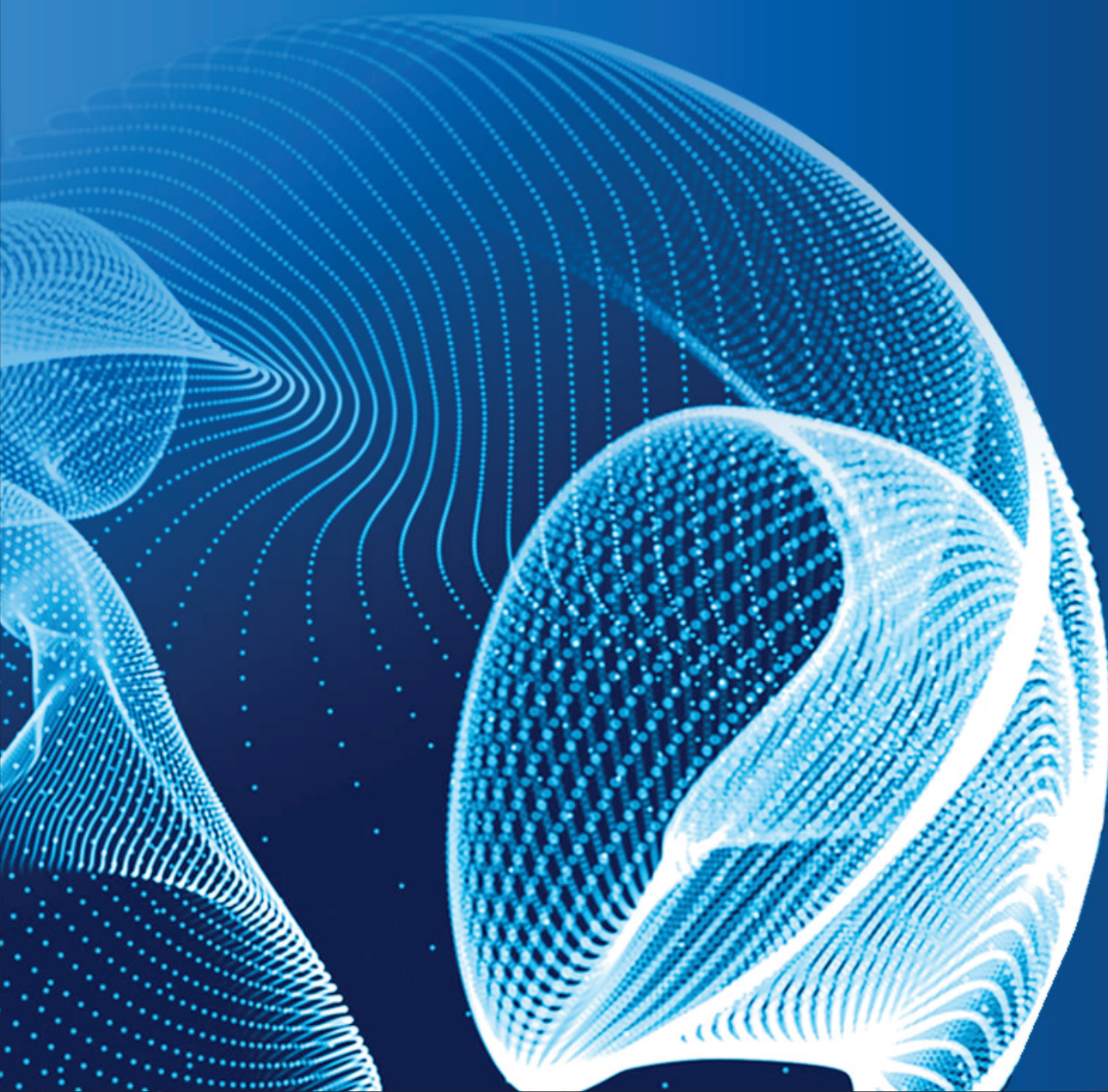


ENGINEERING JOURNAL of Satbayev University

Volume 148 (Issue 4)
August 2026



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Overview of the main pathways for biochar utilization in iron and steelmaking

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Abstract. This paper summarizes the main applications and property requirements of biochar in iron and steel production as a renewable alternative to fossil carbon materials. It discusses its application in cokemaking, iron ore sintering, blast furnace (BF) injection, basic oxygen furnace (BOF), and electric arc furnace (EAF). For each process, the functions of biochar and the requirements for its main properties, reactivity, porosity, density, and mechanical strength are systematized. It is shown that in cokemaking, the biochar share is typically limited to about 10 wt% because it deteriorates coke strength and reactivity. In iron ore sintering, 40-60 wt% of coke breeze can be replaced by biochar, and in BF injection, the substitution level depends on combustion conditions and the need to maintain a stable temperature in the tuyere zone. Biochar has the greatest potential in BOF and EAF, where it can be used as a supplementary energy source, carburizer, and slag foaming agent. The main limitations of industrial biochar application include instability of properties, low density and strength, heterogeneous ash composition, and a tendency to self-heat. It is concluded that specific biochar requirements need to be developed for each metallurgical process.

Keywords: carbon materials, metallurgy, reactivity, biochar, biocoke, iron ore sintering, recarburization, electric furnaces.

Received: 20 May 2026

Received in revised form: 06 August 2026

Accepted: 17 August 2026

Available online: 31 August 2026

1. Introduction

Carbon materials are practically indispensable components of present pyrometallurgy, which perform a complex range of thermophysical, chemical, and structural-mechanical functions. In metallurgical processes, carbon is the primary source of high-potential thermal energy and the main chemical reducing agent [1, 2]. Under the thermodynamic conditions of smelting, it directly reduces metal oxides and generates carbon monoxide, which indirectly reduces them. In addition, high-carbon materials are irreplaceable in related processes as carburizers for carbonizing the melt to a specified chemical composition, as well as electrically conductive elements in electrothermal and electrolytic aggregates.

Carbon plays a uniquely critical role in the blast furnace (BF) process, where metallurgical coke, in addition to its energy and chemical functions, serves as a drainage agent and helps maintain the structure of the charge materials at high temperatures. With its high hot strength, coke withstands the enormous pressure from the overlying layers under counterflow conditions of materials and gases. At the current stage of technological development, it is not physically or technologically viable to fully replace fossil-based coke in this load-bearing role in large-scale BFs. However, this unalterable dependence is precisely what makes the

metallurgical industry one of the key emitters of anthropogenic greenhouse gases, primarily carbon dioxide.

In the face of stringent climate constraints and the impossibility of completely abandoning carbon-based technology, one key practical avenue for decarbonizing the industry is the accelerated transition to renewable carbon materials [3-6]. The use of biochars allows a drastic reduction in the carbon footprint of metal products. Since biochars are of plant origin, the CO₂ emitted during their use is considered carbon-neutral within the context of a short natural cycle. In the medium term, partially replacing fossil carbon with renewable carbon is the main strategic way for the ecological transformation of traditional metallurgy [7-9].

Depending on the technological process for iron and steel production, the possibilities for integrating biochar vary significantly and are determined by the requirements for the mechanical, chemical, and reactive properties of the carbon-bearing material. Figure 1 shows the ways in which biochar can be used in iron and steelmaking. In the integrated BF–basic oxygen furnace (BOF) process, the potential for replacing fossil carbon is limited. The main issue is that metallurgical coke serves not only as a fuel and reducing agent but also as the skeleton of the charge column to provide gas permeability and effective drainage. Consequently, completely replacing coke with biochar in a BF is currently not feasible.

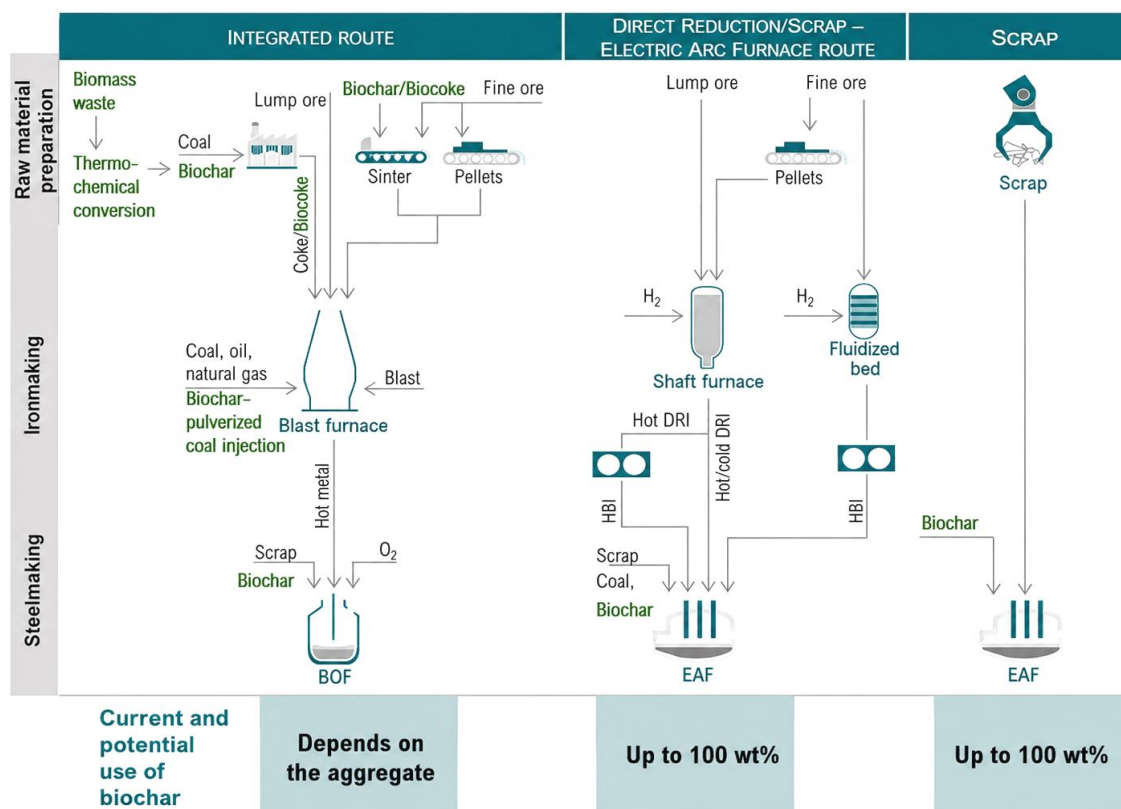


Figure 1. Main pathways for using biochar in iron and steelmaking (adapted from [10])

The most realistic option is to inject pulverized biochar through the tuyeres (pulverized coal injection, PCI), which allows partial replacement of pulverized coal without significantly altering furnace design [11-13]. Additionally, biochar can be used in sintering and pelletizing operations. However, the acceptable extent of its use is determined by the quality requirements for iron ore feedstock and products [14-18].

The greatest potential for biochar integration lies in the route of direct reduced iron (DRI) technologies combined with electric arc furnaces (DRI-EAF), as well as in the production of steel from scrap metal in electric arc furnaces. In direct reduction processes, biochar can be used as a reducing agent and a source of carbon, and in electric arc furnaces as a carburizer, for slag foaming, and as an additional energy source [19-24]. Since these processes do not require preserving the charge structure, the proportion of fossil carbon replaced by biochar can be significantly higher than in BF metallurgy and, in certain operations, could theoretically reach complete replacement.

The effectiveness of carbon materials in metallurgical processes is determined by a combination of their physico-chemical and physico-mechanical properties and microstructure. Biochar properties vary significantly with biomass type, thermo-chemical conversion conditions, and subsequent processing, leading to substantial differences in metallurgical behavior.

Ultimate and proximate analyses provide the primary characterization of carbon materials. Ultimate analysis determines the content of the main chemical elements as carbon, hydrogen, oxygen, nitrogen, and sulfur, which influence the formation of gaseous products, the material's calorific value, and the potential for introducing undesirable impurities into the metal and slag. Proximate analysis includes determining the moisture, volatile matter, and ash, which are the primary indicators of a carbon material's suitability for metallurgical applications.

Ash yield and its chemical composition are particularly important. The mineral phase determines how the carbon material interacts with the slag and metal phases, influences the reactivity and dissolution of carbon, and may either promote the formation of a mineral layer on the particle surface or, conversely, catalyze reactions [25-27]. Therefore, when assessing the potential for biochar use, it is necessary to consider not only the ash amount but also the ratio of acidic to basic oxides, and the presence of catalytically active components, such as potassium, sodium, calcium, and iron compounds.

The structural characteristics of carbon materials play an important role. The type of chemical bonds, the degree of aromatization of the carbon matrix, the microstructure, particle morphology, pore sizes, and the development of the internal surface determine the availability of active sites for heterogeneous reactions. These parameters directly influence the material's reactivity, the rate of iron oxide reduction, the dissolution of carbon in the melt, and other metallurgical processes.

Thermochemical properties, including the kinetics of thermal decomposition, gasification, and oxidation, are also key criteria for evaluating carbon materials. They determine the material's behavior at high temperatures and its ability to effectively function as a fuel, reducing agent, or carburizer in various metallurgical processes.

It should be noted that the individual properties of a carbon material cannot be considered in isolation. Reactivity and mechanical strength are integral characteristics that are shaped by the combined influence of fixed carbon, ash amount and chemistry, degree of graphitization, porous structure, particle morphology, and the material's thermo-chemical behavior. Figure 2 presents a scheme of the main parameters and properties of carbon materials and their inter-relatedness.

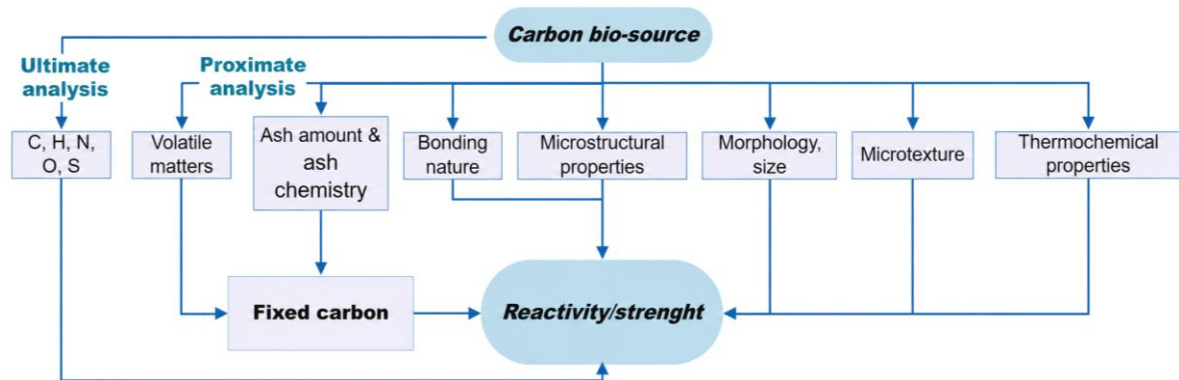


Figure 2. Scheme of the key parameters and properties of carbon materials for iron and steelmaking

2. Biochar utilization in cokemaking

One of the most widely researched areas of biomass and biochar application in the integrated BF-BOF process is its use in cokemaking to produce biocoke. In this approach, biomass or pre-produced biochar is added to the coal charge as a partial substitute for coking coals [28-32]. After co-coking, a composite coke is formed that contains both fossil and renewable carbon. In most studies, the biomass or biochar content in the coal charge is up to 10 wt%. This range allows the biocoke to retain acceptable technological properties. The tolerable degree of substitution is determined by the type of biomass, the temperature of its thermochemical treatment, the volatile matter, the ash value, the chemical composition of the ash, and the material's ability to interact with the plastic phase of the coal during the coking process.

Using biochar in coal blends offers several potential advantages. Biochar typically has a low ash amount and very low sulfur and phosphorus levels compared to coal. As a result, the concentration of undesirable elements in biocoke is reduced. The mineral composition of biochar ash also differs from that of coal ash and can alter the processes involved in the formation of the mineral phase of biocoke, affecting its structure and performance characteristics.

At the same time, increasing the proportion of biochar is accompanied by several technological limitations. Table 1 compares the characteristics of conventional coke and biocoke.

Table 1. Comparison of the general requirements of conventional coke and biocoke

Parameters	Coke	Biocoke
	Values	
Proximate analysis, wt%		
Moisture, ad	<5.0 (wet quenching) <0.7 (dry quenching)	
Volatile matters (VM ^{db}), db	≤1.0	
Ash, db	≤11.0	5.8-10.8
Sulfur (S _i ^{db}), db	<1.0	0.2-1.0
Fixed carbon (fC ^{db}), db	app. 86.0-88.0	app. 87-92
Ultimate analysis, wt%		
Carbon, db	app. 85.0–87.0	app. 84.5–92
Hydrogen, db	app. 0.18–0.4	>0.2
Nitrogen, db	app. 1.0–1.9	~1.0
Oxygen, db	app. 0.2–0.9	~2.0
Other parameters		
Specific surface area (SSA), m ² /g	app. 2.0	app. 2.0-6.0
Coke reactivity index (CRI), %	<25	>25
Coke strength after reaction with CO ₂ (CSR) %	>65	<65

In Table 1, ad denotes the as-determined basis, while db denotes the dry basis. The high volatile content and the unique structure of biochar can lead to a lower yield of solid product during coking. Additionally, biocoke is usually characterized by higher reactivity toward carbon dioxide (coke reactivity index, CRI) and lower coke strength after reaction (CSR). These changes are due to increased porosity, a larger specific surface area, and a less ordered structure of the carbon matrix compared to traditional metallurgical coke.

3. Biochar utilization in iron ore sintering

The sintering process of iron ore is one of the most energy-intensive stages of integrated BF production and produces the sinter for BF. Coke breeze is traditionally used as fuel, providing the necessary heat release as the combustion front moves through the sintering charge layer. In recent years, significant attention has been paid to the possibility of partially replacing coke breeze with biomass, biochar and biocoke in order to reduce fossil carbon consumption and lower greenhouse gas emissions [15, 33-37].

During the sintering process, biochar acts as a fuel, providing the thermal energy necessary for the formation of the liquid phase and the subsequent sintering of iron ore particles. In contrast to coke, biochar cannot support mechanical loads, therefore, the strength requirements for it are significantly lower. However, its effectiveness is determined by a set of physico-chemical characteristics, including fixed carbon, volatile matter, moisture, ash, particle size, bulk density, and calorific value.

