EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2026, 27(4), 164–175
https://doi.org/10.12912/27197050/218759
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Received: 2026.02.01
Accepted: 2026.03.16
Published: 2026.04.01

Enriched humic fertiliser based on oxidised lignite and natural minerals of Kyrgyzstan

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ABSTRACT

This study aimed to develop and experimentally validate an integrated humic organomineral fertiliser based on oxidised lignite, vermicomposted humus and glauconite from Kyrgyz deposits and to evaluate its physicochemical properties and compliance with national standards. A comprehensive physicochemical and mineralogical characterisation of raw materials and the final product was conducted using X-ray diffraction (XRD), X-ray fluorescence (XRF) spectroscopy, inductively coupled plasma spectrometry and thermogravimetric analysis. Oxidised lignite was subjected to alkaline extraction followed by enrichment with vermicompost humus and glauconite concentrate to obtain an integrated organomineral fertiliser. XRD analysis identified up to 65.2% CO_2-associated phases, including 11.2% stichtingite and 9.8% munirite. Glauconite concentrate contained 2.6–5.3% K_2O. The resulting fertiliser contained 27.5% humic acids (dry matter), 73.9% organic matter, 2.2% total N, 2.6% total P_2O_5 and 1.4% total K_2O, exceeding the minimum requirements of GOST R 50335:2022. XRF analysis revealed Ca (34.93%), K (26.85%), Fe (15.84%) and Si (16.29%) as dominant elements. The product complied with regulatory standards and demonstrated a 15–20% increase in plant biomass under practical application conditions. The study was limited to laboratory-scale production without long-term field trials. Unlike previous studies that examined individual humic or mineral components, this study provides the first integrated technological approach combining oxidised lignite, vermicompost humus and glauconite from Kyrgyz deposits with comprehensive physicochemical validation.

Keywords: oxidised brown coal, humic acids, glauconite mineral, humic organomineral fertiliser, soil.

INTRODUCTION

Increasing anthropogenic pressure on agricultural ecosystems has intensified the need for sustainable soil management strategies. The intensive development of land use in the agricultural sector has led to excessive chemicalisation of soils, erosion, salinity and a decrease in the content of organic matter. The problem arises of finding safe solutions in the context of fertilisers that are complementary to the needs of the natural environment. Such fertilisers are physiologically active compounds of natural origin, including humic substances (HS), which are present in natural waters, peat, sapropel and brown coal. They constitute the bulk of the organic matter of solid fossil fuels, especially the upper oxidised layer of Leonardite brown coal. Humic acids (HA) are complex naturally occurring organic macromolecules containing aromatic structures and functional groups such as carboxyl and phenolic groups (Kozyatnyk et al., 2015; Grinfelde et al., 2017). They are found mainly in peat, oxidised brown coal and weathered hard coal. HA molecules contain aromatic groups (Merkhatuly et al., 2017; Mukhametov et al., 2023). At the same time, molecular forms can be very diverse, which is determined by the natural features of the source of their formation, as well as the specifics of biochemical reactions during the formation process. The conditions of geochemical transformation also have some influence.

As a result of intensive land use, humus reserves in the soil are declining (Mukhametov et al., 2024). During the period 2010–2024, a negative balance of nutrients and humus in the soils of agricultural areas in the southern region of Kyrgyzstan was characteristic. Organic mineral fertilisers have a positive effect on plants: they increase plant resistance, crop yield and soil fertility (Shahini et al., 2023a; Rudavska et al., 2023). Kyrgyzstan remains largely dependent on fertiliser imports due to the absence of domestic production of both chemical and organic fertilisers.

Recent studies in agrochemistry and organic fertiliser production have focused on the utilisation of HS derived from oxidised coal and mineral resources. Aldasheva (2019) examined the extraction of HS from oxidised coal of the Uzgen deposit using electrochemically activated water, demonstrating the feasibility of obtaining humic compounds through controlled electrolysis and confirming their potential agronomic value. The study primarily addressed extraction efficiency and did not consider the integration of additional mineral or organic components capable of enhancing the functional composition of the resulting fertiliser.

