soil's water-retention ability and structural integrity. This is particularly important for arid regions with low moisture content, where such mixtures help reduce ground deformation, minimize settlement, and increase the bearing capacity of soils.

3. Incorporating lime-sulfur decoction into the moisturizing mixture provides a reinforcing effect on the surface soil layers due to the binding properties of calcium compounds. This can be effectively used for wind erosion control and improving soil resistance to external impacts; however, further evaluation is needed regarding its influence on mechanical properties such as shear strength.

4. Using natural water without additives showed minimal improvement in geotechnical parameters, highlighting the necessity of applying organic and synthetic additives when working with weak or arid soils in engineering projects.

5. Comprehensive geotechnical analysis confirmed that the incorporation of organo-mineral components into soil reduces erosion risks, improves resistance to loading and deformation, and enhances structural stability and the durability of engineering constructions—especially in conditions of high aridity and land degradation.

6. The study's results can be applied in the design and implementation of geotechnical engineering solutions such as slope reinforcement, foundation stabilization, erosion control, and the development of stable soil bases for infrastructure and agro-engineering facilities.

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