To have a stable sintering process, the carbon materials must meet several technological requirements. Moisture should generally not exceed 15 wt%, as high moisture content impairs the granulation of the charge and increases the thermal energy required for water evaporation. It is recommended to keep volatile matter below 3 wt% to maintain a stable combustion front without excessively rapid release of gaseous products. The ash value of the fuel should be less than 12 wt%, since an increase in the amount of mineral impurities leads to an increase in the volume of the slag phase, a change in the mineralogical composition of the sinter, and a decrease in the iron content of the product. Fixed carbon should be in the range of 80-85 wt% to provide the necessary calorific value and combustion duration. Additional requirements include a minimum sulfur content, a particle density of more than 700 kg/m³, a particle size of 0.3-3.0 mm (with a possible increase to 10 mm), and a higher heating value of 25-30 MJ/kg. The main properties of fuel for iron ore sintering are presented in Table 2.

Table 2. Requirements for the properties of fuel for iron ore sintering

Parameters	Value
Moisture, wt%	<15.0
Volatile matters (VM ^{db}), wt%	<3.0
Ash (A ^{db}), wt%	<12.0
Fixed Carbon (fC ^{db}), wt%	80.0-85.0
Sulphur (S _t ^{db}), wt%	<2.0
Particle density, kg/m ³	>700
Size, mm	0.3-3.0 or 10.0

One of the main advantages of biochar is the ability to partially replace coke breeze without modifying the existing sintering technology. According to published studies, the degree of substitution can reach 40-60 wt%. However, the optimal range is determined by the properties of the specific biochar and the quality requirements for the sintered product [14, 38-41]. Experimental data also show that as the degree of substitution of coke breeze with biochars increases, the sinter yield gradually decreases [15, 37, 42]. Despite these limitations, biochar use offers significant environmental benefits. Because it contains almost no fossil carbon, the overall carbon footprint of the sintering process is reduced. In addition, the low sulfur content in most biochar types reduces SO₂ emissions, and the absence of significant bound nitrogen helps reduce NO_x formation. Biochar's high reactivity also allows more complete fuel combustion and reduces unburned carbon emissions.

4. Biochar utilization for injection into a blast furnace

Pulverized Coal Injection (PCI) technology is one of the most effective ways to reduce metallurgical coke consumption in the BF process. In modern BFs, the consumption of injected fuel typically ranges from 150 to 250 kg/t of pig iron, and in the most advanced facilities, it can reach 250 to 300 kg/t of pig iron, which significantly reduces the consumption of expensive coke and lowers production costs [43-46]. In recent years, biochar has been viewed as a promising alternative to fossil pulverized coal fuel due to its renewable origin and virtually neutral carbon balance.

When injected through the BFs' tuyeres, biochar serves two main functions, namely, it acts as an additional source of thermal energy and participates in reduction processes. In the combustion zone, biochar rapidly heats to 1800-2200°C, releasing volatile compounds. The residual carbon then reacts with blast oxygen and carbon dioxide to form CO. The resulting carbon monoxide is the primary reducing agent involved in the reduction of iron oxides in the BF shaft. In contrast to coke, biochar is characterized by significantly higher porosity, a large specific surface area, and greater reactivity, which contributes to its rapid ignition and nearly complete combustion within the confined space of the tuyere zone.

To apply biochar in PCI technology, it should meet several technical requirements. The moisture content before drying must not exceed 15 wt%, and after drying, 2 wt%, since excess moisture increases the energy required for water evaporation and impairs the stability of powder transport in the pneumatic injection system. It is recommended to maintain volatile matter at 20-25 wt% to achieve rapid fuel ignition and preserve sufficient solid carbon for subsequent reduction reactions. Fixed carbon must exceed 75 wt%, and ash should be limited to less than 10 wt% to minimize the introduction of mineral impurities into the BF and prevent deterioration of slag properties. Table 3 lists the main requirements for pulverized coal fuel for injection into a BF.

Table 3. Key requirements for PCI for BF

Parameters	Value
Moisture before drying, wt%	<15.0
Moisture after drying, wt%	<2.0
Volatile matters (VM ^{db}), wt%	<20.0-25.0
Ash (A ^{db}), wt%	<10.0
Fixed Carbon (fC ^{db}), wt%	>75.0
Sulphur (S _t ^{db}), wt%	<0.45-0.5
Phosphorus (P), wt%	<0.05
Alkalis, wt%	<0.3
Ash fusion temperature, °C	1250-1450

Particular attention is paid to harmful impurities. The sulfur concentration must be less than 0.50 wt%, the phosphorus content less than 0.05 wt%, and the total content of alkali elements must be less than 0.3 wt%, since their accumulation in the BF leads to intensified internal circulation of alkalis, accelerated deterioration of refractories, and deterioration of the process's gas dynamics. The melting point of the fuel ash should be in the range of 1250-1450°C, which prevents the formation of molten deposits in the tuyere zone and ensures stable BF operation.

Several factors determine the maximum possible rate of substitution of traditional pulverized coal fuel with biochar. One of the most important factors is the material's grindability. Because of its lower hardness, biochar typically requires less energy to grind than bituminous coal. However, its high porosity leads to the formation of more ultrafine particles, which can complicate powder transportation and alter its combustion characteristics.

Another important characteristic of biochar is its higher oxygen content compared to some bituminous coals. The increased oxygen concentration reduces the fuel's calorific value and lowers the combustion temperature. In the BF process, this effect is compensated for by increasing the oxygen content of the blast air, thereby maintaining a practically constant adiabatic combustion temperature in the tuyere zone (Raceway Adiabatic Flame Temperature, RAFT). Maintaining RAFT is a prerequisite for stable furnace operation and maintaining productivity as the proportion of biochar increases. As the rate of fossil coal substitution with biochar increases, it is necessary to optimize the blast parameters, oxygen flow rate, and fuel injection regime.

5. Biochar utilization in the basic oxygen furnace process

Basic oxygen steelmaking remains the dominant steelmaking process and forms part of the BF-BOF route, which accounts for approximately 70% of global crude steel production [9, 47]. During BOF refining, oxygen is blown onto and/or into a bath of hot metal containing steel scrap and fluxes, promoting the oxidation of carbon, silicon, manganese, phosphorus, and other elements. These exothermic reactions provide the heat required to refine and melt the added scrap. Despite the autothermal nature of the process, additional energy sources are often used to maintain the required heat balance to allow a higher proportion of scrap metal in charge and reduce liquid pig iron consumption.

One promising renewable source of additional energy is biochar. In an oxygen converter, it serves as both a fuel and a carbon-containing material, the oxidation of which is accompanied by the release of a significant amount of thermal energy. The requirements for its mechanical strength can be significantly lower, while its chemical composition, ignition rate, and oxidation kinetics become the key factors.

When biochar is introduced into the melt, its particles rapidly heat to 1600-1700°C, after which intense oxidation of carbon by oxygen begins, primarily forming carbon monoxide. The following exothermic reactions take place, according to Equations 1 and 2:



These reactions provide an additional heat input to the converter, contributing to maintaining the required temperature of the molten steel without increasing the consumption of molten pig iron. The high porosity of biochar and its large internal surface area ensure rapid ignition and a high rate of oxidation compared to traditional fossil carbon materials.

The additional thermal energy compensates for the loss of physical heat that occurs when the scrap metal content in the charge is increased [48-51]. Increasing the scrap content is one of the most effective ways to reduce total CO₂ emissions, as steel production from recycled metal results in a significantly smaller carbon footprint compared to the use of molten pig iron.

The use of biochar reduces the consumption of traditional chemical energy sources used to regulate the converter's heat balance, such as ferrosilicon, aluminum, coke breeze, or anthracite. Thus, a portion of fossil carbon can be replaced with a renewable alternative without significantly altering existing steel production technology.

For effective use in a BOF, biochar moisture should not exceed 2 wt%, as its evaporation leads to additional heat losses and impairs the stability of the material feed. It is recommended to limit volatile matter to 3-6 wt% to have a sufficient ignition rate with minimal release of gaseous products. Ash should be less than 10 wt% to prevent excessive influx of mineral components into the slag and avoid increased flux consumption. Fixed carbon should typically be around 75-90 wt% to possess a high calorific value and efficient use of the material as a source of chemical energy. Table 4 lists the main requirements for fuel used in the BOF process.

Table 4. The main requirements for fuel in BOF

Parameters	Value
Moisture, wt%	<2.0
Volatile matters (VM ^{db}), wt%	<3.0-6.0
Ash (A ^{db}), wt%	<10.0
Fixed Carbon (fC ^{db}), wt%	75.0-90.0
Sulphur (S ^{db}), wt%	<0.6
Phosphorus (P), wt%	low
Alkalis, wt%	low
Density, kg/m ³	>500

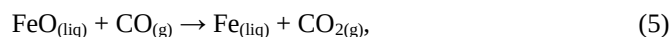
Special attention is paid to the concentration of harmful impurities. The sulfur value should be less than 0.6 wt%, and the content of phosphorus and alkali elements should be kept to a minimum, as their presence degrades steel quality, increases the load on refining processes, and may negatively affect the durability of the refractory lining. It can be advised to maintain biochar density above 500 kg/m³ to reduce dust generation.

6. Biochar utilization in electric arc furnaces

The EAF is the primary unit for producing steel from scrap metal and direct reduced iron (DRI/HBI). Compared to the integrated BF route, the main energy source in the EAF is electricity. However, carbon-based materials remain a critical

component of the process [14, 28, 52-54]. They reduce iron oxides, recarburize molten steel, and provide additional chemical energy through exothermic carbon oxidation reactions. Because carbon materials do not require high mechanical strength, biochar is considered one of the most promising renewable substitutes for fossil carbon, particularly in electric arc metallurgy.

In modern EAFs, carbon can be introduced either as part of the metal charge or by injecting powdered material. Biochar can perform both functions, making it possible to partially or nearly completely replace traditional carbon materials in certain process operations. One of the most important functions of carbon in an EAF is slag foaming [19, 21, 55-57]. During melting, the slag contains some amount of iron oxide (FeO), which reacts with carbon and can also react with CO, according to Equations 3 and 5. Additionally, some reactions can occur with carbon according to Equations 4 and 6.



The generated carbon monoxide causes slag foaming. The foamy slag covers the electric arcs, reducing heat loss through radiation, protecting the furnace lining, and ensuring more uniform heat distribution throughout the melt. As a result, specific electricity consumption decreases, the electrical energy utilization factor improves, and the service life of the refractories is extended.

On average, 10-20 kg of carbon per metric ton of steel is required for effective slag foaming, although actual consumption depends on slag composition, FeO content, oxygen blowing regime, and the technology used at a specific metallurgical plant. Because of biochar's high reactivity, CO formation occurs more rapidly than when using traditional coke breeze, which promotes more intense slag foaming. However, excessively high reactivity can lead to foam instability, so biochar properties should be adapted to the process conditions.

Another important function of biochar is related to the reduction of iron oxides present in the slag. During oxygen blowing, some of the iron inevitably ends up in the slag as FeO. The reduction reaction allows the iron to return to the metal bath, increasing the yield of usable metal and reducing iron losses in the slag. The efficiency of this process is determined by the reactivity of the carbon, its surface area, and the rate of CO reduction gas formation.

Biochar is also widely considered as a material for the recarburization of molten steel or steel alloying [20, 24, 58]. After the period of intensive oxidation ends, the carbon content in the metal is usually lower than required, so additional recarburization of the melt can be carried out to achieve the required chemical composition of the steel. In this case, carbon should also dissolve effectively in the molten metal. Typically, carbon-bearing material consumption during the recarburization stage is 2-5 kg per metric ton of steel. However, specific values depend on the steel grade and the final carbon content.

Overall, total consumption of carbon-containing materials in an EAF is approximately 12-25 kg per metric ton of steel produced, including materials for slag foaming and recarburization. When transitioning to DRI-EAF technology, carbon demand may increase due to the higher iron oxide content in the metalized source.

To use biochar effectively in an EAF, it should meet the basic requirements listed in Table 5. It is recommended to keep moisture below 2 wt%. Volatile matter is typically limited to 2-7 wt%. Fixed carbon should exceed 80-85 wt%, while ash should be limited to less than 10 wt% to avoid excessive slag volume and changes in physico-chemical properties. Sulfur and phosphorus concentrations should be kept to a minimum, as these elements can transfer into the metal and degrade steel quality. The optimal particle size is approximately 0.5-5 mm.

Table 5. Basic requirements for carbon materials for use in EAFs

Parameters	Value
Moisture, wt%	1.0-7.0
Volatile matters (VM ^{db}), wt%	2.0-7.0
Ash (A ^{db}), wt%	<10.0
Fixed Carbon (fC ^{db}), wt%	>85.0
Sulphur (S _t ^{db}), wt%	low
Phosphorus (P), wt%	low
Size, mm	0.5-5.0

The effectiveness of biochar in EAF conditions depends on a combination of its physico-chemical properties. The most significant factors are fixed carbon, reactivity, particle size distribution, porosity, degree of microstructural development, volatile matter, and ash chemistry. High porosity increases reaction surface area and accelerates FeO reduction. However, it can also reduce particle mechanical strength and alter the rate of carbon dissolution in the metal. The mineral components of the ash can catalyze gasification reactions and alter the slag's composition and viscosity, thereby affecting the stability of the foam layer.

An important advantage of biochar is its high reactivity compared to coke breeze, petroleum coke, and anthracite [52, 59, 60]. Because biochar has a more developed porous structure and more active sites, it participates in reduction and gasification reactions more quickly, improving slag foaming efficiency and reducing melting time. At the same time, excessive reactivity can accelerate carbon consumption and reduce process stability. Therefore, different biochar characteristics may be required for various operations (e.g., slag foaming, recarburization).

7. Outlook

Despite biochar's significant potential as a renewable carbon source for metallurgical processes, its widespread industrial adoption faces several scientific, technical, and technological challenges. Unlike traditional fossil carbon materials, whose properties are relatively stable and standardized, biochar characteristics depend heavily on biomass origin, growing conditions, pretreatment technology, and pyrolysis and post-furnace treatment parameters. This variability makes it difficult to predict the material's behavior under high-temperature metallurgical conditions and requires new approaches to classification and standardization.

One of the main challenges is the variability of biochar's physico-chemical properties. Even with a single biomass type, fixed carbon can vary widely (60 to over 90 wt%), ash from less than 1 to over 10 wt%, and volatile matter from 5 to 30 wt%, depending on pyrolysis temperature. Similarly, the specific surface area, porosity, density, degree of order, and chemical composition of the ash vary significantly. This heterogeneity complicates the direct replacement of fossil carbon materials and requires selecting biochar for each metallurgical process.

Special attention is given to the relatively low mechanical strength and density of biochars. Depending on the feedstock, biochar density typically ranges from 200 to 600 kg/m³, which is significantly lower than that of metallurgical coke (700-900 kg/m³). Increased brittleness contributes to fine-particle formation during transportation and storage, impairs dosing conditions, and limits the use of biochar in processes where the material is subjected to significant mechanical stress. Therefore, densifying biochar is essential for improving its application efficiency.

High oxygen and hydrogen content also significantly affects the metallurgical behavior of biochar. Although oxygen-containing functional groups increase the material's reactivity, they also reduce its calorific value and increase the rate of gasification. Furthermore, an increase in the content of volatile matter can lead to changes in the fuel's combustion characteristics and a redistribution of heat fluxes in metallurgical units.

In some cases, the chemical composition of the ash poses an additional limitation. Various types of biomass may contain elevated concentrations of alkali metals (K, Na), calcium, magnesium, silicon, and phosphorus. These elements have a significant impact on reactivity, slag formation, high-temperature corrosion of equipment, and the quality of metal products. Controlling the content of phosphorus and alkali elements is particularly important, as their accumulation can negatively affect the technological characteristics of the metallurgical process.

At the same time, the high variability of biochar's properties opens up significant opportunities for its targeted adaptation to specific metallurgical processes. Unlike fossil carbon materials, biochar properties can be controlled as early as the production stage by selecting the feedstock and adjusting the pyrolysis temperature and duration, heating rate, process atmosphere, and post-treatment methods. This approach allows the production of materials with predetermined characteristics optimized for specific technological tasks.

One of the most promising areas of research is developing function-oriented requirements for biochar. It is advisable to determine specific quality criteria for each metallurgical process. An equally important area of research involves studying the mechanical strength of biochar, as well as its behavior during transportation and long-term storage. For industrial applications, it is necessary to determine the mechanisms of particle fracture, the material's susceptibility to abrasion and dust formation, the effect of ambient humidity on property changes, and the possibility of compacting the material through briquetting or granulation. Increasing biochar density can significantly improve conditions for transportation, storage, dosing, and use in metallurgical production.

Special attention should be paid to industrial safety issues. Due to their high specific surface area and increased reactivity, some types of biochar may be prone to self-heating and spontaneous combustion, especially after drying or when stored in the presence of oxygen [61-63]. This effect is caused by intense oxidation of active surface sites and may pose a hazard during transportation and storage. Therefore, for each type of biochar, it is necessary to determine the oxidation onset temperature, the kinetics of self-heating, and the conditions for safe storage.

Meanwhile, variability in biochar properties can be a significant advantage. Depending on the biomass type and processing technology used, it is possible to produce materials

with low ash, minimal sulfur and nitrogen content, high fixed carbon content, and optimal reactivity. This opens opportunities to create specialized biochar for various ferrous metallurgy processes, allowing not only reduced fossil carbon consumption but also improved production performance metrics.

7. Conclusions

The study shows that biochar is one of the most promising renewable carbon materials for defossilizing the ferrous metallurgy industry. Because it can be produced from various types of biomasses, is highly reactive, and has a practically neutral biogenic carbon cycle, biochar can partially or completely replace traditional fossil carbon materials in metallurgical processes. However, its effectiveness depends significantly on the specific technology's requirements and the material's complex physico-chemical properties.

In the cokemaking process, biochar can be used as a component of the coal blend to produce biocoke. However, most studies show that the acceptable biochar content is typically up to 10 wt%, since a further increase in its proportion leads to a decrease in the plasticity of the coal mixture, a reduction in the degree of development of the anisotropic coke structure, an increase in CRI, and a decrease in CSR. At the same time, the use of biochar makes it possible to reduce the sulfur and phosphorus content in biocoke and to lower its ash.

The iron ore sintering process offers more favorable conditions for using biochar as a fuel in place of coke breeze. According to established practices, the optimal substitution rate is typically 40-60 wt%, which keeps the yield of usable sinter above 80% while reducing fossil carbon consumption. An additional benefit is reduced CO₂, SO₂, and NO_x emissions due to the low sulfur and nitrogen content in the biomass.