Research has also examined mineral resources suitable for integration into humic-based fertiliser systems. Zholdoshova et al. (2014) investigated the activation of glauconite through thermal and chemical treatment, demonstrating its suitability as a potassium-containing mineral additive for soil fertilisation. However, this work focused on the properties of activated glauconite itself and did not examine its combined application with HS derived from oxidised lignite or organic humus, nor the technological integration of these components into a unified fertiliser composition.

Subsequent studies have examined the production and application of humate-containing fertilisers derived from coal resources. Anarbayev et al. (2025) investigated the formation and properties of complex phosphohumate mineral fertilisers, highlighting the functional role of humic compounds in nutrient retention and soil conditioning. Similarly, Omarov et al. (2024) evaluated technological approaches for obtaining humate-containing fertilisers from brown coal and identified key process parameters influencing product quality. While these studies confirm the agronomic and technological potential of coal-based humic fertilisers, they primarily address individual production pathways and do not consider the combined utilisation of lignite, vermicompost-derived humus, and natural mineral additives within an integrated multi-component fertiliser formulation.

At the regional level, Kazangeldina et al. (2023) reported positive effects of humic-containing biofertilisers on soil fertility indicators in southern Kyrgyzstan. Broader analyses of agricultural development in Kyrgyzstan have emphasised the importance of organic fertilisation and sustainable land management strategies (Abdiev et al., 2024; Kozhogulova et al., 2023). At the same time, research on the implementation of organic agriculture has identified persistent institutional and structural constraints, including coordination challenges and infrastructural limitations affecting sectoral development (Taranov and Kawabata, 2024; Aliyeva et al., 2024).

Despite these contributions, existing research remains fragmented. Previous studies have addressed either the extraction of HS from oxidised coal, the activation of mineral components such as glauconite, or the agronomic application of humic fertilisers in regional contexts. However, an integrated technological approach combining oxidised lignite, vermicompost-derived humus, and glauconite from Kyrgyz deposits, supported by comprehensive physicochemical validation of the resulting fertiliser, has not been systematically examined. This gap limits the development of locally adapted organomineral fertilisers capable of reducing import dependency and supporting sustainable soil management in Kyrgyzstan.

Therefore, this study aims to develop and experimentally validate an integrated humic organomineral fertiliser based on oxidised lignite, vermicompost humus, and glauconite from Kyrgyz deposits, with comprehensive physicochemical and mineralogical characterisation of both raw materials and the resulting product.

To achieve this aim, the study pursued the following objectives:

- to determine the technical, chemical, and physical characteristics of oxidised brown coal, organic waste-derived humus, and glauconite;
- to establish technological parameters and assess the feasibility of producing an enriched humic organomineral fertiliser using these components;
- to evaluate the compositional characteristics and regulatory compliance of the resulting fertiliser.

MATERIALS AND METHODS

Raw materials and sample selection

This study employed laboratory-scale experimental procedures to characterise oxidised brown coal from the Kyzyl-Kyi deposit (Abshir area) and glauconite from the Kyzyl-Tokoy deposit (Kyrgyz Republic), with the aim of developing an integrated humic organomineral fertiliser.

Physicochemical, mineralogical and technological methods were used to determine the composition and technological parameters of oxidised brown coal from the Kyzyl-Kyi deposit (Abshir area). The component composition of glauconite minerals from the Kyzyl-Tokoy deposit (Kyrgyz Republic) was also investigated.

Three representative samples of oxidised brown coal from the Kyzyl-Kyi deposit were analysed using XRD at the Musa Adyshev Institute of Geology of the National Academy of Sciences of the Kyrgyz Republic. K_2O content in glauconite sandstones was determined by standard chemical laboratory procedures. The selection of samples was based on their geological representativeness for southern Kyrgyzstan and their relevance to potential agricultural application. All analytical procedures, including XRD and elemental analysis, were conducted in accordance with established laboratory protocols and internationally accepted analytical guidelines.

Physicochemical and mineralogical characterisation

The experimental programme included granulometric, chemical, mineralogical, and thermal analyses. Granulometric analysis was conducted to determine particle-size distribution of loose rock material. Elemental composition was determined using an Optima 2000 DV inductively coupled plasma optical emission spectrometer (ICP-OES). Exchangeable Na^+, Ca^{2+}, K^+ and Mg^{2+} cations were determined by displacement with aluminium chloride solution followed by spectrometric measurement.

Thermogravimetric analysis (DTA-DTG, TG-DSC) was performed under programmed temperature conditions to assess mass loss and thermal behaviour of samples. Optical microscopy and electron microscopy were used to evaluate structural features. Electron paramagnetic resonance analysis was applied to identify and quantify paramagnetic centres.

Quantitative and qualitative phase analysis was carried out using an automated DRON-4 X-ray diffractometer with CuKα radiation and a β-filter. Diffractometer operating conditions were: U=35 kV; I=20 mA; time constant 2 s; θ–2θ scan mode; scan speed 2°/min; scale 2000 impulses. Diffractograms of powdered samples were interpreted using the American Society for Testing and Materials (ASTM) reference database and reference patterns of impurity-free minerals.

Additional analyses included low-temperature nitrogen adsorption and differential thermomagnetic analysis. Compositional analysis of oxidised brown coal was conducted at the Akmatbek Dzhamanbaev Institute of Natural Resources of the National Academy of Sciences of the Kyrgyz Republic.

Development of humic organomineral fertiliser

For fertiliser production, oxidised brown coal was ground in a laboratory mill to a particle size of 0.25–0.10 mm. The powdered coal was mixed with water at a solid-to-liquid ratio of 1:10 and subjected to alkaline extraction with solid potassium hydroxide (KOH) at 60–70 °C under continuous mechanical stirring for 6–8 h. Following extraction, vermicompost-derived humus obtained using California red worms (*Eisenia foetida*) and mechanically separated glauconite concentrate from Kyzyl-Tokoy sandstone were added to the H_2O:C:KOH system. After completion of the reaction, the mixture was separated into soluble and insoluble fractions by centrifugation. The liquid fraction containing dissolved humic components was transferred to storage containers for stabilisation.

The sequential stages of raw material preparation, alkaline extraction, component integration and product stabilisation are summarised in Figure 1 to provide a schematic representation of the technological workflow.

As illustrated in Figure 1, the production process includes controlled particle-size reduction, alkaline extraction under defined thermal conditions, sequential addition of organic and mineral components, and subsequent separation of the liquid fertiliser fraction for analytical evaluation.

Product assessment

The resulting fertiliser was subjected to compositional and toxicological evaluation in a specialised laboratory of the Department of Chemicalisation, Plant Protection and Quarantine of the Ministry of Agriculture of the Kyrgyz Republic to assess compliance with national agricultural and toxicological safety requirements.

RESULTS

This section presents the physicochemical and mineralogical characteristics of oxidised brown coal and glauconite used as raw materials, as well as the compositional parameters of the developed humic organomineral fertiliser. The results include XRD, elemental composition and compliance of the final product with national regulatory standards.