PCI technology also represents a promising way for integrating biochar into BF production. In this technology, biochar serves as both a fuel and a reducing agent, and the absence of requirements for high mechanical strength makes it possible to partially replace traditional pulverized coal. However, the maximum permissible substitution rate is determined by oxygen and volatile matter content, particle size distribution, grindability, and the need to maintain the adiabatic combustion temperature in the BF zone to provide process stability.

Biochar shows significantly greater potential for use in the BOF process, where it can effectively serve as an additional source of chemical energy, thereby reducing the consumption of traditional energy sources, offsetting the decline in the heat balance caused by an increase in the proportion of scrap metal, and thus improving the resource efficiency of steel production.

Promising areas for the industrial application of biochar include EAF. It can be used for slag foaming, reducing iron oxides, recarburizing molten steel, and as an additional source of chemical energy. Depending on the process operation and material characteristics, it is possible to partially or nearly completely replace traditional carbon materials with renewable carbon.

Author contributions

Conceptualization: LK, AK; Data curation: LK, AK; Formal analysis: LK, AK; Funding acquisition: AK; Investigation: LK, AK; Methodology: LK, AK; Project administration: AK; Resources: LK, AK; Supervision: LK, AK; Validation: LK, AK; Visualization: LK; Writing – original draft: LK, AK; Writing – review & editing: LK, AK. All authors have read and agreed to the published version of the manuscript.

Funding

The contribution of A. Koveria was funded by the Ministry of Education and Science of Ukraine within the Ukrainian-Austrian Joint Programme of Scientific and Technological Cooperation (Project No. 0125U003439, “Production and Quality Characterization of Biofuels and Bioreducing Agents for the Metallurgical Industry”).

Acknowledgements

A. Koveria gratefully acknowledges the support provided within the framework of the Ukrainian-Austrian Joint Programme of Scientific and Technological Cooperation. The authors sincerely thank the reviewers for their valuable comments, suggestions, and thorough evaluation of the manuscript, all of which significantly improved its quality.

Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Шойын және болат өндірісінде биокөмірді пайдаланудың негізгі бағыттарына шолу

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Андатпа. Осы мақалада биокөмірді шойын және болат өндірісінде қолданудың негізгі бағыттары, сондай-ақ оның қазба негізіндегі көміртекті материалдарға жаңартылатын балама ретіндегі қасиеттеріне қойылатын талаптар жинақталған. Биокөмірді кокстеу, темір кенін агломерациялау, домна пешіне (ДП) үрлеу, оттекті-конвертерлік балқыту (ОКБ) және доғалы болат балқыту пешіндегі (ДБП) электрболат балқыту өндірісі процестерінде пайдалану қарастырылған. Әрбір процесс үшін биокөмірдің атқаратын функциялары және оның негізгі сипаттамаларына, соның ішінде реакциялық қабілеттілігіне, кеуектілігіне, тығыздығына және механикалық беріктігіне қойылатын талаптар жүйеленген. Кокстеу кезінде биокөмірдің үлесі, әдетте, шамамен 10 масс.% деңгейімен шектелетіні көрсетілген, өйткені оны қосу кокстың беріктігі мен реакциялық қабілеттілігіне кері әсер етеді. Темір кенін агломерациялау кезінде кокстық ұсақтығының 40–60 масс.%-ын биокөмірмен алмастыруға болады, ал домна пешіне үрлеу кезінде алмастыру дәрежесі

жану жағдайларына және фурмалық аймақта тұрақты температураны сақтау қажеттілігіне байланысты болады. Биокөмірді оттекті конвертерлер мен доғалы болат балкыту пештерінде пайдалану ең жоғары әлеуетке ие, мұнда ол қосымша энергия көзі, көміртектендіргіш және қожды көбіктендіруге арналған материал қызметін атқара алады. Биокөмірді өнеркәсіптік деңгейде қолданудың негізгі шектеулеріне оның қасиеттерінің тұрақсыздығы, төмен тығыздығы мен беріктігі, күл құрамының біркелкі болмауы және өздігінен қызуға бейімділігі жатады. Әрбір металлургиялық процесс үшін биокөмірге қойылатын арнайы талаптарды әзірлеу қажеттілігі туралы қорытынды жасалған.

Негізгі сөздер: көміртекті материалдар, металлургия, реакциялық қабілеттілік, биокөмір, биококс, темір кенін агломерациялау, көміртектендіру, электр пештері.

Обзор основных направлений использования биоугля в производстве чугуна и стали

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Аннотация. В данной статье обобщены основные направления применения биоугля в производстве чугуна и стали, а также требования к его свойствам как возобновляемой альтернативы ископаемым углеродсодержащим материалам. Рассмотрено использование биоугля в процессах коксования, агломерации железной руды, вдувания в доменную печь (ДП), кислородно-конвертерной плавки (ККП) и электросталеплавленного производства в дуговой сталеплавильной печи (ДСП). Для каждого процесса систематизированы функции биоугля и требования к его основным характеристикам, включая реакционную способность, пористость, плотность и механическую прочность. Показано, что при коксовании доля биоугля, как правило, ограничивается приблизительно 10 мас%, поскольку его добавление отрицательно влияет на прочность и реакционную способность кокса. При агломерации железной руды биоуглём можно заменить 40-60 мас% коксовой мелочи, тогда как при вдувании в ДП степень замещения зависит от условий горения и необходимости поддержания стабильной температуры в фурменной зоне. Наибольшим потенциалом биоуголь обладает при использовании в кислородных конвертерах и ДСП, где он может выполнять функции дополнительного источника энергии, науглероживателя и материала для вспенивания шлака. К основным ограничениям промышленного применения биоугля относятся нестабильность его свойств, низкие плотность и прочность, неоднородный состав золы и склонность к самонагреванию. Сделан вывод о необходимости разработки специальных требований к биоуглю для каждого металлургического процесса.

Ключевые слова: углеродистые материалы, металлургия, реакционная способность, биоуголь, биококс, спекание железной руды, науглероживание, электропечи.

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<https://doi.org/10.51301/ejsu.2026.i4.02>

Distribution of Cu, Pb, Zn and As between the products of the reduction melting of slag from the Vanyukov furnace in the conditions of the Balkhash copper smelter

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Abstract. The results on the distribution of Cu, Pb, Zn and As between the products of the reduction melting of slag from the Vanyukov Furnace (VF) in the conditions of the Balkhash Copper Smelter (BCS) are presented. Optimal technological parameters of the process of two-stage reducing depletion of slags by natural gas in the presence of coal at a temperature of 1300°C. have been established. It is shown that under conditions of two-stage reductive depletion of VF slags, the residual metal content in the reduced slag is: copper – 0.35%; lead – 0.08%; zinc – 0.18%; traces of arsenic. High recovery of metals into target products has been achieved: copper in matte – up to 98%; gold, silver in matte – 96%; arsenic in dust at the first stage of slag treatment with natural gas – up to 99% and lead, zinc in dust at the second stage – up to 98%. The results obtained were used in the development of an innovative technological platform for a comprehensive waste-free technology for processing current and accumulated BCS slags to produce marketable products.

Keywords: VF slag, recovery, coal, natural gas, extraction, valuable metals, gas and coal consumption.

Received: 08 February 2026

Received in revised form: 05 August 2026

Accepted: 17 August 2026

Available online: 31 August 2026

1. Introduction

In modern metallurgy, where autogenous melting processes are actively used [1-6], the issue of processing emerging slag waste is acute. According to the information given in [7], approximately 2.2 tons of slag are formed during the production of each ton of metal. The disposal or reuse of these significant volumes of slag creates a number of environmental and spatial difficulties. The urgency of recycling these wastes is determined not only by economic, but also by environmental factors. The accumulation of slag heaps occupies significant territories, posing a threat to the environment, including pollution of soils, water resources and atmospheric air.

Environmental issues related to the storage and disposal of slags are coming to the fore. The leaching of toxic elements from slag masses into groundwater, dusting of landfills, as well as the release of greenhouse gases under certain storage conditions are just some of the negative consequences. Due to stricter environmental regulations and increased public attention to issues of sustainable development, the search for effective methods of slag processing is becoming a priority.

In the context of the cyclical economy and the desire for waste-free production, the processing of metallurgical slags

opens up new opportunities for the extraction of valuable components and their reuse. Slags contain a wide range of valuable various elements that can be returned to the production cycle or used in other industries [8, 9, 10].

Today, there are various technologies for processing autogenous smelting slags, ranging from simple crushing methods and use in road construction to more complex processes involving the extraction of valuable components such as non-ferrous and rare metals [11, 12]. The choice of a specific technology depends on the chemical composition of the slag, its physical properties, and economic feasibility. However, despite the variety of solutions offered, the problem of efficient and cost-effective slag processing remains relevant, requiring further research and development.

Industrial slags formed as a result of melting a complex copper-containing charge in a furnace, as well as stored slags, are a significant source of secondary raw materials. Reducing enrichment is a promising method of slag processing aimed at extracting valuable components such as non-ferrous and precious metals, mineral phases, and preparing them for further use.

The research carried out in the work is aimed at the development and optimization of reduction depletion technologies for various types of industrial slags. The developed technology of two-stage reduction processing of slags will

increase the efficiency of extraction of valuable components and reduce energy consumption, and is an important area of resource conservation and sustainable production development. The introduction of technology for processing VF slags in the conditions of the Balkhash Copper Smelter (BCS) will not only reduce the negative impact on the environment, but also ensure the economically beneficial use of secondary resources.

Currently, six large Vanyukov furnaces are successfully operating in Russia and Kazakhstan, processing over 2.5 million tons per year of copper, copper-nickel sulfide ores and concentrates, with an annual capacity of about 500 thousand tons of copper. Technological and design solutions were developed and tested at Vanyukov's experimental furnaces located in Norilsk, the Urals (SUCS) and Balkhash (the Kazakhmys Corporation Copper Smelter).

The versatility of purge mode control allows the Vanyukov furnace to be used for processing both copper-rich and zinc-containing slags formed during lead production. The technology remains applicable to different types of slags, requiring only minor adjustments.

The Vanyukov process, based on emulsion pyrometallurgy, has a number of advantages: simple and economical preparation of raw materials, eliminating drying, grinding and mixing; high productivity, reaching 4 tons of charge per hour per 1 m² of furnace cross-section, due to mixing of matte with oxygen-air blast (O₂ content from 40 to 96%, consumption up to 1000 m³/(m²·h)); intensification of heat and mass transfer, ensuring thermodynamic phase equilibrium and reliable forecast of raw material processing indicators; the possibility of creating multi-chamber devices for solving complex tasks.

The process is effective for the two-stage processing of slags formed in the production of copper and lead, to produce matte, lead-zinc sublimates and demetallized slag. The resulting slags, which are difficult to process using other processing methods, comply with the requirements of the Romelt process, developed at the Moscow Institute of Steel and Alloys and similar to the Vanyukov process.

The Romelt process can be used for processing iron silicate slags obtained after two-stage processing of copper-produced slags. This will make it possible to combine the extraction of copper, lead and zinc in the Vanyukov furnace with the production of an iron-carbon alloy from depleted slag and ensure waste-free technology.

The choice of the Vanyukov process for complex slag processing is due to:

- its suitability for processing iron-containing materials with a low content of iron oxides containing copper and volatile metals;
- using coal and natural gas as a fuel and reducing agent;
- the possibility of integrating the Vanyukov furnace with copper and lead smelting furnaces, as well as with the Romelt furnace.

The integrated resource-saving technology proposed in the study is focused on the organization and expansion of production for processing the generated and stored industrial slags of the BCS.

The key goal is the complex extraction of valuable metals into target products and the expansion of the range of marketable products.

To achieve this goal, in this work, the patterns of distribution of Cu, Pb, Zn, and As between the products of VF slag smelting under deeply reducing conditions, in relation to the conditions of the BCS, are investigated.

The study of the distribution patterns of elements such as Cu, Pb, Zn, and As in the products of VF slag smelting is important for optimizing the technological process. Understanding how these elements behave under deeply reducing conditions allows us to develop effective methods for their extraction and separation, as well as minimize the loss of valuable components.

The results of the research conducted in relation to the conditions of the BCS will make it possible to adapt the Vanyukov process to the specific characteristics of the processed slags and achieve maximum efficiency in extracting valuable metals. The introduction of integrated resource-saving technology will allow BCS not only to solve environmental problems related to slag storage, but also to make additional profits through the production of new types of products.

2. Materials and methods

The experiments were carried out with VF slag from the Balkhash Copper Smelter (BCS) of the composition, % by weight: 2.1 Cu; 1.02 Pb; 4.22 Zn; 0.1 As; 38.4 Fe; 30.3 SiO₂; 4.1 CaO; 5.1 Al₂O₃; 0.5 MgO; others.

To obtain the optimal slag composition, % by weight: 30 SiO₂; 50 FeO; 10 CaO; others, it was adjusted by adding lime.

To purge the slag melt, natural gas was used with a content, % vol.: 92.6 CH₄; 4.07 C₂H₆; 1.07 C₃H₈; others. Shubarkul coal with a content of 74% carbon was used as a solid reducing agent.

X-ray phase analysis of powder slag samples was performed using a D8 Advance device (Bruker AXS GmbH), α -Cu, X-ray tube voltage 40/40. The processing of the obtained diffractogram data and the calculation of interplane distances were carried out using EVA software. The samples were decrypted and the phases were searched using the Search/match program using the ASTM Card Database.

The elemental analysis of slag samples was determined using an inductively coupled plasma mass spectrometer Agilent 7700 Series ICP-MS (USA).

A Neophot microscope (Carl Zeiss AG, Germany) is used for mineralogical studies of polymetallic samples.

A distinctive feature of the conducted research is the implementation of a two-stage depletion of high-sulfur slags under deeply reducing conditions of purging the slag melt with natural gas in the presence of coal.

The method of conducting the experiments was as follows. At the first stage, a beryllium crucible with an initial slag sample of 100 g was loaded into a quartz reactor and placed in a heating furnace. After installation, the furnace was heated to a set temperature of 1300°C. From the moment the furnace was heated, continuous purging of the reactor's free zone with natural gas began. The position of the alund purge tube is above the melt. After the slag was melted, the blast tube was immersed in the melt, and its purging began. The consumption of natural gas was set based on the calculation of exceeding its consumption by 20% of the theoretically necessary for the reduction of arsenic oxide As₂O₅ to the volatile compound As₂O₃. The gas flow rate was monitored using a rotameter.

The experiments were carried out on the installation shown in Figure 1.

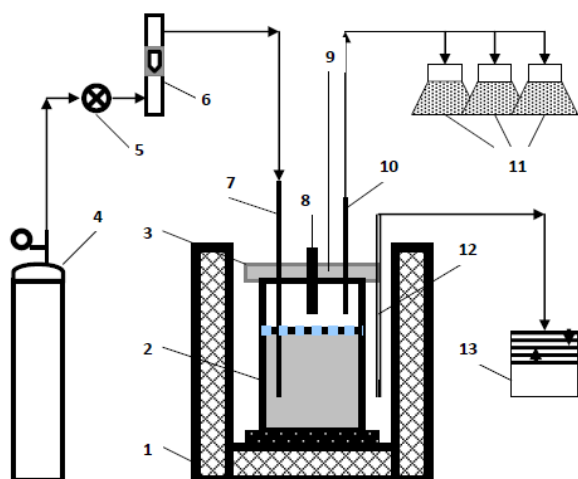


Figure 1. Schematic diagram of an installation for two-stage depletion of VF slags: 1 – Nabertherm GmbH RHTV 120-150/16 high temperature furnace; 2 – alund crucible; 3 – lid; 4 – natural gas cylinder; 5 – valve; 6 – rheometer; 7 – tube for supplying gas to the melt; 8 – coal loading window; 9 – slag melt; 10 – gas discharge; 11 – vessels with water; 12 – thermocouple PP-1; 13 – KSP-4

Preliminary experiments have shown that after purging the melt with natural gas for 5-10 minutes, a high extraction of arsenic into the gas phase is achieved. It was also found that during the prescribed time, the residual arsenic content in the slag reaches a minimum value and remains practically at the same level, regardless of the time of further purging.

The compositions of the slags did not undergo significant changes after their treatment with natural gas. The obtained results served as the basis for achieving the equilibrium of reducing depletion of slag by natural gas for arsenic. According to the results of preliminary experiments, the optimal time for purging slag with natural gas at the first stage for all subsequent experiments was assumed to be 10 minutes.

After a predetermined time of purging the slag with natural gas, the tube was removed from the melt and the second stage of reducing depletion of the slag began. The method of conducting the experiments was as follows. A pre-crushed coal powder was loaded onto the surface of the melt at a rate exceeding the set flow rate from the stoichiometrically required amount (SRA) for the reduction of lead and zinc oxide. Next, a purge tube was lowered into the melt and purging with natural gas began. The gas consumption was selected based on the calculation of exceeding its consumption by 10, 20, 30, 40, 50 and 60% of the SRA to reduce lead and zinc oxides to a metallic state. Each experiment was repeated three times in order to achieve reliable results. After purging, the crucible with the melt was settled for 20 minutes to separate the slag and matte, after which the crucible was removed from the furnace. The smelting products (slag and matte) were subjected to elemental analysis and mineralogical studies.

3. Results and discussion

The results of the elemental analysis of the slags obtained after purging the melt with natural gas at the first stage showed a slight decrease in the content of lead in the slags – from 1.02 to 0.9% and zinc – from 4.22 to 4.03%.

Figure 2 shows the dynamics of changes in the As content in the slag during purging of the melt with natural gas.

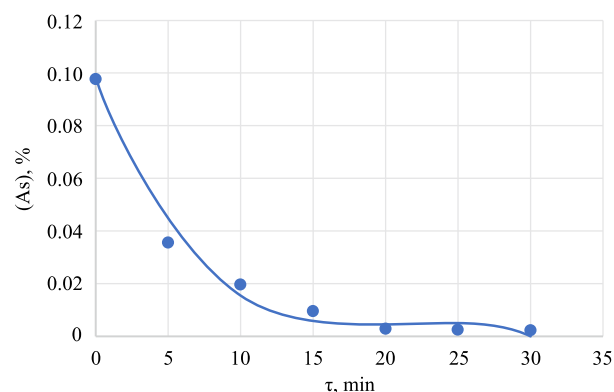


Figure 2. Dynamics of changes in the As content in the slag during purging of the melt with natural gas

It was found that even when purging the melt for 10 minutes, almost complete removal of arsenic from the slag is achieved.