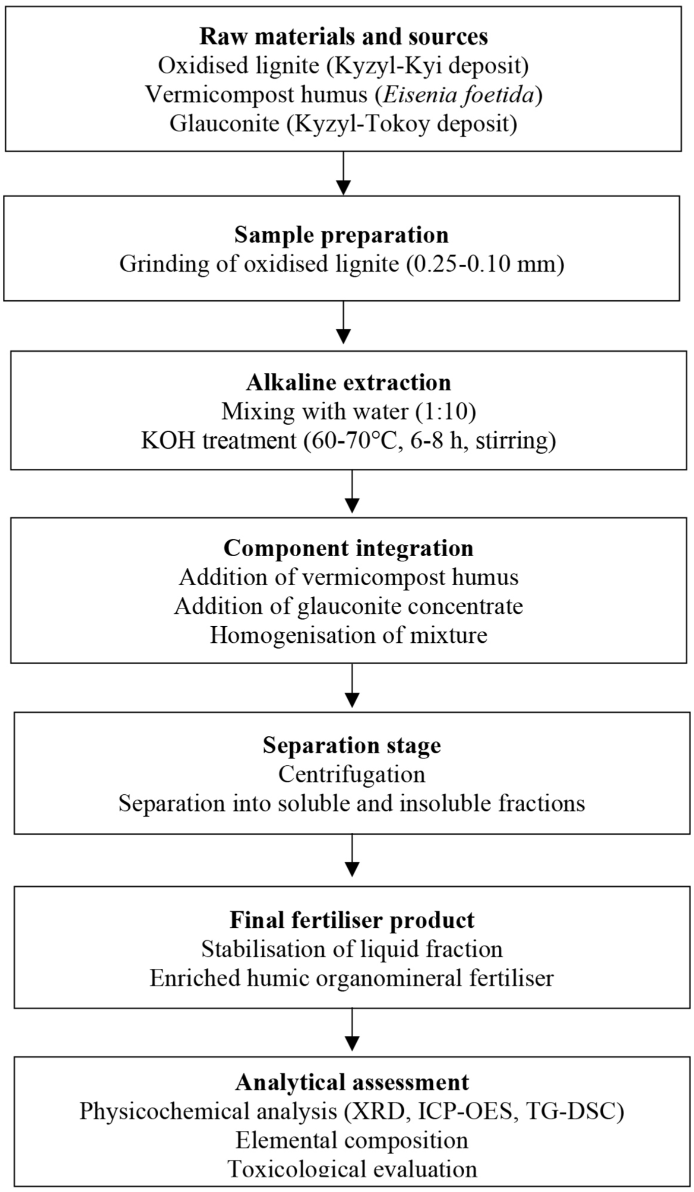

Figure 1. Technological workflow of enriched humic organomineral fertiliser production and assessment

Samples of oxidised brown coal from the Kyzyl-Kyi deposit (Abshir area) are presented in Figure 2. Sample "u1" represented the primary coal fraction used for mineralogical analysis, whereas samples "u2" and "u3" represented impurity inclusions. The diffraction characteristics of sample "u1" are presented in Figure 3.

XRD analysis of sample u1 revealed predominance of CO_2-associated phases (65.2%), along with stichtingite (11.2%), munirite (9.8%), S (9.5%), Si (2.8%) and U (1.5%). Sample u2 was identified as hydrocalumite, whereas sample u3 exhibited CO_2-associated phases (68.7%), glauconite (15.3%), S (11.5%) and Si (4.5%).

The mineral and elemental composition of glauconite from the Kyzyl-Tokoy deposit (Kyrgyz Republic) was further analysed to determine its suitability as a mineral component of the fertiliser. Elemental analysis enabled determination of exchangeable K, Na, Ca and Mg ions and evaluation of cation-exchange characteristics. The cation concentrations were quantified using inductively coupled plasma optical emission spectrometry and expressed as percentage composition of exchangeable ions.

The analysed glauconite sand samples are presented in Figure 4. Previous chemical analyses of glauconite sandstones indicated K_2O content in the range of 2.6–5.3%.

Quantitative phase composition determined by XRD is presented in Table 1 and Figure 5. The highest interplanar distance values were recorded for layered silicate minerals (LSM), glauconite and calcite, with LSM and glauconite showing the greatest relative reflection intensity. The diffractogram of the glauconite concentrate sample is shown in Figure 5.

The obtained phase composition confirms the predominance of layered silicate structures and glauconite within the analysed sample.

The diffractogram demonstrates pronounced diffraction maxima corresponding to LSM and glauconite phases. Based on the characterised raw materials, a laboratory prototype of a humic

Figure 2. Coal samples from the Kyzyl-Kyi deposit (Abshir section)

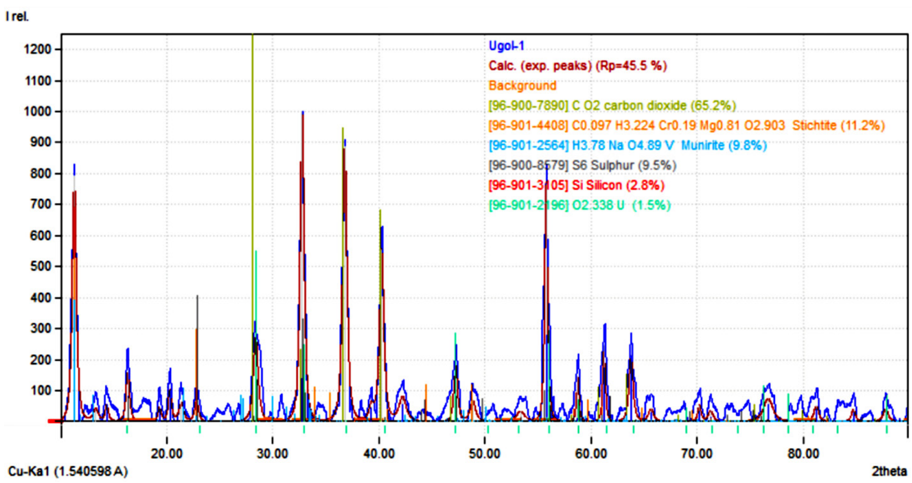

Figure 3. Graph of diffraction bands of sample "u1"

Figure 4. Glauconite sand concentrate
Adapted from Anarbayev et al. (2025)

Table 1. Phase composition and interplanar distances of a glauconite concentrate sample

d, Å	I, %	Mineral
10.427	85	LSM
4.573	83	Glauconite
3.352	73	Glauconite
3.039	76	Calcite
2.604	87	Glauconite
2.427	77	Glauconite
2.285	73	Calcite
2.091	75	Calcite
2.008	68	Glauconite
1.668	79	-
1.522	92	LSM
1.508	84	Glauconite

Note: d (Å) – interplanar distance, and I (%) – phase composition; adapted from Anarbayev et al. (2025).

organomineral fertiliser was developed. Oxidised brown coal and glauconite served as principal components. The resulting fertiliser incorporated vermicompost-derived humus and glauconite resulting in a balanced macro- and microelement composition.

The elemental composition of the obtained fertiliser determined by XRF analysis is presented in Figure 6 and Table 2.

XRF analysis showed predominance of Ca (34.93%), K (26.85%), Fe (15.84%) and Si (16.29%), indicating mineral enrichment of the fertiliser. Following synthesis and separation of soluble and insoluble fractions, the final fertiliser product was evaluated against national quality standards (Table 3).

The obtained fertiliser met the requirements of the national standard for organomineral fertilisers in terms of moisture content, organic matter, HA and nutrient composition. The developed fertiliser demonstrated stable elemental composition and exceeded minimum regulatory thresholds for HA, total N, P_2O_5 and K_2O, confirming its compositional consistency.

DISCUSSION

Interest in humic-based organic fertilisers has grown alongside the expansion of sustainable agricultural practices and the search for alternatives to intensive chemical soil treatment. The structural heterogeneity of HS, formed through natural processes of molecular transformation and selective biodegradation, determines their high chemical reactivity and functional diversity (Bergstrand, 2022; Adekenov and Gafurov, 1992). HA and associated fulvic components contain aromatic and functional groups capable of binding metal cations and interacting with mineral phases, which explains their stability in soils and their role in nutrient retention and transformation (Rasouli et al., 2022; Sarlaki et al., 2023).

The mineralogical and elemental analyses performed in this study confirm the suitability of oxidised brown coal and glauconite as raw materials for humic organomineral fertiliser production. The predominance of LSM and glauconite identified by XRD, together with elevated concentrations of K, Ca, Fe and Si revealed by XRF analysis, indicates a balanced macro- and microelement composition of the developed fertiliser. These characteristics are consistent with the structural and functional properties reported for humic-based fertilisers in previous studies.