The achievement of thermodynamic equilibrium between the slag melt and the matte at the second stage of slag depletion was determined by the stabilization of the gas phase. Preliminary experiments have shown that a state close to the thermodynamic equilibrium of the slag–matte system is achieved within 20 minutes. With an increase in natural gas consumption from SRA, the recovery of PbO and ZnO is enhanced by the influence of both coal and natural gas. At the same time, the extraction of lead and zinc from slag into dust increases dramatically (Figure 3).

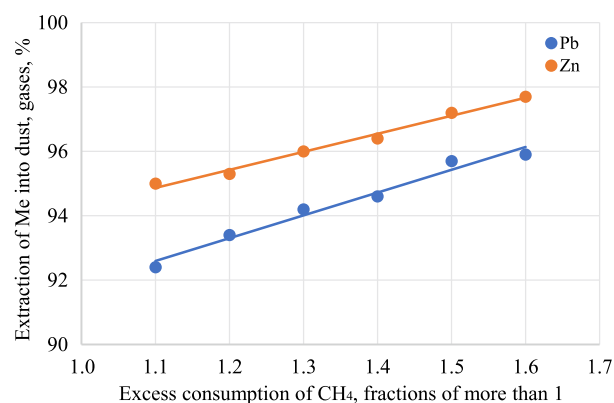


Figure 3. Dependence of the extraction of Pb, Zn into dust on the consumption of natural gas from the SRA, a fraction of more than 1

The resulting dusts are solid fine particles (sublimes) formed as a result of condensation of volatile metals and their compounds (oxides) from the vapor-gas phase with a decrease in temperature. With intensive continuous mixing of the melt with natural gas, favorable conditions are created for the coalescence of matte inclusions dispersed in the slag, which leads to an increase in copper extraction into the matter.

The results of mineralogical studies of the grinding of solid slag samples in each series of experiments showed the presence of ferrites in them, represented by compounds of iron oxides with calcium oxides, aluminum and, in a mini-

imum amount, copper oxide, in the form of delafossite (CuFeO_2). It was found that after depletion, the content of magnetite in the slags decreases from 15-18% to 5-7%. This indicates a deep reduction of magnetite by carbon from coal and natural gas.

The revealed dependencies are fully consistent with the results shown in Figures 2 and 3. With an increase in natural gas consumption exceeding the SRA for the reduction of lead, zinc and arsenic oxides, their maximum extraction into combustion is achieved, which, all other things being equal, increases dust yield. At the same time, the excess consumption of natural gas and carbon is spent on the recovery of slag magnetite. The destruction of magnetite is accompanied by the formation of iron oxide, which binds to silica in a stable phyllyte $\text{FeO} \cdot \text{SiO}_2$. The additional introduction of lime into the charge reduces the viscosity of the slag, which creates additional favorable conditions for reducing mechanical losses of copper with slag.

The yield of slag depletion products was, % of the weight of the initial charge: matte – 2.5; dust, gases – 10.4.

The dust yield in the experiments was determined by the difference between the amount of the corresponding metals in the initial slag and their amount in the resulting slag and matte (based on the calculation of the material balance of each experiment). The insignificant yield of matte is explained by the dominant extraction of copper from slag by reducing its mechanical losses.

The optimal consumption of natural gas, which ensures a minimum metal content in the slag, corresponds to a consumption exceeding its value from the SRA by 30% for the reduction of their oxides (Figure 4).

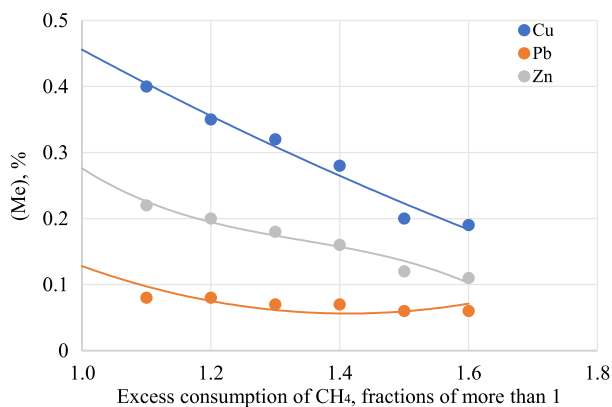


Figure 4. Dynamics of changes in the content of Cu, Pb, Zn in slag depending on the consumption of natural gas

At the same time, the minimum content of copper in the slag (0.35%) and lead, zinc (0.08% and 0.18%, respectively) is achieved.

Assay analysis of depleted slag for the content of Au and Ag in it showed their minimum values: 0.13 and 7.4 g/t, which indicates their maximum extraction into matte as a result of coalescence of mechanical suspensions of matte.

Based on the conducted experiments and the results of the material balance of each experiment, the distribution of non-ferrous metals and arsenic between the products of reducing depletion of slag by natural gas in the presence of coal is calculated, depending on the consumption of natural gas. The results are shown in Figure 5.

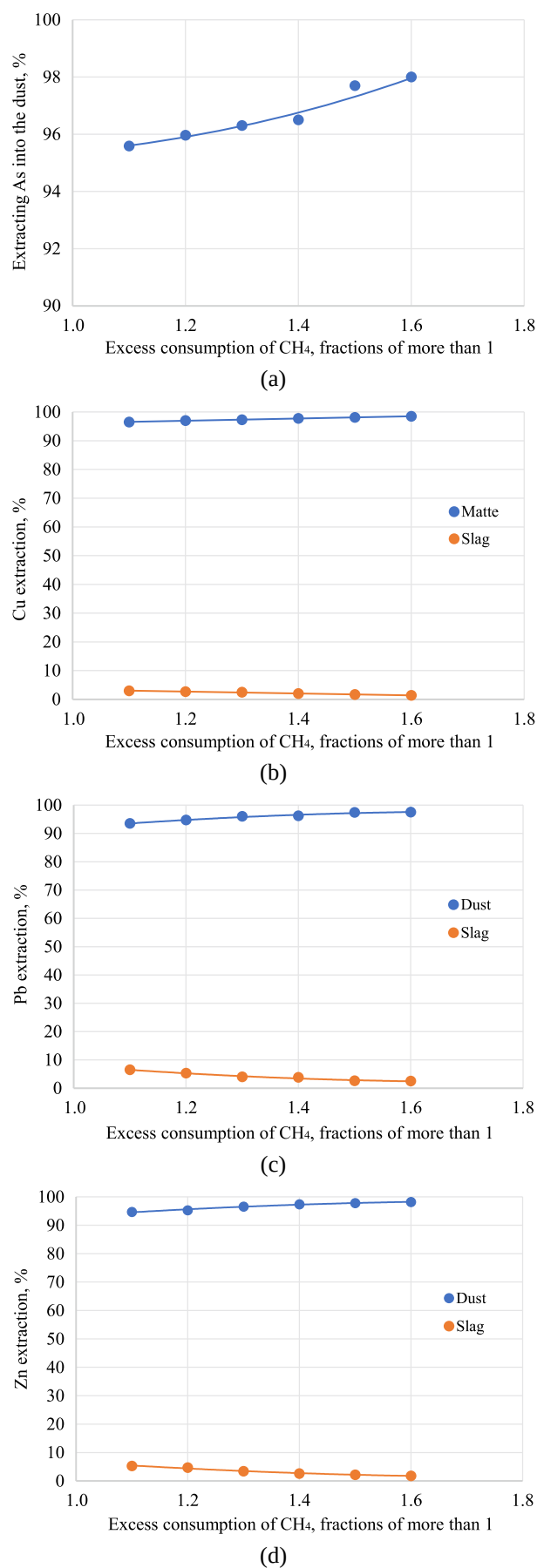


Figure 5. Distribution of elements between the products of reducing depletion of slags by natural gas in the presence of coal: (a) As; (b) Cu; (c) Pb; (d) Zn

The established optimal technological parameters of the process of reducing depletion of high-sulfur slags by natural gas in the presence of coal at a temperature of 1300°C meet the following criteria:

- The duration of slag purging with natural gas at the first stage is 10 minutes. The gas consumption exceeds by 10% its consumption from the SRA for the reduction of stable arsenic (V) oxide to its highly volatile compound, As_2O_3 ;

- The duration of the second stage of slag purging with natural gas in the presence of solid coal is 20 minutes:

- a) coal consumption is 10% more than the SRA for the reduction of lead oxide, zinc;

- b) the consumption of natural gas is 30% higher than the SRA for the recovery of magnetite and for intensive bubbling of the melt for coalescence of fine matte suspensions.

With the specified technological parameters, high technological indicators of the process of reducing depletion of slag have been achieved:

- the matte yield is 2.5% of the weight of the charge;
- the output of dust and gas is 10.4% of the weight of the charge;

- metal content in the recovered slag: copper – 0.35%; lead – 0.08%; zinc – 0.18%; arsenic – traces.

- extraction of metals: copper in matte – up to 98%; gold, silver in matte – 96%; arsenic in the dust – up to 99% (removed in the first stage of the technology by purging the slag with natural gas); lead, zinc in dust – up to 98% (removed in the second stage of the technology).

4. Conclusions

The results obtained indicate the high efficiency of the process of reducing depletion of slag, which makes it possible to extract valuable metals and remove harmful impurities. The low content of copper, lead and zinc in the recovered slag indicates a deep degree of depletion, which minimizes metal losses and reduces the environmental burden.

The high extraction of copper in matte, reaching 98%, demonstrates the efficiency of the process in terms of the concentration of copper in the valuable product. The extraction of gold and silver in matte at the level of 96% confirms the possibility of complex slag processing with the extraction of precious metals.

Selective removal of arsenic into dust, reaching 99%, is an important environmental advantage of the technology. The removal of arsenic in the first stage of the process using natural gas avoids its distribution to other products and reduces environmental pollution.

High extraction of lead and zinc into dust, reaching 98%, also helps to reduce the environmental burden and allows dust to be recycled to extract these valuable metals. The obtained indicators allow us to consider this technology as an effective and environmentally safe way of processing non-ferrous metallurgy slags.

Author contributions

Conceptualization: ND; Data curation: BS; Formal analysis: EZ; Funding acquisition: ND; Investigation: BS; Methodology: MK; Project administration: ND, BS; Resources: ND, BS; Software: EZ, MK; Supervision: ND; Validation: ND; Visualization: ND, EZ; Writing – original draft: ND, BS; Writing – review & editing: EZ, MK. All authors have read and agreed to the published version of the manuscript.

Funding

This research was carried out within the framework of grant funding from the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan for 2023-2025 in the priority area «Geology, extraction and processing of mineral and hydrocarbon raw materials, new materials, technologies, safe products and designs» of the project AP19676951 «Development of resource saving, combined technology for the complex processing of multicomponent non-ferrous metallurgy dust with the production of marketable products».

Acknowledgements

The authors would like to express their sincere appreciation to the Editor and the reviewers for the time and effort devoted to the evaluation of this manuscript. The editorial guidance and thoughtful feedback received during the review process are gratefully acknowledged.

Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Балқаш мыс балқыту зауыты жағдайында Ванюков пеші қождарының тотықсыздандырылған балқыту өнімдері арасында Cu, Pb, Zn және As-тың таралуы

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Аңдатпа. Балқаш мыс балқыту зауыты (БМЗ) жағдайында Ванюков пеші (ВП) қождарының тотықсыздандырылған балқыту өнімдері арасында Cu, Pb, Zn және As элементтерінің таралу нәтижелері келтірілген. 1300°C температурада көмірдің қатысуымен табиғи газды пайдалана отырып, қождарды екі сатылы тотықсыздандырып кедейлендіру процесінің оңтайлы технологиялық параметрлері анықталған. ВП қождарын екі сатылы тотықсыздандырып кедейлендіру жағдайында тотықсыздандырылған қождағы металдардың қалдық мөлшері: мыс – 0.35%; қорғасын – 0.08%; мырыш – 0.18%; мышьяк – іздік мөлшерде болатыны көрсетілген. Металдардың мақсатты өнімдерге жоғары дәрежеде алынуына қол жеткізді: мыстың штейнге алынуы – 98%-ға дейін; алтын мен күмістің штейнге алынуы – 96%; қожды табиғи газбен өңдеудің бірінші сатысында мышьяқтың шаңға алынуы – 99%-ға дейін, ал екінші сатыда қорғасын мен мырыштың шаңға алынуы – 98%-ға дейін. Алынған нәтижелер БМЗ-ның ағымдағы және жинақталған қождарын тауарлық өнімдер ала отырып кешенді, қалдықсыз өңдеудің инновациялық технологиялық платформасын әзірлеу барысында пайдаланылды.

Негізгі сөздер: ВП шлактары, тотықсыздандыру, көмір, табиғи газ, бөліп алу, бағалы металдар, газ және көмір шығыны.

Распределение Cu, Pb, Zn и As между продуктами восстановительной плавки шлаков печи Ванюкова в условиях Балхашского медеплавильного завода

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Аннотация. Приведены результаты по распределению Cu, Pb, Zn и As между продуктами восстановительной плавки шлаков Печи Ванюкова (ПВ) в условиях Балхашского медеплавильного завода (БМЗ). Установлены оптимальные технологические параметры процесса двухстадийного восстановительного обеднения шлаков природным газом в присутствии угля при температуре 1300°C. Показано, что в условиях двухстадийного восстановительного обеднения шлаков ПВ остаточное содержание металлов в восстановленном шлаке составляет: меди – 0.35%; свинца – 0.08%; цинка – 0.18%; мышьяка – следы. Достигнуто высокое извлечение металлов в целевые продукты: меди в штейн – до 98%; золота, серебра в штейн – 96%; мышьяка в пыль на первой стадии обработки шлака природным газом – до 99% и свинца, цинк в пыль во второй стадии – до 98%. Полученные результаты использованы при разработке инновационной технологической платформы комплексной безотходной технологии переработки текущих и накопленных шлаков БМЗ с получением товарных продуктов.

Ключевые слова: шлак ПВ, восстановление, уголь, природный газ, извлечение, ценные металлы, расход газа и угля.

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<https://doi.org/10.51301/ejsu.2026.i4.03>

Germanium production from Kazakhstan coals: resource potential, technological solutions and prospects

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Abstract. Germanium (Ge) is a rare trace element belonging to the group of materials that are critical for the development of high-tech industries, including semiconductor manufacturing, optoelectronics, space technologies, infrared optics, and defense systems. This review examines global models of germanium production, including traditional extraction from zinc concentrates and the development of the coal-based route in China; it analyzes the geochemistry of germanium accumulation in promising coal basins of Kazakhstan and assesses the prospects for establishing high-purity germanium production in Kazakhstan based on coal feedstock and technogenic products of its processing in the power and metallurgical industries. The prerequisites are shown for forming a new model of germanium production in Kazakhstan, based on a combination of two sources - zinc metallurgy and germanium-bearing coals – as well as the considerable potential of brown-coal (lignite) basins, including the Turgai and Zhilanshik basins. A technological model is proposed for obtaining germanium concentrates from coal feedstock, producing germanium dioxide (GeO₂), and producing high-purity metallic germanium. This approach is proposed as a basis for developing an export-oriented critical materials industry.

Keywords: *germanium, coal, Kazakhstan, critical materials, zinc metallurgy, hydrometallurgy, fly ash.*

Received: 04 June 2026

Received in revised form: 11 August 2026

Accepted: 17 August 2026

Available online: 31 August 2026

1. Introduction

Germanium (Ge) is a rare trace element that plays a key role in the production of microchips, optoelectronic devices, space technologies, and defense-related products. Growing demand for germanium is driven by the rapid development of digital infrastructure and critical technologies associated with artificial intelligence, large-scale data centers, and next-generation telecommunications networks.

In recent years, the strategic importance of germanium has increased significantly in the context of national technological and economic security. This is particularly relevant given the high geographical concentration of global germanium production, a substantial share of which is accounted for by China. The European Union, the United States, Japan, South Korea, and several other industrialized economies have therefore included germanium in their lists of critical raw materials or minerals essential to economic and national security.

Against the backdrop of the ongoing transformation of global critical-material supply chains, interest in Kazakhstan as a potential source of germanium is increasing. Unlike most countries, Kazakhstan potentially possesses two independent sources of germanium – zinc metallurgy and germanium-bearing coals. This combination creates favorable conditions for establishing a stable domestic raw-material base and developing an integrated production chain for high-

purity metallic germanium, which is in demand on international markets. The extraction of germanium from zinc concentrates and products generated during their metallurgical processing is consistent with the most widely used industrial practices for germanium recovery worldwide. At the same time, germanium-bearing coals, coal combustion ash from thermal power plants, and industrial waste generated by the energy and metallurgical sectors represent promising alternative sources of this critical element.

The aim of this study is to assess Kazakhstan's resource potential for germanium production from germanium-bearing coals and industrial waste generated during their utilization in the energy and metallurgical sectors; to analyze existing and prospective technological routes for germanium extraction from various types of feedstock; and to develop conceptual approaches to establishing an export-oriented industry for the production of high-purity metallic germanium in Kazakhstan.

The scientific novelty of the study lies in the comprehensive assessment of Kazakhstan's germanium-bearing coals and associated industrial waste as an alternative raw-material base for high-purity germanium production, as well as in substantiating a dual-source model for the development of a national germanium industry based on the integration of the conventional zinc-based feedstock source with the prospective coal-based source.

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Engineering Journal of Satbayev University. eISSN 2959-2348. Published by Satbayev University

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2. International experience and the structure of the global germanium market

2.1. Development of the global germanium industry

Historically, centers of germanium production formed in countries with a developed non-ferrous metallurgy sector. The first industrial technologies for extracting germanium were developed in Europe in the first half of the 20th century, primarily in Belgium and Germany, which had a strong base for processing polymetallic and zinc ores. The concentration of germanium in sulfide zinc ores was the reason that zinc metallurgy became the foundation of the global germanium industry.

For many years, the unique germanium-copper-lead-zinc deposits of Tsumeb and Kipushi in Africa provided the basis for germanium production. The technological scheme for extracting germanium from zinc concentrates, adopted at the plant in Balen (Belgium), is still used today in practically every country. The ore is beneficiated on-site by flotation, as a result of which germanium passes into copper-lead and copper concentrates. Special flotation and magnetic separation are then used to obtain the main germanium concentrate, containing up to 1% Ge. During roasting of zinc concentrates and zinc leaching, most of the germanium remains in the solid residue, which is subjected to fuming. Sulfuric-acid leaching of fuming sublimes, precipitation, repeated roasting, leaching, and hydrolysis yield GeO_2 [1]. The main centers of germanium production worldwide and their principal feedstock sources are summarized in Table 1.