The effectiveness of potassium humate in soil fertilisation is attributed to its content of essential micronutrients (Cu, Fe, Mo, B, Mn and Zn), which enhance nutrient uptake and support fundamental physiological processes, including protein synthesis, photosynthesis and cell division (Tiwari et al., 2023; Valujeva et al., 2022). Improving the nutritional quality of the crop with the help of HA helps to increase the content of fibre and nutrients (Shahini et al., 2023b; Kurta, 2011). In the case of mineral fertilisers, the simultaneous use of HA stimulates the absorption of synthetic minerals (Xiong et al., 2023; Yeraliyeva et al., 2016).

Previous studies indicate that the application of potassium humate may increase green biomass

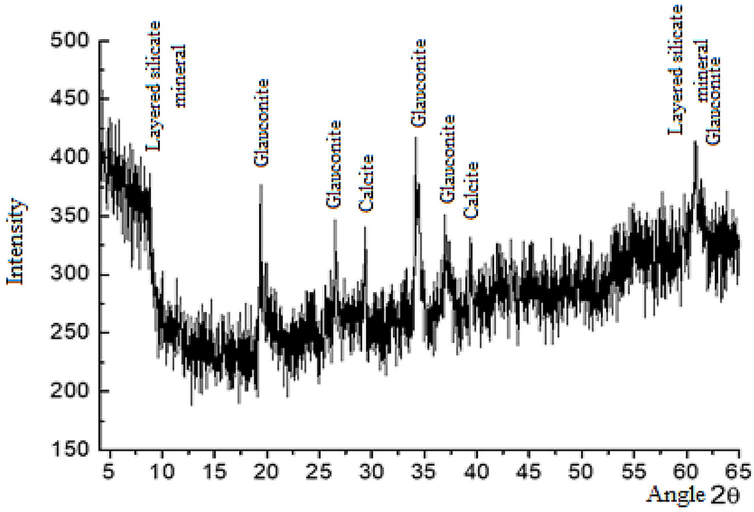

Figure 5. Diffractogram of a sample of glauconite concentrate

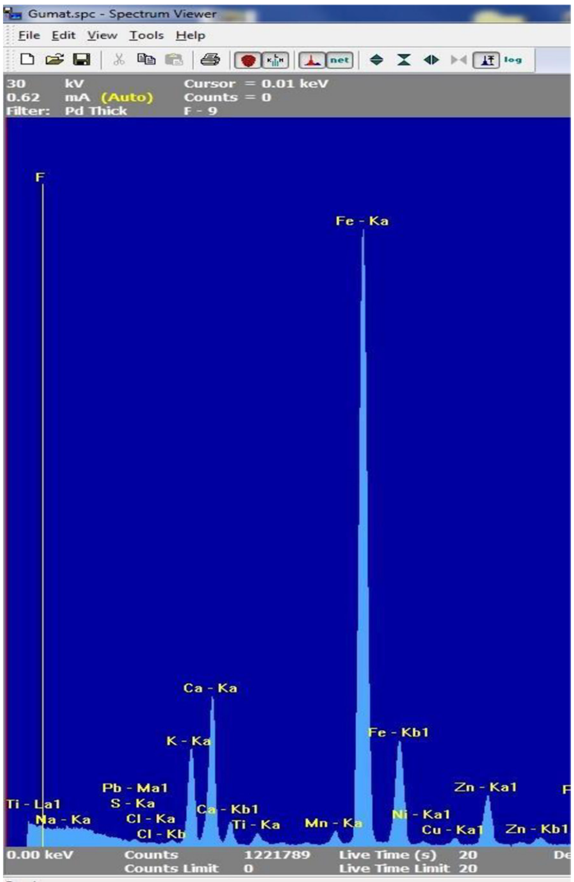

Figure 6. XRF analysis results (humate fertiliser, dry, powder)

and root development by up to 15–20%, contributing to yield improvement. In addition, potassium humate acts as a natural immunostimulant that protects plants from fungi and mould (Sedlář et al., 2023; Lanno et al., 2022). The composition of the fertiliser developed in the present study corresponds to these functional characteristics, as it contains substantial concentrations of macro- and microelements associated with plant growth stimulation and nutrient balance.