Table 1. Main centers of germanium production in the world

Country	Role in global production	Main feedstock sources
China	Largest global producer and processor	Zinc concentrates, germanium-bearing coals, coal ash, technogenic feedstock
Russia	Historical producer	Zinc feedstock, coal feedstock, secondary resources
USA	Producer and consumer of high-purity germanium	Zinc metallurgy, secondary feedstock
Canada	Producer of germanium as a by-product	Zinc concentrates
Belgium	One of the historical refining centers	Metallurgical residues, secondary feedstock
Germany	Historical center of processing technologies	Secondary feedstock, metallurgical products
Finland	Production from non-ferrous metallurgy products	Zinc feedstock

Modern industrial germanium production is characterized by a high degree of concentration and a limited number of producers. Unlike most industrial metals, germanium is not mined as an independent mineral resource but is extracted mainly as a by-product in the processing of other feedstocks – primarily zinc concentrates (60-70%), coal feedstock (20-30%), as well as through secondary processing of scrap and metallurgical waste.

In the United States, germanium production has historically been based on the processing of zinc feedstock and secondary resources. Despite considerable scientific interest in extracting germanium from coal and ash-and-slag waste, these directions have not achieved industrial development comparable to that in China. The American model is more closely associated with the processing of metallurgical waste and secondary metal recovery. Canada, Belgium, Germany, and Finland retain their significance as technological centers for germanium production, using feedstock mainly associat-

ed with non-ferrous metallurgy. Their experience demonstrates a high level of technological maturity in processes for extracting germanium from zinc concentrates and metallurgical by-products [1].

China occupies a special place in the global system. According to data from the U.S. Geological Survey (USGS), China is the leading producer of germanium and holds a dominant position in the global supply chain, including extraction and refining operations. A substantial share of production is provided not only by zinc concentrates but also by the use of germanium-bearing coals, thermal power plant ash, and products of coal and energy industry processing. Through this, China has formed a unique industrial model combining the metallurgical and energy circuits of germanium extraction [2]. China has become the only country in the world able to scale up industrial germanium production from coal to a global level. The associated waste products – coal ash, gas-cleaning system dust, and other technogenic products in which germanium concentrates after the energy use of coal are regarded as a key link in the beneficiation stage of refined-germanium production technology.

Thus, the modern global germanium production system has formed around two main models. The first is the traditional metallurgical model, based on extracting germanium from zinc concentrates, characteristic of Europe, the USA, and Canada. The second is the combined resource model, uniting metallurgical and coal feedstock, which has achieved its fullest development in China. This is an extremely important precedent for Kazakhstan, which possesses significant coal reserves and a large energy sector.

2.2. China's experience in producing germanium from coal feedstock

The prerequisite for the large-scale development of this direction was the presence, in a number of regions of China, of coal deposits with anomalously high germanium content. The best-known germanium-bearing coals are located in the provinces of Inner Mongolia, Yunnan, Guizhou, and a number of other coal-mining regions of the country. In certain seams, the germanium content in coal significantly exceeds average global values, which created the prerequisites for industrial development of this resource. The main germanium-bearing coal deposits of China and their characteristic germanium contents are summarized in Table 2.

Table 2. Main germanium-bearing coal deposits of China [3-4]

Deposit / basin	Region (province)	Coal type	Ge content, g/t	Max. Ge content (g/t) / features
Lincang	Yunnan	Lignite	~850	Up to 2500-3000 in individual seams. Largest deposit in the world.
Xilin Gol (Wulantuga)	Inner Mongolia	Lignite	~137-244	Individual samples contain 820-1530. Second in importance.
Mentou	Yunnan	Lignite	~100-120	Local anomalies up to 400-600 in organic-rich interlayers.
Xuanwei	Yunnan	Bituminous / lignite	~30-55	Local nest-like enrichments. Above the national average (2.8 g/t).
Fushun	Liaoning	Lignite	~15-36	Low in the bulk mass but effectively concentrated in the collected fly ash.

For industrial extraction of the metal in China, a threshold content of 100 g/t is considered the minimum. Germanium in coal is concentrated mainly in the organic matter (80-90%), in the form of humates and germanium-organic complexes. Mineral forms (silicates and sulfides) of germanium compounds in coal do not exceed 20-25%.

During coal combustion, most of the germanium oxidizes and volatilizes – GeO at a temperature of 700°C, GeO₂ at $t > 1000^{\circ}\text{C}$ – concentrating in fly ash and dust products of gas cleaning, with the germanium concentration increasing 10-15 times compared with the coal. This effect has made it possible to regard ash-and-slag waste not as a by-product of power generation, but as technogenic feedstock for obtaining rare metals.

This allows the use of germanium-bearing coal in the energy sector to be regarded as a necessary technological stage in the beneficiation of feedstock for germanium production.

The technological scheme for producing germanium from coal feedstock in China generally includes several sequential stages: coal mining and preparation, its use for energy generation, collection of ash and dust, hydrometallurgical leaching of germanium, production of a germanium dioxide (GeO₂) concentrate, and then production of high-purity metallic germanium. At the final stages, deep purification and refining of the metal are applied [4].

It should be noted that an analogous technological scheme is also possible in non-ferrous and ferrous metallurgy during converter blowing of copper matte melts or germanium-containing pig iron, the air or oxygen flow entrains volatile vapors of GeO monoxide and GeS sulfide, which condense as aerosol particles, forming converter dust enriched in GeO, GeO₂, and GeS. This is followed by the collection and processing of converter dust according to the technological scheme described above [5-7].

China is also developing technology for extracting germanium from coal without combustion, using coal-chemistry methods. The high concentration of germanium in the organic matter of coal makes it possible to obtain not only germanium but also humic and fulvic acids - valuable feedstock for fertilizer production and soil reclamation. The alkali extraction-acid precipitation-chlorination and subsequent distillation method is regarded as a promising environmentally friendly approach to producing germanium from coal [8].

The Chinese model is based on the integration of the coal-mining, energy, and metallurgical industries. Within this system, coal is used for its main purpose - generating heat and electricity, as well as producing coke for metallurgical needs. The ash, sludge, and dust generated in the process are regarded as an additional source of valuable components. This achieves a dual economic effect: the main energy and metallurgical production processes are combined with the extraction of strategic metals.

Chinese experience is particularly significant from the standpoint of forming a comprehensive state policy in the field of critical materials. The development of germanium production was carried out not as a separate metallurgical project, but as an element of the national strategy for ensuring the country's technological independence in microelectronics, photonics, and high-tech engineering. As a result, China has formed a complete production cycle from raw material to high-value-added products becoming the largest participant in the global germanium market.

For Kazakhstan, China's experience is of particular interest. First, both countries possess substantial coal reserves and a developed coal-fired power industry. Second, Kazakhstan has accumulated significant volumes of ash-and-slag waste potentially containing germanium and other rare elements. Third, the existing energy infrastructure creates prerequisites for forming a similar resource model combining energy production with the extraction of strategic metals.

Thus, China's experience demonstrates the fundamental possibility of creating an independent model for developing a germanium industry, based on the use of national advantages in coal mining and the energy sector.

2.3. Prospects for germanium production from coal in Kazakhstan

Kazakhstan possesses one of the largest coal bases in Central Asia, represented by deposits of various geological-industrial types and characterized by substantial reserves and significant resource potential. Traditionally, the country's coal resources have been regarded as a source of energy feedstock. At the same time, the modern concept of integrated use of mineral resources assumes a transition from a single-component model of resource development to the extraction of associated valuable components, including rare and trace elements.

As a rule, trace elements are associated with the organic matter of coal (in a sorbed state, in the form of salts of organic acids or complex compounds), and less often with mineral components (their own minerals). Germanium, tungsten, beryllium, vanadium, and lithium are always associated with the organic part of coal, while lead, zinc, and scandium are associated with the mineral part. The organic part, acting as a reducing agent and sorbent (humic and fulvic acids), ensures the accumulation (sorption) of trace elements during coal formation from surrounding hydrothermal and aqueous solutions [9].

From a geochemical standpoint, brown coals (lignites) with a high organic-matter content and the presence of chemically active functional groups are the most promising for germanium accumulation. That is, elevated concentrations of germanium, lithium, and other rare metals are characteristic specifically of brown coals [10].

At the same time, bituminous (hard) coals generally do not exhibit high contents of rare elements. As the degree of coal metamorphism increases, the structure of organic matter changes, its sorption capacity decreases, and, as a rule, the concentration of a number of rare elements decreases as well.

Table 3 summarizes the coal deposits of Kazakhstan that are currently under development or prepared for industrial development. As shown in Table 3, these coals contain a broad range of rare elements and non-ferrous metals, typically at concentrations of up to 0.1-0.2%.

Analysis of the data presented shows that the highest potential for forming a coal-based source of germanium is associated primarily with the brown-coal (lignite) basins of Kazakhstan – the Turgai and Zhilanshik basins. For individual deposits in these basins, elevated concentrations of germanium, lithium, titanium, tungsten, rare-earth elements, and other strategically important components have been established. In terms of germanium content, some of these deposits are comparable to the well-known germanium-coal deposits of China (Table 2) and Russia.

Table 3. Coal deposits of Kazakhstan [11-19]

Basin / deposit	Formation (svita)	Reserves	Coal type	Ge content, g/t	Germanium reserve estimate / geochemical specialization
Developed					
Karaganda	Tentek Fm.	43.1 bn t	Bituminous	n/d	Y, Sc, Ge, Hg
	Dolinskaya Fm.			20-40	REE, Mo, Ge, Hg
	Nadkaragandinskaya Fm.			n/d	REE, Mo, Hg
	Karagandinskaya Fm.			n/d	REE, Mo, Hg
	Ashlyarikskaya Fm.			n/d	Sc, Hg
	Dubovskaya Fm.			n/d	Ga, REE, Sc, Be
	Mikhailovskaya Fm.			n/d	REE, Sc
Ekibastuz	Nadkaragandinskaya, Karagandinskaya, Ashlyarikskaya Fms.	9.7 bn t	Bituminous	Absent	REE, Al, Ti, Zr, Sc, Ba, Hg
Shubarkol deposit	–	2.3 bn t	Bituminous	7	REE, U, Y, Sc, Nd, Gd, Ti, Li, Be, Cu, U, Zn, Ni, Co, Ga, W
Alakol deposit	–	47 mn t	Lignite / Bituminous	10-30	Ge – 80 t, Sc – 180 t, REE
Prepared for industrial development					
Turgai basin. Deposits: Kushmurun, Eginsai, Priozernoye, Chernigovskoye, Orlovskoye, Kyzyltal	Duzbay, Karagan, Kushmurun, Chernigov Fms.	61.9 bn t	Lignite	500-10000	Ti (1.5-1.7%), Ge, REE, Li, Ag
Zhilanshik	Chilikin Fm.	14.5 bn t	Lignite	100-1000	Ge, Re, REE, Au, Mo

At the same time, the degree of study of the Turgai brown-coal basin in terms of germanium distribution, its forms of occurrence, and the possibility of industrial extraction remains insufficient. Industrial development requires additional geochemical studies, including determination of the spatial distribution of germanium, its mineral forms of occurrence, and the technological properties of the coal feedstock [1].

At the current stage, individual bituminous-coal deposits already under development - Dolinskoye, Shubarkol, Alakol – are of interest for germanium extraction as a by-product of energy use. The coal from these deposits is currently used both for power generation and for producing coke for metallurgical needs.

During coal combustion, germanium is redistributed among the combustion products, with the element's concentration in fly ash, dust, and fine fractions increasing 10-15 times compared with the original coal – up to 70-100 g/t. This creates prerequisites for forming a technogenic source of germanium based on coal-fired power facilities.

Technogenic waste from metallurgical enterprises, in which germanium can concentrate during the processing of the corresponding feedstock, is also of interest. During converter blowing of copper matte melts or germanium-containing pig iron, volatile vapors of GeO monoxide and GeS sulfide condense as aerosol particles. The high concentration of GeO, GeO₂, and GeS makes it possible to regard converter dust as valuable feedstock for obtaining germanium.

In this connection, technogenic waste from the Karmet and Kazakhmys enterprises can potentially be considered as sources of germanium, provided that specialized processing technologies are developed. The collection of fly-ash dust is particularly significant when processing germanium-ferruginous ores, such as those at the Western Karazhal and Taldysay deposits in the Atasu ore district. A Ge content in the ore of 8-27 g/t makes it possible to obtain high germanium concentrations in the collected fly ash.

Thus, the prospects for germanium production from Kazakhstan's coal feedstock are associated not only with the development of promising coal deposits, but also with the formation of a comprehensive technological system, including the mining and processing of germanium-bearing coals from operating deposits, the use of dust and ash-and-slag

waste from the energy sector, and the involvement of metallurgical technogenic resources.

Creating such a coal-based germanium production circuit will make it possible to form an additional raw-material base for producing high-purity metallic germanium and to ensure the development of a new direction in the field of critical materials in Kazakhstan.

3. Concept of the technological chain for germanium production from coal feedstock in Kazakhstan

3.1. Key stages of the proposed technological chain

Unlike the traditional production of germanium from zinc concentrates, the coal-based direction is based on the use of technogenic waste generated during the thermal processing of coal. A key element of the model is the transfer of ash-and-slag waste and fly-ash dust from the category of industrial waste to the category of secondary mineral feedstock. A potential technological chain for germanium production from Kazakhstan's coal feedstock can be represented as follows.

The proposed technological chain begins with the identification and development of a germanium-bearing coal deposit, followed by coal mining and preparation. The prepared coal is then used for energy generation or metallurgical purposes, resulting in the formation of ash, fly-ash dust, and other processing products in which germanium can become concentrated. These germanium-enriched materials are subsequently subjected to hydrometallurgical extraction and purification to produce a germanium dioxide (GeO₂) concentrate. At the final stage, the obtained GeO₂ is reduced and refined to produce high-purity metallic germanium.

At the first stage, a geochemical assessment of the coal feedstock is important, along with identification of areas with elevated concentrations of germanium and other rare elements. For Kazakhstan, this stage is particularly important, since a number of promising brown-coal sites – primarily in the Turgai and Zhilanshik basins – require further study in terms of germanium distribution, forms of occurrence, and industrial recoverability.

The next important stage is the organization of separate collection of coal-processing products. Chinese practice shows that the efficiency of germanium extraction increases substantially when separate streams of ash, fly-ash dust, and

other fine-dispersed products where rare elements concentrate are separated. In this connection, modernization of gas-cleaning systems and accounting for ash-and-slag materials is one of the key conditions for creating a coal-based germanium production circuit.

At the metallurgical processing stage, known hydrometallurgical methods of germanium extraction can be used, including leaching, solution purification, obtaining a GeO_2 concentrate, and subsequent reduction to high-purity metallic germanium. The choice of a specific technological scheme should be determined by the composition of the initial feedstock and associated components.

A distinctive feature of Kazakhstan is the possibility of forming an integrated processing model in which germanium can be extracted together with other valuable components of the coal feedstock – lithium, scandium, rhenium, and other rare-earth and rare elements.

Thus, the prospective model for germanium production from Kazakhstan's coal feedstock should be regarded not as a separate metallurgical process, but as an element of a comprehensive system for using coal resources. Its implementation will make it possible to transform coal deposits and accumulated technogenic waste into a source of strategic materials for high-tech industries.

3.2. Main directions of further research and technological challenges

One of the key aspects of further research is a detailed geochemical characterization of Kazakhstan's coal basins in order to identify zones of elevated germanium concentration. Systematic studies are needed to determine the Ge content in coals of various stages of metamorphism, as well as to establish its relationship with the organic and mineral components of the coal matter.

A second important direction is the study of germanium distribution during the thermal processing of coal. Particular attention should be paid to the distribution of the element among fly ash, slag, and gas emissions, as well as to the mechanisms of its concentration in fine-dispersed fractions. This data is key to developing effective industrial extraction schemes.

A third direction is the development and adaptation of hydrometallurgical technologies for extracting germanium from ash, fly-ash dust, and other technogenic products. In particular, optimization is required of leaching processes, solution purification, selective extraction, and production of germanium dioxide (GeO_2), as well as subsequent reduction to high-purity metallic form.

Special attention should be given to creating an experimental and pilot-industrial base for testing germanium extraction technologies under Kazakhstan's conditions. Such facilities will make it possible to assess the technological and economic efficiency of processing specific types of coal and technogenic feedstock, as well as to determine optimal parameters for industrial implementation.

Among the systemic challenges is also the need to form a regulatory and institutional framework for the transition from treating ash-and-slag waste as industrial waste to regarding it as secondary mineral feedstock. This implies changes in approaches to accounting, storage, and processing of technogenic materials.

Finally, an important direction is the development of a comprehensive economic model for germanium production,

considering the multicomponent nature of the feedstock, the high degree of product processing, and dependence on world prices for critical metals. Such a model should serve as a basis for investment decision-making and for shaping state policy in the field of critical materials.

Thus, further development of this direction requires the synergy of geological, technological, economic, and institutional research aimed at forming a new high-tech germanium production industry in Kazakhstan.

4. Conclusions

The review confirms that Kazakhstan has substantial potential to develop a national germanium industry based on two complementary raw-material sources: the traditional zinc-metallurgical route and the emerging coal-based route. The greatest prospects for the latter are associated with the Turgai and Zhilanshik lignite basins, as well as several operating bituminous-coal deposits, including Dolinskoye, Shubarkol, and Alakol. In addition, metallurgical and energy-sector waste generated by major industrial enterprises may represent an important secondary source of germanium. Together, these resources create the basis for establishing an integrated and potentially export-oriented production chain for high-purity metallic germanium.

The practical implementation of this potential requires a coordinated program of geological, technological, and institutional development. Priority should be given to detailed geochemical characterization of germanium-bearing coals, assessment of germanium distribution in ash, fly ash, and metallurgical dust, and adaptation of effective hydrometallurgical recovery technologies to Kazakhstan's feedstock characteristics. Equally important is the development of pilot-scale processing facilities and a regulatory framework that recognizes ash-and-slag materials and other technogenic products as secondary mineral resources. Such measures would enable Kazakhstan to diversify its critical-materials base, increase the added value of domestic mineral resources, and strengthen its position in the global germanium supply chain.