Potassium humate is positioned as a versatile organic fertiliser that can be used for seed soaking, foliar treatment and root irrigation (Parpieva et al., 2023; Fedoniuk et al., 2025). It is used for growing legumes, flowers, cereals, root crops, vegetables and industrial plants. During the growing season, HA functions as an anti-stress agent, improving the plant's resistance to weeds and pests (Mockeviciene et al., 2022; Mukambaeva et al., 2024). In terms of soil conditions, the application of HA can regulate acidity and salinity, contributing to the restoration of the fertile soil layer. The compliance of the obtained formulation with national regulatory standards and its elevated HA and nutrient content support its applicability under regional soil conditions characterised by mineral heterogeneity and variable fertility.

Many studies emphasise the transition to ecologically oriented fertilisation and plant protection systems. Karunathilake et al. (2023) identify organic farming approaches as a viable strategy for improving product quality, environmental indicators and public health. The experimental and compositional results obtained in the present study support this position, demonstrating the feasibility of producing humic organomineral fertiliser from locally available mineral and organic raw materials with stable nutrient characteristics and compliance with regulatory standards.

In continuation, Abdulraheem et al. (2023) studied the specifics of organic farming,

Table 2. Analysis results of humate fertiliser

Elements	Concentration, %	Error, %	Peak values (cps/mA)	Background values (cps/mA)
Al	3.08	0.047	97	12
Si	16.29	0.071	891	-117
K	26.85	0.05	18,227	-3,287
Ca	34.93	0.06	22,949	-2,796
Cu	0.08	0.0061	50	18
Zn	0.39	0.0073	407	-18
Rb	0.09	0.0024	519	41
Sr	0.32	0.0035	2,056	-29
Y	0.03	0.0022	204	381
Zr	0.07	0.003	544	677
Ti	1.61	0.024	210	-4
V	0.09	0.018	11	54
Mn	0.34	0.0089	148	73
Fe	15.84	0.033	10,219	-540

Note: Concentration – %, error – %, peak values – cps/mA, background values – cps/m.

Table 3. Physicochemical characteristics of the developed fertiliser

Parameter	Result	Standard
Appearance	Homogeneous dark brown suspension	Dark brown to black
Moisture, %	68.5	65–80
Organic matter (dry basis), %	73.9	50–90
HA (dry basis), %	27.5	10
Total N, % (dry basis)	2.2	0.8
P_2O_5, % (dry basis)	2.6	1.0
Available phosphorus, mg/kg	200	200–300
K_2O, % (dry basis)	1.4	0.1

Note: The standard is defined concerning the National Standard of the Kyrgyz Republic GOST R 50335:2022 “Organomineral Fertiliser ‘Biogum’. Technical Specifications” (2022).

highlighting the impact of global climate dynamics on crop production. They analysed potential environmental risks to the adaptive capacity of agroecosystems. Their findings emphasise the importance of integrating environmentally compatible technologies with region-specific resource utilisation, which aligns with the approach adopted in this study.

The results of studies by Tavakol et al. (2021), Chen et al. (2021) emphasised the criterionality of assessing the effectiveness of environmental, socio-economic and managerial measures aimed to intensify the process of greening agricultural production, which significantly increases the competitive position of enterprises participating in the international agricultural market. These considerations are consistent with the experimental results obtained in this study, where the developed fertiliser demonstrated stable elemental composition and compliance with regulatory nutrient thresholds, indicating its potential for practical implementation within sustainable agricultural systems.

Many scientists, for example, Peng et al. (2021), believe that in the future, the predominant role should be given to modern innovative methods of soil fertilisation. The researchers noted the effectiveness of organic humic fertilisers containing humates. The authors recommended using them primarily on low-fertility clay and sandy soils, calcareous and alkaline soils with low iron content. Furthermore, on fertile chernozems, HA will not produce the expected intensification effect, while at the same time they will help maintain a high level of soil fertility. The mineral composition identified in the present study, particularly the presence of glauconite and layered silicates, supports the applicability of such fertilisers to soils with heterogeneous fertility and mineral structure, which are characteristic of many regions of Central Asia.