Author contributions

Conceptualization: FSK, DEF; Data curation: FSK, DEF; Formal analysis: FSK; Funding acquisition: DEF; Investigation: FSK; Methodology: FSK, DEF; Project administration: DEF; Resources: FSK, DEF; Software: FSK; Supervision: DEF; Validation: FSK, DEF; Visualization: FSK; Writing – original draft: FSK; Writing – review & editing: FSK, DEF. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Acknowledgements

The authors express their gratitude to the Institute of Metallurgy and Ore Beneficiation (Satbayev University) and the International Research Complex «Astana» for providing research support.

Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Қазақстан көмірінен германий өндіру: ресурстық әлеуеті, технологиялық шешімдер және келешегі

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Аңдатпа. Германий (Ge) – жартылай өткізгіштер өндірісін, оптоэлектрониканы, ғарыштық технологияларды, инфрақызыл оптиканы және қорғаныс жүйелерін қоса алғанда, жоғары технологиялық салаларды дамыту үшін аса маңызды материалдар тобына жататын сирек шашыранды элемент. Осы шолуда германий өндірудің әлемдік модельдері, соның ішінде мырыш концентраттарынан дәстүрлі түрде бөліп алу және Қытайда көмір негізіндегі бағыттың дамуы қарастырылған; Қазақстанның перспективалы көмір бассейндерінде германийдің жинақталу геохимиясы талданып, көмір шикізаты мен оны энергетика және металлургия өнеркәсібінде өңдеу нәтижесінде түзілетін техногендік өнімдер негізінде Қазақстанда жоғары тазалықтағы германий өндірісін құру перспективалары бағаланған. Қазақстанда германий өндірудің екі көзді – мырыш металлургиясы мен германийлі көмірлерді - ұштастыруға негізделген жаңа моделін қалыптастырудың алғышарттары, сондай-ақ Торғай және Жыланшық бассейндерін қоса алғанда, қоңыр көмір (лигнит) бассейндерінің елеулі әлеуеті көрсетілген. Көмір шикізатынан германий концентраттарын алу, германий диоксидін (GeO₂) өндіру және жоғары тазалықтағы металл германий алу жөніндегі технологиялық модель ұсынылған. Бұл тәсіл экспортқа бағдарланған критикалық материалдар индустриясын дамыту үшін негіз ретінде ұсынылады.

Негізгі сөздер: германий, көмір, Қазақстан, критикалық материалдар, мырыш металлургиясы, гидрометаллургия, ұшқын күл.

Производство германия из углей Казахстана: ресурсный потенциал, технологические решения и перспективы

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Аннотация. Германий (Ge) – редкий рассеянный элемент, относящийся к группе материалов, критически важных для развития высокотехнологичных отраслей промышленности, включая производство полупроводников, оптоэлектронику, космические технологии, инфракрасную оптику и оборонные системы. В данном обзоре рассмотрены мировые модели производства германия, включая традиционное извлечение из цинковых концентратов и развитие угольного направления в Китае; проанализирована геохимия накопления германия в перспективных угольных бассейнах Казахстана и оценены перспективы создания в Казахстане производства германия высокой чистоты на основе угольного сырья и техногенных продуктов его переработки в энергетической и металлургической промышленности. Показаны предпосылки для формирования в Казахстане новой модели производства германия, основанной на сочетании двух источников – цинковой металлургии и германиеносных углей, а также значительный потенциал бурогоугольных (лигнитовых) бассейнов, включая Тургайский и Жыланшиковский бассейны. Предложена технологическая модель получения германиевых концентратов из угольного сырья, производства диоксида германия (GeO₂) и высокочистого металлического германия. Данный подход предлагается в качестве основы для развития экспортно-ориентированной отрасли критических материалов.

Ключевые слова: германий, уголь, Казахстан, критические материалы, цинковая металлургия, гидрометаллургия, зола уноса.

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<https://doi.org/10.51301/ejsu.2026.i4.04>

Comprehensive monitoring of the meliorative state of irrigated lands as the basis for sustainable water utilization in the Turkistan Region

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Abstract. In the conditions of a growing water scarcity, comprehensive state monitoring of irrigated lands is of particular importance. The study is based on data from the Ministry of Agriculture of the Republic of Kazakhstan and the South Kazakhstan Hydrogeological and Meliorative Expedition. The aim of the work is to assess the current state of the land in the Turkistan Region, analyze the dynamics of groundwater levels and mineralization, and identify the causes of soil degradation. The monitoring covers an area of over 550 thousand ha and includes the systematization of data from laboratory studies and hydrogeological observations. The results of the work substantiate recommendations for the restoration of drainage systems and the optimization of water use. The conclusions formed contribute to the sustainable development of the agrarian sector and the enhancement of the region's food security in the conditions of climate change.

Keywords: meliorative state of lands, irrigated lands, water resources, state monitoring, hydrogeological observations.

Received: 13 March 2026

Received in revised form: 01 August 2026

Accepted: 17 August 2026

Available online: 31 August 2026

1. Introduction

Modern climate change, growing anthropogenic load, and increasing demand for water resources significantly complicate the tasks of sustainable management of water systems and the ensuring of food security. Of particular importance is the efficient utilization of water resources in regions with arid and sharply continental climatic Conditions, where the sustainability of agricultural Production directly depends on the state of irrigation systems, the groundwater regime, and the meliorative state of lands [1, 2].

Changes in the temperature regime, an increase in the frequency of extreme hydrometeorological events, and the uneven Distribution of atmospheric precipitation have a significant impact on the formation of the water balance of the territories. This leads to the deterioration of water quality, increased groundwater mineralization, intensified soil salinization, and degradation of agricultural land [3, 4]. Under limited freshwater resources, a special role is played by the rational use of surface and groundwater sources, as well as by the improvement of water regulation and conservation systems [5].

The Turkistan Region belongs to regions with a high dependence of agriculture on artificial irrigation. Here, natural Conditions, including a hot climate, an unstable precipitation regime, and significant evaporation, necessitate continuous Control over the state of irrigated lands [6]. Disruption of the water regime, insufficient drainage efficiency and high min-

eralization of irrigation water can lead to secondary salinization, reduced land productivity and deterioration of the ecological state of agrolandscapes [7, 8].

In this regard, comprehensive monitoring of the meliorative state of irrigated lands, including hydrogeological observations, water quality analysis, assessment of soil salinization, and the efficiency of drainage and irrigation systems, is of particular relevance [9, 10]. The obtained data make it possible to identify negative trends, forecast changes in natural and meliorative Conditions, and develop scientifically grounded recommendations for the rational utilization of water and land resources [11].

Particular attention should also be paid to infiltration and colmatation processes, as they directly influence water movement in the soil profile, groundwater recharge, and the overall efficiency of drainage systems [12]. At the same time, the suitability of water for irrigation should be assessed according to established water quality criteria and indicators, including mineralization and other parameters that may affect soil properties and crop productivity [13].

The purpose of this study is to comprehensively assess the natural, hydrological, and water management conditions of irrigated areas in the Turkistan Region, and to analyze the factors affecting their meliorative state. Special Attention is paid to the study of the water and salt regimes of soils, the dynamics of groundwater levels and mineralization, the efficiency of irrigation and drainage systems, and the identification of the causes of agricultural land degradation.

The research results aim to provide practical recommendations to improve the condition of irrigated lands, increase water-use efficiency, and ensure the ecological sustainability of the region's agricultural area.

2. Materials and methods

The methodological research complex is based on the integration of field hydrogeological surveys, precision laboratory analyses, and mathematical modeling methods of filtration processes. The object of the study is the irrigated arrays of the Turkistan Region with a total area of 551.4 thousand ha, characterized by complex natural and meliorative conditions of the arid zone. The study relies on a representative sample of state monitoring data for the 2021-2022 cycle, which enables a high degree of reliability in assessing the correlations between climatic factors and the dynamics of the water-salt balance [14, 15].

The basis for collecting primary data was the baseline state observation network, including 1,396 monitoring wells. The well was designed to intercept the main exploited horizons: mid-Quaternary alluvial-proluvial deposits and deeper Upper Pliocene and Upper Cretaceous aquifer systems. The methodology for field measurements of groundwater levels (GWL) was strictly regulated by the observation schedule. Measurements were carried out three times a Month, totaling 23855 instrumental Settlements during the reporting period.

Hydrogeological electrical level meters (EU type) and steel plummets with anti-corrosion coating, calibrated with an accuracy of up to ± 0.01 m, were used to record the level. Before each measurement cycle, a control check of wellhead tightness and a cleaning of the filter space were carried out to eliminate errors associated with clogging. The depth of GWL occurrence was recorded relative to the wellhead with subsequent Settlement into absolute elevations to construct hydro-isohypse maps.

The analysis of the natural and climatic impact on the meliorative state of lands was carried out using data from 12 meteorological stations of RSE «Kazhydromet». The methodology included the calculation of Selyaninov's hydrothermal coefficient (HTC), which makes it possible to assess the degree of aridity of each specific irrigation array:

$$HTC = \frac{\sum P}{0.1 \sum T} \quad (1)$$

where $\sum P$ is the sum of precipitation for the period with temperatures above $+10^\circ\text{C}$; $\sum T$ is the sum of active temperatures.

The use of this indicator made it possible to differentiate the region's territory into zones of critical (Kyzylkum, Zhetysai) and moderate water deficit. To verify the evapo-

ration data, the Lichev-Lebedev method, adapted to the conditions of Southern Kazakhstan, was applied.

To substantiate the possibility of using groundwater from the Bugunskoye, Suzakskoye, and Michurinskoye Fields as alternative irrigation sources, pumping test data were interpreted. The Settlement of transmissivity (km) and storativity (a) coefficients was performed based on the results of tracking the recovery of the level in wells after the cessation of pumping using the Hantush-Jacob method. For the conditions of confined horizons of Upper Pliocene deposits («Darmina» site), the calculation was made using the formula:

$$S = \frac{0.183Q}{km} \lg \frac{2.25at}{r^2} \quad (3)$$

where S is the drawdown of the level; Q is the well discharge; t is the time from the start of pumping. The obtained parameters (transmissivity up to $2.617 \text{ m}^2/\text{day}$) served as input data for numerical modeling of water intake operations over a final period of 10000 days.

Monitoring of the soil salt regime was conducted on 16 key plots, covering a total area of 20000 ha. Soil sampling was carried out layer-by-layer (0-20, 20-50, 50-100, 100-150, 150-200 cm) using the soil profile and drilling method. In total, 11045 samples processed at SKHME's accredited laboratory were analyzed.

The chemical-analytical block included:

1. Preparation of aqueous extract (1:5). Determination of dry residue and total mineralization by the gravimetric method.

2. Titrimetric analysis. Determination of chloride ion content (Cl^-) by the Argentometric method and sulfate ion (SO_4^{2-}) by barium precipitation.

3. Flame photometry. Determination of sodium (Na^+) and potassium (K^+) cations on PFA-378 type instruments.

4. Toxicity assessment. Settlement of the sum of toxic salts using the Bazilevich-Pankova formula, which made it possible to classify soils by the degree of salinization (from non-saline to takys).

To assess the quality of irrigation waters of the fields, the SAR (Sodium Adsorption Ratio) classification was applied, which was calculated as:

$$SAR = \frac{\text{Na}^+}{\sqrt{0.5(\text{Ca}^{2+} + \text{Mg}^{2+})}} \quad (4)$$

This indicator, together with Stepanov's irrigation coefficient, enabled assessment of the risk of secondary sodicity when using mineralized groundwater (up to $2.5\text{-}3.0 \text{ g/L}$). The technical characteristics of the monitoring network and the scope of the research performed in 2021-2022 are summarized in Table 1.

Table 1. Technical characteristics of the monitoring network and scope of performed research (2021-2022)

Monitoring object	Quantitative indicator	Control method	Observation schedule
Observation wells	1396	Electrical level meters EU-50 plummet	3 times a month (ten-day)
Hydroposts on canals	48	GRM-21 M current meters, GR-31 rods.	Daily during the growing season
Key plots (salt survey)	16 (20000 ha)	Drilling (0-200 cm) core samplers	Before and after the irrigation period
Meteorological stations	12	Automatic complexes (Kazhydromet)	Continuously
Laboratory analyses, water samples (soil, water)	11045 samples	Titrimetry, flame photometry	According to GOST 26423-85

Spatial interpolation of GWL and mineralization data was performed in ArcGIS 10.8 using the Geostatistical Analyst module. The use of the ordinary kriging method enabled the construction of prognostic maps of the meliorative state with minimal standard error. Statistical processing of the entire data array was carried out using Student's t-test to assess the significance of differences between the indicators of 2021 and 2022, as well as regression analysis to identify the relationship between the volume of water supply and the rate of rise of the groundwater table. The hydrogeological parameters of the exploited aquifer systems are presented in Table 2.

Table 2. Hydrogeological parameters of the investigated aquifer systems

Field (site)	Aquifer system	Formation thickness, m	Transmissivity km), m/day	Storativity (a), m ² /day
Bugunskoye (Timursky)	Q _{III-III} Alluvium	40-65	1730-2411	2.6·10 ⁴
Suzak (Northern)	R ₂ -K ₂ Melpogen	80-120	116-2617	1.5·10 ⁵ -2.5·10 ⁶
Michurinskoye	Q _{IV} modern Alluvium	15-30	208-1514	1.8·10 ⁴
Darmina	N ₂ upper Pliocene	50-90	450-890	2.2·10 ⁵

The parameters indicate considerable variability in the filtration properties and storage capacity of the investigated aquifer systems, reflecting differences in their geological and hydrogeological conditions. The identified differences in transmissivity and storativity demonstrate the heterogeneous hydrogeological properties of the investigated aquifers and should be considered when assessing their potential for irrigation water supply.

3. Results and discussion

3.1. Factors affecting the meliorative state

The natural and climatic potential of the Turkistan Region is a decisive factor in the intensity of soil formation processes. The relief of the region, characterized by the transition from the desert plains of Betpak-Dala (in the north) to the high-mountain systems of the Tien Shan (Sayram Peak, 4299 m), creates a complex hydrodynamic situation.

According to weather monitoring data for 2021-2022, the region's climate remains sharply continental, with a pronounced moisture deficit during the growing season. The average July temperature (28.4°C) and extreme maximums up to +45.0°C (at the Kyzylkum station) cause high evaporation rates that significantly exceed precipitation.

Precipitation analysis showed that its distribution is highly uneven, with up to 89% of the annual norm falling in the autumn-winter period. A critically low level of precipitation in August (0.4 mm), combined with anomalous heat and high evaporation, forms the «evaporative» type of soil water regime. Under such conditions, in the absence of adequate drainage, mineralized groundwater is drawn to the surface, contributing to salt accumulation and secondary salinization over an area of 7.4 thousand ha.

At the end of 2022, the total area of the irrigated land in the region was 551.4 thousand ha. A comparative analysis of the land-use structure revealed a critical problem - excessive fragmentation of plots. The presence of 99593 economic entities with an average allotment size of only 4.9 ha creates insurmountable barriers to systemic land reclamation.

The groundwater monitoring results revealed substantial spatial variations in mineralization and chemical composition across the districts of the Turkistan Region, as summarized in Table 3.

Table 3. Characteristics of mineralization and chemical composition of groundwater in the Turkistan Region (max/min indicators for 2022)

№	Districts	Sampling time	Sampling location	Salinity, mg/dm ³	Chemical composition
1	Otyrar	18.09.22	No 58 Temir	57500	SO ₄ ²⁻ Cl Na+K
2	Otyrar	18.09.22	No 31 Otyrar	1000	SO ₄ ²⁻ HCO ₃ Na+K
3	Sauran	01.09.22	No 2007 Ushkayyk	80870	SO ₄ ²⁻ Cl Na+K
4	Sauran	02.09.22	No 415 Ushkayyk	200	SO ₄ ²⁻ HCO ₃ Ca+
5	Shardara	16.09.22	No 6 Kosseit	3940	SO ₄ ²⁻ HCO ₃ Na+K
6	Shardara	16.09.22	No 18 Sutkent	540	SO ₄ ²⁻ HCO ₃ Na+K
7	Kazygurt	30.08.22	No 45 Kyzylkyya	5100	SO ₄ ²⁻ Cl Ca+
8	Kazygurt	31.08.22	No 45 Kakpak	330	SO ₄ ²⁻ HCO ₃ Mg+
9	Saryagash	01.09.22	No 114 Saryagash	7190	SO ₄ ²⁻ HCO ₃ Ca+
10	Saryagash	02.09.22	No 105 Kyzylzhar	170	SO ₄ ²⁻ HCO ₃ Ca+
11	Ordabasy	13.09.22	No 6 Bugen	25000	SO ₄ ²⁻ Cl Na+K
12	Ordabasy	12.09.22	No 170 Tortkol	160	HCO ₃ SO ₄ ²⁻ Mg+
13	Maktaaral	12.09.22	No 42 Nurlybayev	9780	ClSO ₄ ²⁻ Mg+
14	Maktaaral	10.09.22	No 097 Dostyk	830	SO ₄ ²⁻ HCO ₃ Ca+
15	Zhetysai	10.09.22	No. 137 Atameken	9910	ClSO ₄ ²⁻ Na+K
16	Zhetysai	11.09.22	Nos. 226 Kyzysru	850	SO ₄ ²⁻ HCO ₃ Ca+

Small-scale Production in the Sairam and Saryagash districts (1.2-2.0 ha) makes it impossible to introduce modern agricultural technologies and observe crop rotations. This leads to the degradation of on-farm distribution canals and disruption of design irrigation regimes.

Out of the total area of 551.4 thousand ha, only 489.6 thousand ha were actually used. A detailed analysis of the causes of idleness on 61.8 thousand ha (11.2% of the total fund) highlights key destabilizing factors.

Special Attention is deserved by the situation in the Arys region, where 14.863 ha are idle. Here, the highest percentage of land withdrawal due to a combination of salinization and water scarcity has been recorded. At the same time, the Maktaaral and Zhetysai districts demonstrate intensive land use (over 99% involvement), which, against the backdrop of cotton monoculture (40.4-49.5 thousand ha), poses a threat of long-term depletion of land reclamation.

The hydrological network of the region (Syrdarya, Arys, Keles rivers) and reservoirs (Shardara, Bogen) provide a baseline resource for irrigation. However, the high degree of deterioration of the collector-drainage network (CDN), reduces the overall efficiency of water use.

The presence of 3.1 thousand ha of land with a critically high groundwater table indicates low performance of vertical and horizontal drainage. Under the temperature conditions of 2022 (average $T_{year} = 14.2^{\circ}\text{C}$), a groundwater table depth of above 2.5 m is critical. Capillary rise of mineralized solutions in such zones occurs continuously, which is confirmed by salinization data in the Zhetysai massif.

Comparison of the obtained data with the monitoring results of previous years shows that the region is in a state of «hydrological stress». The increase in the area of used land in Zhetysai (from 82917 to 82978 ha) while maintaining irrigation water shortages in other massifs indicates the need to review water use limits. The technological factor is reflected in the fact that 58% of the lands (36 thousand ha) are not used for «various reasons», which in technical terms means the destruction of on-farm networks. This requires not only reclamation, but also civil engineering investments.

Biological land reclamation is also important, as the dominance of cotton (125.8 thousand ha) should be reduced by increasing the share of alfalfa and grain crops. Perennial grasses in the Kazygurt district (11.2 thousand ha of crops) have already proven their effectiveness as natural drainage.

Water sovereignty is another important aspect. Considering the transboundary nature of the Syrdarya River, the development of artesian irrigation from the Bugun and Suzak fields is a strategic task to compensate for precipitation deficits.

3.2. Technical condition of the collector-drainage network (CDN) and its impact on the salt regime

The efficiency of land reclamation in the Turkistan Region is directly limited by the condition of the drainage infrastructure. The total length of the region's CDN is 5941.34 km, but a significant part of the network is in unsatisfactory condition due to long-term operation (over 40-50 years) and violation of maintenance regulations.

As shown in Figures 1 and 2, open thereby raising collectors are subject to intensive siltation and overgrown with macrophytes (reeds). This reduces their hydraulic efficiency, turning drainage canals into «evaporators», which leads to a rise in the groundwater table in adjacent fields.



Figure 1. Mechanical cleaning of an overgrown drainage collector using an excavator



Figure 2. Mechanical cleaning and restoration of a drainage collector

Of the 1655 vertical wells created earlier, a significant number require major rehabilitation. The period from 1990 to 2002, characterized by a lack of unified Control over hydro-reclamation systems, led to the loss of the design discharge operating mode. The implementation of the WURMIP-2 projects and the activities of the Saryagash SUE «Turan Su»

in the Maktaaral, Zhetysai and Shardara districts have allowed for the stabilization of the water-salt balance. However, without transferring all rehabilitated systems (including 3.3 km of ownerless networks) into state ownership, the risk of re-degradation remains high. The mineralization of drainage water significantly exceeds that of irrigation water, ranging from 1.5 to 5.0 g/l. Chlorides and sulfates dominate in the anion composition, while sodium and magnesium dominate in the cation composition.

The observed chemical composition of drainage water indicates a substantial risk of salt redistribution within irrigated areas, particularly under conditions of insufficient drainage and repeated water reuse. Therefore, maintaining the operational capacity of the collector-drainage network is essential for regulating groundwater levels, limiting salt accumulation in the root zone, and preventing further deterioration of the meliorative state of irrigated lands.

Under the low water availability conditions recorded in 2022, the use of drainage water becomes a necessary measure. However, high salinity requires precise hydrometric accounting using current meters (GR-21M) (as shown in Figures 3 and 4) to prevent secondary soil salinization during re-irrigation.



Figure 3. Zhanaaryk drainage collector affected by siltation and vegetation overgrowth, Saryagash district



Figure 4. Water discharge into the Eastern «Kazakhstan» collector, Shardara district

Thus, the deterioration of the collector-drainage network significantly reduces drainage efficiency and contributes to groundwater rise and secondary soil salinization. Restoration and regular maintenance of drainage infrastructure, together with systematic monitoring of drainage-water quantity and mineralization, are therefore essential for maintaining a stable water-salt regime in irrigated lands.

3.3. Water-salt balance as a management tool

Monitoring results indicate that drainage runoff represents an important component of the water balance in the Syrdarya, Keles, Arys, and Bogen river basins. At the same time, its mineralization and chemical composition determine the potential impact of drainage discharges on the quality of receiving surface waters.

The deterioration and insufficient maintenance of drainage systems since the 1990s have contributed to a rise in the groundwater table and subsequent accumulation of salts in the upper soil horizons. These processes have adversely affected the meliorative state of irrigated lands and increased the risk of secondary soil salinization.

Restoring the productive use of the currently unused 61.8 thousand ha requires more than an increase in irrigation water supply. Rehabilitation of collector-drainage infrastructure, regulation of groundwater levels, and systematic control of the water-salt balance are also required to prevent further land degradation.

The discharge of highly mineralized drainage water into river channels can deteriorate downstream water quality, including in the Kyzylorda Region. Therefore, systematic monitoring of drainage runoff and its mineralization is essential for sustainable reclamation management and has both interregional and, within the wider Syrdarya basin, transboundary significance.

4. Conclusions

Monitoring of irrigated lands in the Turkistan Region during 2021-2022 revealed the principal factors affecting their meliorative state and identified priority measures for reducing land degradation and improving water management.

Extremely high summer temperatures, reaching +45.0°C, together with a severe precipitation deficit during the growing season, form an evaporative soil-water regime. Under these conditions, capillary rise of mineralized groundwater promotes salt accumulation in the upper soil horizons and contributes to secondary salinization over an area of approximately 7.4 thousand ha.

Considerable spatial variability in groundwater mineralization was established across the region. The highest value was recorded in the Sauran district, reaching 80,870 mg/dm³. The predominance of sulfate-chloride water types at highly mineralized sites substantially limits the suitability of such groundwater for direct irrigation.

Of the total 551.4 thousand ha of irrigated land, 61.8 thousand ha remain unused. The main limiting factors include irrigation water shortages, affecting approximately 15.3 thousand ha, and the unsatisfactory technical condition of the collector-drainage network.

The total length of the drainage network is 5941.34 km. Siltation, reed overgrowth, and deterioration of open collectors reduce their hydraulic efficiency and contribute to groundwater rise. The effectiveness of the existing system is further limited by the poor technical condition of a considerable proportion of the 1,655 vertical drainage wells, many of which were constructed 40-50 years ago.

Drainage waters are characterized by mineralization of approximately 1.5-5.0 g/L and predominantly sulfate-chloride composition. Their reuse for irrigation therefore requires systematic monitoring and regulation to reduce the risk of secondary soil salinization and deterioration of surface-water quality.

The high fragmentation of agricultural land, with an average farm size of approximately 4.9 ha, complicates the implementation of coordinated reclamation measures, rehabilitation of irrigation infrastructure, and modern water-saving technologies.

Author contributions

Conceptualization: AZI, VMM; Data curation: AZI, NAB; Formal analysis: AZI, VMM, NAB; Funding acquisition: AZI; Investigation: AZI; Methodology: AZI, VMM; Project administration: AZI, VMM; Resources: AZI, VMM; Software: AZI, NAB; Supervision: AZI; Validation: AZI; Visualization: AZI, NAB; Writing – original draft: AZI; Writing – review & editing: VMM, NAB. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Acknowledgements

The authors sincerely thank the reviewers for their constructive comments and valuable suggestions, which helped improve the quality of the manuscript.

Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Түркістан аймағында суармалы жерлердің мелиоративтік жағдайын кешенді бақылау тұрақты суды пайдаланудың негізі ретінде

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Аңдатпа. Су ресурстарының тапшылығының артуы жағдайында суармалы жерлерді кешенді мемлекеттік бақылау ерекше маңызды. Зерттеу Қазақстан Республикасы Ауыл шаруашылығы министрлігі мен Оңтүстік Қазақстан гидрогеологиялық және мелиоративтік экспедициясының деректеріне негізделген. Жұмыстың мақсаты - Түркістан аймағындағы жерлердің нақты мелиоративтік жағдайын бағалау, жер асты суларының деңгейі мен тұздылығының динамикасын талдау және топырақтың деградациясының себептерін анықтау. Мониторинг 550 000 гектардан астам аумақты қамтиды және зертханалық деректерді және гидрогеологиялық бақылауларды жүйелеуді қамтиды. Зерттеу нәтижелері дренаждық жүйелерді қалпына келтіру және суды пайдалануды оңтайландыру бойынша ұсыныстарды негіздеуге мүмкіндік береді. Зерттеу нәтижелері климаттың өзгеруі жағдайында аймақтағы ауыл шаруашылығы секторының тұрақты дамуына және азық-түлік қауіпсіздігін арттыруға ықпал етеді.

Негізгі сөздер: жерлердің мелиоративтік жағдайы, суармалы жерлер, су ресурстары, мемлекеттік мониторинг, гидрогеологиялық бақылаулар.

Комплексный мониторинг мелиоративного состояния орошаемых земель как основа устойчивого водопользования в Туркестанской области

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Аннотация. В условиях растущего дефицита водных ресурсов особое значение приобретает комплексный государственный мониторинг орошаемых земель. Исследование базируется на данных Министерства сельского хозяйства РК и Южно-Казахстанской гидрогеолого-мелиоративной экспедиции. Целью работы является оценка фактического мелиоративного состояния земель Туркестанской области, анализ динамики уровня и минерализации грунтовых вод, а также выявление причин деградации почв. Мониторинг охватывает площади свыше 550 тыс. га и включает систематизацию данных лабораторных исследований и гидрогеологических наблюдений. Результаты работы позволяют обобщать рекомендации по восстановлению дренажных систем и оптимизации водопользования. Сформированные выводы способствуют устойчивому развитию аграрного сектора и повышению продовольственной безопасности региона в условиях климатических изменений.

Ключевые слова: мелиоративное состояние земель, орошаемые земли, водные ресурсы, государственный мониторинг, гидрогеологические наблюдения.

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<https://doi.org/10.51301/ejsu.2026.i4.05>

Rationale for the development of large-scale underground water storage systems in Central Kazakhstan using managed aquifer recharge

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Abstract. This paper presents a rationale for typical artificial groundwater recharge schemes, considering the physical, geographical, and hydrogeological conditions of large underground reservoirs in Central Kazakhstan. The aim of the paper is to analyze modern aquifer recharge methods and assess their effectiveness and applicability depending on reservoir characteristics, the availability of water sources, and the region's water demand. The paper examines various technological schemes for artificial groundwater recharge and measures to regulate filtration processes, assessing their technical and economic feasibility. The obtained results allow for the development of recommendations for the optimal use of the region's water resources, ensuring a sustainable water supply, and mitigating the negative impact on natural ecosystems. Furthermore, the paper emphasizes the importance of an integrated approach to water use planning that considers both geological and socioeconomic factors.

Keywords: groundwater, artificial recharge, aquifers, technological schemes, Central Kazakhstan, hydrogeology, water demand.

Received: 03 June 2026

Received in revised form: 07 August 2026

Accepted: 17 August 2026

Available online: 31 August 2026

1. Introduction

Rational use of groundwater is a key factor in ensuring sustainable water supply and preventing the degradation of natural ecosystems. Managed aquifer recharge (MAR) is considered an effective tool for increasing aquifer resources, regulating filtration processes, and meeting water needs in arid and semi-arid regions [1, 2].

The effectiveness of MAR is determined by a combination of physical, geographical, and hydrogeological conditions, including the geomorphological structure of the territory, the lithological composition of rocks, the filtration properties of the vadose zone, the groundwater regime, as well as climatic parameters (precipitation, temperature, evaporation), and the characteristics of the hydrographic network [3-5].

Managed aquifer recharge (MAR) and aquifer storage and recovery (ASR) are widely used in various countries worldwide, including Europe, the United States, Israel, and Australia [1]. The main applications of this technology include ensuring water supply in resource-scarce conditions, creating strategic water reserves, preventing aquifer salinization, and improving water resource management [2, 3]. Surface water, including flood runoff, can be used as recharge sources, which is especially relevant for arid areas [4].

The artificial groundwater recharge method is based on increasing the water inflow into an exploited aquifer throughout the year or during individual seasons. This is

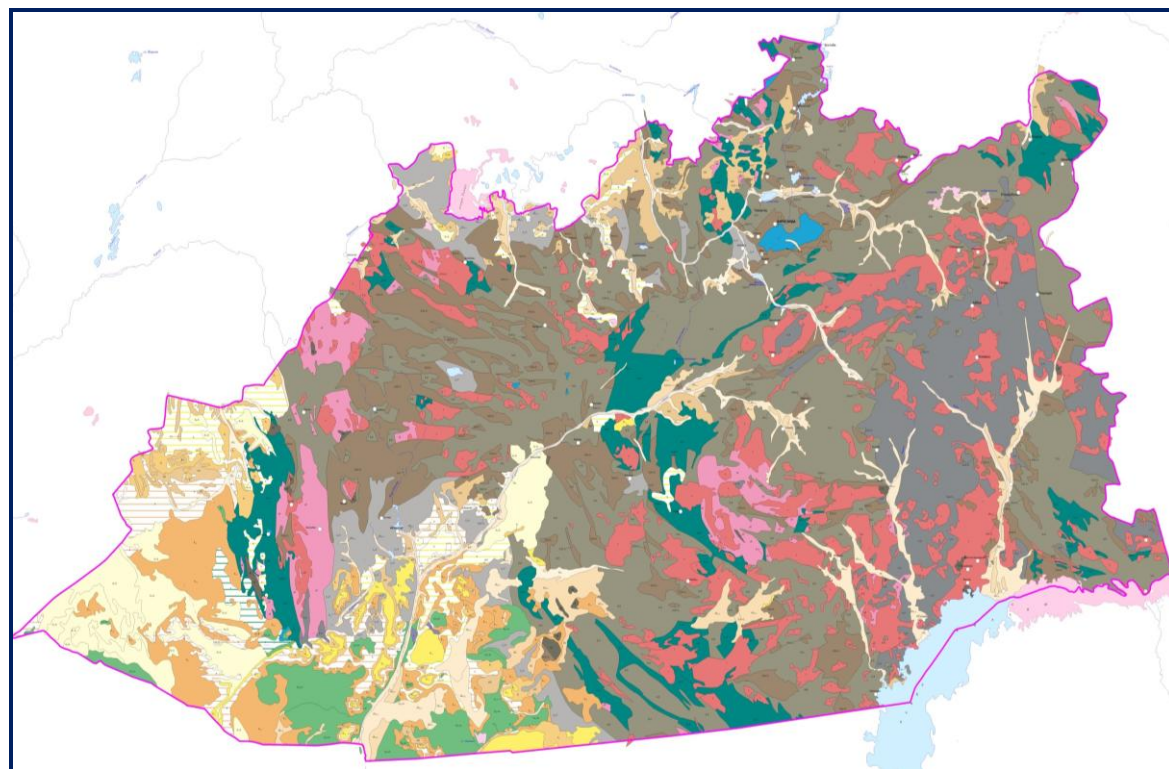
achieved through surface water infiltration through special structures (pools, canals, absorption wells, etc.) or by temporarily flooding natural depressions.

This method addresses a number of important issues, primarily in the area of domestic and drinking water supply, and also contributes to environmental improvements. Artificial recharge makes it possible to regulate the hydrogeological regime during water withdrawal, considering both the quantity and quality of water at the recharge source.

Furthermore, the accumulation of water in the aquifer and the presence of infiltration structures make it possible to shut off the water supply if necessary, for example, if its quality deteriorates (increased turbidity, contamination, odors, etc.), thereby reducing the risk of groundwater contamination.

Storing groundwater during periods of high-water levels increases the reliability of water supply, especially for alluvial horizons, and helps avoid interruptions in water supply during low-water periods.

Central Kazakhstan is characterized by a distinctly continental arid climate, complex, low-hill terrain, and a poorly developed river network (Figure 1). The region's rivers have a pronounced seasonal regime, with up to 80-90% of annual runoff occurring in the spring [6, 7]. Furthermore, the alluvial sediments of river valleys have high filtration capacity, creating productive conditions for groundwater infiltration and accumulation [6].