Among the modern approaches to the study of this topic, Li (2020) highlights the priority property of HA to transform the physical properties of soils. The scientist determined that carbon-humic fertilisers increase the capillary moisture capacity of the soil, improve its structure, and reduce its density. The mineral phase composition identified in the present study, including layered silicate structures and glauconite, supports the potential of the developed fertiliser to contribute to such soil structural modifications.

This idea was partially considered by Ampong et al. (2022). According to the scientists, humic fertilisers are a powerful yield booster, having a qualitative effect on plants in direct and indirect aspects. The direct effect is the direct regulation of plant development throughout the entire growing season. The indirect effect of the HA is to optimise the water and physical properties of soils, intensify the migration of useful organic substances, while simultaneously binding toxic substances, including heavy metals. These functional characteristics correspond to the compositional properties of the fertiliser obtained in this study, which combines humic components with mineral phases capable of enhancing nutrient retention and soil conditioning.

Zhao et al. (2022) consider the potential of humic organic fertilisers to be particularly relevant.

Mahmood et al. (2020) addressed the possibilities of changing soil properties through the integration of organic humic fertilisers. Scientists covered the peculiarities of geographical location and climatic factors. The results of the research by Al-Taey et al. (2019) addressed modern soil monitoring capabilities that will optimise the process of humic fertiliser production. Taken together, these studies reinforce the strategic importance of integrating humic-based formulations with regional resource potential and systematic soil monitoring frameworks. In this context, the present results provide material and compositional evidence supporting the feasibility of integrating locally sourced mineral and humic components into fertiliser production systems adapted to regional soil conditions.

The present study provides experimental and compositional evidence for the feasibility of producing humic organomineral fertiliser from locally available brown coal and glauconite resources in Kyrgyzstan. The developed formulation demonstrated compliance with national standards, stable nutrient composition and elevated HA content, supporting its suitability for agricultural application under region-specific soil conditions. These findings extend existing research on humic fertilisers by demonstrating the feasibility of producing balanced organomineral formulations from regionally available raw materials and by providing experimental evidence of their compositional stability and regulatory compliance.

CONCLUSIONS

The results of the study confirm the high efficiency of using organomineral fertilisers based on natural raw materials from the Kyrgyz Republic. For the first time, a technology for producing humic organomineral fertiliser based on oxidised brown coal from the Kyzyl-Kyi deposit (Abshir site), organic humus processed with the participation of California red worms (*Eisenia foetida*), and natural glauconite from the Kyzyl-Tokoy deposit was developed and successfully tested. A comprehensive chemical, mineralogical and spectral analysis confirmed that the product meets the requirements for modern agrochemicals.

The study determined that the resulting fertiliser contains a full range of macro- and microelements necessary for normal plant growth and development, including K, P, N, Ca, Mg, Fe, Mn and Zn. This composition improves the nutrient environment and supports key physiological processes such as photosynthesis, cell division, protein synthesis, and water and oxygen metabolism. The use of HA contributes to a significant increase in plant biomass and strengthening of the root system by 15–20%. Potassium humate also demonstrates anti-stress, fungicidal and immunomodulatory effects, increasing plant resistance to adverse conditions.

From an environmental perspective, humic fertilisers help restore the fertile soil layer, reducing its acidity and salinity, and contribute to the formation of a sustainable agricultural ecosystem. Due to its versatility, potassium humate can be used for seed treatment, foliar spraying and irrigation, and for growing a wide range of crops: cereals, vegetables, industrial, legumes and fruit and berry plants.

The possibility of scaling the production technology using local resources, which makes the process economically viable and environmentally sound, should be addressed. This is especially relevant in the southern regions of Kyrgyzstan, where there is a decrease in humus content and land degradation. The study is limited to laboratory-scale production and controlled experimental conditions, without long-term multi-site field validation under diverse agroclimatic environments. The potential of HA to restore the protective function of soils and ecological balance within the concept of sustainable agriculture in the Kyrgyz Republic should be a priority for future scientific and practical work in this area.

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