AQUIFERS AND AQUIFER COMPLEXES

aQ_{iv}	Aquifer of modern alluvial deposits. Sands, sandy loams, loams, pebble deposits, gravel-pebble deposits
aQ_{iv-v}	Aquifer of Upper Quaternary-modern alluvial deposits. Sands, sandy loams, loams, pebble deposits, gravel-pebble deposits
aQ_{iv}	Aquifer of Upper Quaternary alluvial deposits. Sands, sandy loams, loams, pebble deposits, gravel-pebble deposits
$adQ_{iv}+vQ$	Aquifer of Upper Quaternary alluvial-deeltaic deposits and the overlying aeolian deposits. Sands, sandy loams, loams
aQ_{iv-iv}	Aquifer of Middle-Upper Quaternary alluvial deposits. Sands, sandy loams, gravel-pebble deposits, loams
aQ_{iv}	Aquifer of Middle Quaternary alluvial deposits. Pebble deposits, gravel-pebble deposits, sands, sandy loams, loams
aQ_{iv}	Aquifer of Lower Quaternary alluvial deposits. Sands, gravel-pebble deposits, conglomerates, sandy loams, loams
fgQ_{iv}	Aquifer of Lower Quaternary fluvioglacial deposits. Boulder-pebble and pebble deposits with a sandy-clayey matrix and sand lenses
apQ	Aquifer complexes of Quaternary deposits of various origins (apQ , fgQ , dpQ , mQ , $mQ+vQ$). Boulder-pebble and gravel-pebble deposits, sands, interbeds of loams and clays, gus-rubble deposits with a sandy matrix, sandy loams, silts
N_2-Q	Aquifer complex of Pliocene-Quaternary deposits. Sands, sandstones, gravelstones with interbeds of silts, sandy loams, and clays
N_2	Aquifer complex of Pliocene deposits. Gravel-pebble deposits, less commonly boulder-pebble deposits, variably grained sands, sandy loams, loams
N_{2sr}	Aquifer of Pliocene Syrt deposits. Sands containing pebbles and loams with clay interbeds (Precaspian Depression)
N_{2-2}	Aquifer complex of Miocene-Pliocene deposits. Sands and gravel-pebble deposits interbedded with loams and sandy loams
N_1	Aquifer of Miocene deposits. Interbeds of sands and gravel-pebble deposits within sandy loams and clays; limestones, marls, gypsum, and sandstones with clay interbeds (Ustyurt and Mangyshlak)
P_2-N_1	Aquifer complex of Oligocene-Miocene deposits. Alternating sandstones, sands, gravelstones and conglomerates with clays, argillites, and siltstones
P_2	Aquifer of Oligocene deposits. Sands, sandstones, gravelstones, clays, sandy loams
P_2^2	Aquifer of Middle Eocene deposits. Variably grained sands and silty sands with clay interbeds
P_{1-2}	Aquifer complex of Paleogene-Eocene deposits. Sands, sandstones, opokas, and siltstones with clay interbeds

K_2	Aquifer complex of Upper Cretaceous deposits. Fine- and medium-grained sands alternating with clays, siltstones, and sandstones
K_1A_2-Sn	Aquifer complex of Upper Turonian-Senonian deposits. Fine- and medium-grained sands with interbeds of clays and siltstones
$K_{1-2}A_1-S$	Aquifer complex of Albian-Cenomanian deposits. Variably grained sands and sandstones interbedded with clays and silts
$K_{1-2}K_2-S$	Aquifer complex of Lower Cretaceous-Cenomanian deposits. Variably grained sands and sandstones, locally clayey, interbedded with clays and silts (Precaspian Depression)
K_2	Aquifer complex of Lower Cretaceous deposits. Variably grained sands with interbeds of clays, silts, and sandstones
J	Aquifer complex of Jurassic deposits. Sands, sandstones, gravelstones, argillites, brown coal
T	Aquifer complex of Triassic deposits. Conglomerates and sandstones interbedded with clays, shales, and argillites
C_2-P	Water-bearing fracture zone of terrigenous Middle Carboniferous-Permian rocks. Sandstones, siltstones, argillites, conglomerates, gravelstones
$C-P$	Water-bearing fracture zone of sedimentary-volcanogenic Carboniferous-Permian rocks. Sandstones, siltstones, conglomerates, tuffaceous sandstones, tuffs, lavas, and tuffs
D_3Jm-C_1	Aquifer complex predominantly composed of Famennian-Lower Carboniferous fractured and karstified carbonate rocks. Limestones, dolomites
D_2-C_1	Water-bearing fracture zone of terrigenous Upper Devonian-Lower Carboniferous rocks. Sandstones, shales, siltstones, gravelstones
$S-D$	Water-bearing fracture zone of volcanicogenic-sedimentary Silurian-Devonian rocks. Porphyries, tuff breccias, tuffs, sandstones, siltstones, clayey-siltaceous shales
$C-O_2$	Aquifer complex predominantly composed of Cambrian-Middle Ordovician fractured and karstified carbonate rocks (Maly Karatau Basin). Limestones, dolomites
$C-O_1$	Water-bearing fracture zone of volcanicogenic-sedimentary Cambrian-Ordovician rocks. Lavas, tuffs, sandstones, siltstones, tuffaceous sandstones, jaspers, shales
PZ	Water-bearing fracture zone of undivided Paleozoic rocks. Sandstones, siltstones, shales, tuffs, conglomerates, tuffaceous sandstones, gneisses, amphibolites
pC	Water-bearing fracture zone of metamorphosed Precambrian rocks. Shales, quartzites, jaspillites, gneisses
Y	Water-bearing fracture zone of predominantly granitoid intrusive rocks of various ages. Granites, granodiorites

LOCAL AQUIFERS AND AQUIFER COMPLEXES

Local Upper Pliocene-Lower Quaternary ($N_2^1-Q_1$), Upper Neogene-Quaternary (N_2-Q_1), Quaternary (aQ_{iv} , aQ_{iv-iv} , aQ_{iv} , dpQ , fgQ , adQ), Neogene (N_1 , N_2), Upper Paleogene-Lower Neogene (P_2-N_1), Paleogene (P_2 , P_1 , P_2-N_1), and Cretaceous (K_{1-2} , K_2) aquifers and aquifer complexes. Interbeds and lenses of sands, gravelstones, and sandstones within clays and siltstones; marls, dolomites, and argillites.

The color and geological index correspond to the age of the water-bearing rocks.

LOCAL AQUIFERS AND AQUIFER COMPLEXES

HYDROLOGICAL

- Seas, lakes
- Rivers
- Intermittent river section
- Freshwater and brackish lakes
- Saline lakes

HYDRAULIC STRUCTURES

- Reservoirs

OTHER SYMBOLS

- Administrative region boundaries
- Cities
- Astana – capital of the Republic of Kazakhstan

Figure 1. Hydrogeological map of Central Kazakhstan

The choice of technological schemes for artificial replenishment of groundwater reserves is determined by the presence and characteristics of aquifers, the availability of replenishment sources, the current and future needs of the region for water supply, as well as the economic efficiency of the implemented measures [1, 4, 5].

The use of zoning of the territory according to the conditions of artificial replenishment of groundwater reserves

allows us to take into account the spatial heterogeneity of hydrogeological conditions and justify the choice of the most effective solutions for groundwater resource management.

The aim of this study is to substantiate large-scale underground water storage systems in Central Kazakhstan by assessing hydrogeological conditions, zoning the territory for managed aquifer recharge, and selecting appropriate recharge schemes.

2. Materials and methods

The territory of Central Kazakhstan is a mountainous and folded region within which unconfined fissure waters with shallow circulation are widespread. They are confined to the fractured zone of volcanogenic-sedimentary complexes of pre-Paleozoic and Paleozoic rocks [8].

Fracture-karst waters of Devonian-Carboniferous carbonate rocks are also widespread, forming numerous brachyanticline and synclinal structures [8, 9]. Each of such structure represents a unique groundwater deposit, containing significant volumes of water resources [2, 3]. Majority of Central Kazakhstan is represented by a mountainous, folded region dominated by shallowly circulating, unconfined fissure waters confined to the open fracture zone of volcanogenic-sedimentary complexes of pre-Paleozoic and Paleozoic rocks, including effusive, intrusive, terrigenous-sedimentary, and metamorphic formations. Good rock exposure facilitates active water exchange and the formation of fresh, slightly brackish, and brackish waters.

Fracture-karst waters of Devonian-Carboniferous carbonate and terrigenous rocks are also widespread, forming numerous small brachyanticline, synclinal, and large complex structures. Each of such structure essentially represents a groundwater deposit with significant reserves, particularly in the southwestern part of the region – the Zhezkazgan-Ulatau, Niyaz-Yerementau, and other districts. The high degree of fracturing and karstification of carbonate rocks ensures intensive absorption of precipitation and floodwaters from rivers and streams; in the Zhezkazgan-Ulatau district, effective precipitation accounts for up to 60% of winter-spring runoff. Furthermore, these aquifers can be replenished by surface water from rivers.

A combination of climatic, topographic, geomorphological, and hydrogeological conditions, including the composition of water-bearing rocks and the presence of large hydrogeological reservoirs, creates favorable conditions for artificial groundwater recharge. This creates large underground reservoirs for multiple purposes: for municipal and industrial water supply of large population centers, as well as for agricultural needs.

Taking into account the region's physical and geographical conditions, including geomorphological, geological, hydrogeological, climatic (precipitation), and hydrological (development of the hydrographic network) factors, a zoning of Central Kazakhstan was conducted based on conditions for artificial groundwater recharge. This allows to determine patterns in the hydrogeological environment and serves as the basis for a differentiated assessment of the potential for artificial groundwater recharge. The zoning methodology is based on taking into account a complex of natural and artificial factors affecting the effectiveness of recharge and is used to identify areas with similar or different conditions for artificial recharge of groundwater reserves. The assessment of natural conditions during zoning is carried out in order to identify:

- 1) the recharge object – a natural or artificial collector;
- 2) recharge sources and methods of preliminary water treatment;
- 3) the need for artificial recharge;
- 4) the economic feasibility of artificial recharge of groundwater reserves.

The methodological basis of the study was a comprehensive hydrogeological analysis of the territory, including:

- Analysis of the geological and hydrogeological conditions of the region;
- Study of the lithological composition of water-bearing rocks;
- Filtration properties of rocks (transmissibility coefficients within 300-1000 m²/day);
- analysis of the hydrological regime of rivers.

The following criteria were taken into account in the process of zoning:

1. Availability of natural reservoirs for groundwater accumulation (alluvial valleys, fissure-karst structures);
2. Availability of replenishment sources (surface water, precipitation, flood runoff from the Nura, Kengir, Sarysu, and other rivers);
3. Water resource requirements;
4. Economic feasibility of artificial groundwater replenishment projects

The geomorphological factor was used as the main classification feature for zoning, allowing to establish the relationship between relief forms, lithological composition of rocks and groundwater occurrence conditions.

3. Results and discussion

Based on the conducted zoning of Central Kazakhstan according to the conditions of artificial replenishment of groundwater reserves, four groups of territories were identified, characterized by a set of geomorphological, geological, hydrogeological and hydrological indicators that determine the possibility of creating various types of underground reservoirs:

1. Large multi-purpose reservoirs – construction is possible:
 - a) in river valleys with high population density and developed industry;
 - b) in areas with developed carbonate aquifers.
2. Medium-sized reservoirs, primarily for agricultural purposes, located in large buried valleys.
3. Small reservoirs – associated with Paleozoic rocks of varying ages, intended for pasture irrigation.
4. Unpromising areas – territories unsuitable for the construction of groundwater reservoirs, for example, due to geomorphological conditions or the absence of aquifers.

A feasibility study was developed for each group of territories, and a standard technological scheme for artificial groundwater replenishment was proposed.

This study focuses on the justification and design of large underground reservoirs, as these facilities provide strategic water reserves for the integrated water supply of settlements, industrial facilities, and agricultural needs in the region. Large reservoirs are considered a key element of groundwater management, enabling the most efficient use of flood and surface water, regulating filtration processes, and increasing the sustainability of water supply in the arid and semi-arid climate of Central Kazakhstan. Geomorphological, hydrogeological, and hydrological characteristics of the territory, as well as the physicochemical properties of aquifers, are analyzed, enabling the substantiation of optimal technological schemes for groundwater replenishment and predicting their long-term effectiveness.

This group of areas includes the valleys of the region's largest rivers: the Nura, Sherubay-Nura, Taldy, Zharly, Kengir, Sarysu, and several other streams. The water-bearing rocks here are modern and Upper Quaternary alluvial deposits, consisting of inequigranular sands, sandy-gravel-pebble formations with interlayers of clays and loams. The thickness of the alluvial deposits is typically 15-30 m, but in some valley sections it can reach 40-50 m.

A characteristic feature of these deposits is the absence of a consistent aquiclude between the Quaternary formations of different ages, resulting in the formation of a single underground groundwater flow.

The depth of the groundwater table within the river valleys ranges from 1.5 m in floodplain areas to 6-8 m on the above-floodplain terraces.

The filtration properties of alluvial deposits are characterized by high values. Transmissibility coefficients reach 300-1000 m²/day, indicating the high-water content of these rocks.

Groundwater recharge occurs primarily through the infiltration of river floodwaters. Spring floods play a decisive role in shaping the water balance of river valleys. During this period, up to 80-90% of the annual runoff passes through river systems.

These conditions create favorable conditions for the application of artificial groundwater recharge (MAR) technologies.

The most effective technological scheme for this group of regions is an open artificial groundwater recharge system using infiltration basins.

Within this scheme, surface water is directed into special infiltration structures, where it gradually seeps through the alluvial sediments into the aquifer.

Such systems are widely used worldwide and have proven their effectiveness in arid climates [1]. Large groundwater reservoirs in Central Kazakhstan are planned primarily in the valleys of the region's main rivers: the Nura, Sherubai-Nura, Taldy, Zharly, Tunduk, Kengir, Sarysu, and others. The water-bearing rocks are modern and Upper Quaternary alluvial deposits-inequigranular sands, sandy-gravel, and pebble layers interbedded with clays, loams, and sandy loams. The absence of a consistent impermeable layer forms a single underground stream with a depth of 1.5-6 m and a water-bearing rock thickness of 15-30 m; the water capacity varies from 300 to 1000 m²/day. The width of the natural stream is 3-5 km, while large valley widenings reach 10-14 km in diameter and up to 40 km in length, forming isolated deposits with high exploitable reserves. Groundwater is primarily recharged by the filtration of river flood discharges, which account for 80-90% of annual runoff.

Topographic, geomorphological, and hydrogeological conditions, including the composition of water-bearing rocks and the presence of large hydrogeological reservoirs, create favorable conditions for the development of multi-purpose reservoirs for municipal, industrial, and agricultural water supply, including irrigation. For such areas, the use of an open Type I MAR system with infiltration basins is recommended. The typical design involves gravity-fed surface water with a settling basin, infiltration basins, and horizontal water intakes (Figure 2).

In Central Kazakhstan, a promising area is the use of innovative technical solutions for groundwater regulation, which can be integrated into MAR schemes. Below are the most interesting devices and methods applicable to the region's river valleys, including the Nura, Sherubai-Nura, Taldy, Zharly, Tunduk, Kengir, and Sarysu.

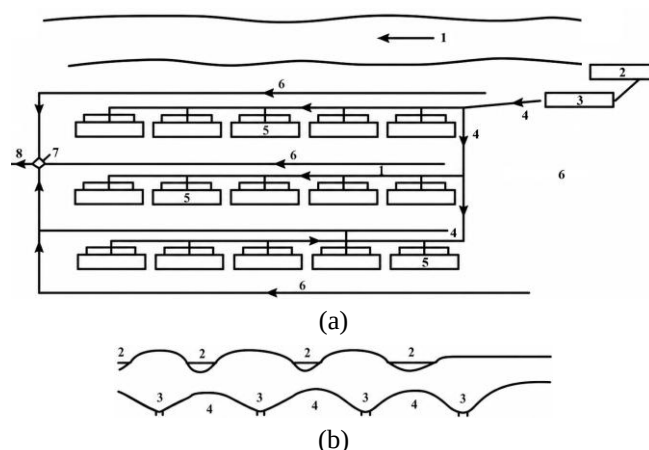


Figure 2. Scheme of the open gravity-flow MAR system, type I: a – plan view: 1 – river; 2 – river water intake; 3 – settling basin; 4 – pipelines supplying water to the infiltration basins; 5 – infiltration basins; 6 – horizontal water intakes (drainage pipes); 7 – collection well with chlorination; 8 – water conduit to the consumer; b – cross-section: 2 – infiltration basins; 3 – drainage pipes; 4 – aquifer

The groundwater accumulation regulating device (patent RU 2621359, Figure 3) pertains to water supply systems. It includes underground water intake wells or boreholes, shut-off and control pipelines, and a watertight barrage that completely seals off the aquifer in thickness and width, creating an underground reservoir.

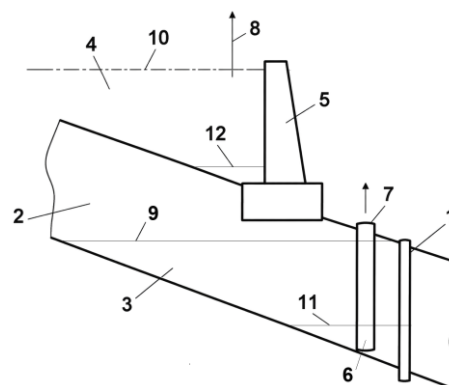


Figure 3. Device for regulating underground water accumulation

Distinctive features from the prototype include:

- the combined location of the above-ground dam and underground barrage within the same section;
- the formation of an underground screen between the piles;
- a water intake well located above the flood level;
- the possibility of mutual water transfer between the underground and above-ground reservoirs;
- reservoir volume control using pipelines;
- minimization of environmental impact.

This combination of features ensures reliable water intake throughout the year, including low-water periods, with efficient use of the underground and above-ground capacity of the mountain river valley (RU 2621359).

Device for regulating freshwater reserves (patent RU 2621268, Figure 4) is used to control underground and surface runoff in mountain river valleys with periodically drying up watercourses, increasing the reliability of water intake and providing the possibility of increasing its volume.

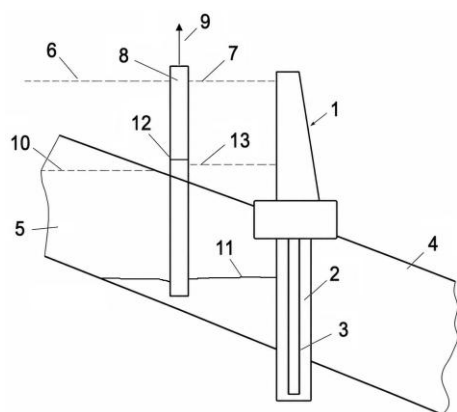


Figure 4. Device for regulating groundwater reserves

Underflow filtering water intake of combined design (patent RU 2518634, Figure 5) is designed for rivers with challenging hydrological conditions. It includes a collection gallery with a filter intake consisting of a metal grate and two rows of flexible filter mats laid along and across the channel flow. This design increases the reliability of the water intake system and allows it to be used for drinking water supply to small towns, enterprises, and as a backup supply for large population centers.

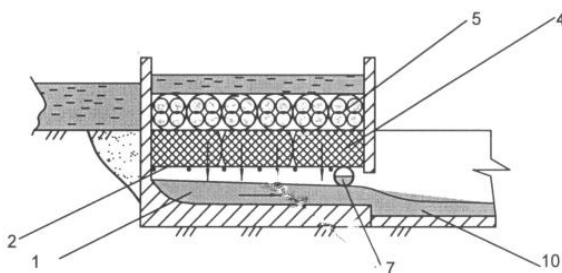


Figure. 5. Underflow filtering water intake

The high-turbidity water treatment unit (patent RU 2321440, Figure 6) is a floating water treatment plant with inclined thin-layer modules, a floating filter bed, water collection channels, and a backwash collector. It ensures the effective removal of suspended solids (up to 5-10 g/l), organic and mineral impurities, and complete water disinfection without the need for additional sedimentation facilities.

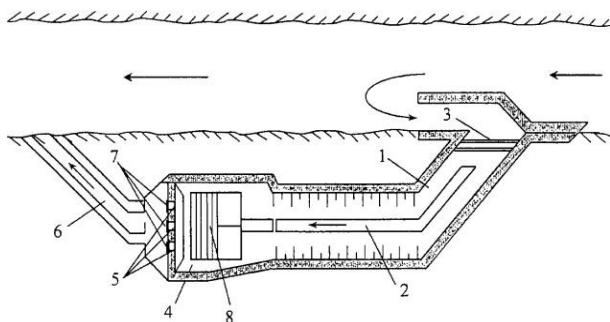


Figure 6. Device for purifying highly turbid waters

Air pumps are installed within the water intake zone, periodically pumping air to form a watertight barrage and an underground reservoir in the upstream pool. As the groundwater level drops, air supply is resumed to maintain the required reservoir capacity.

During the cold season, when groundwater flow accumulates in the unconfined aquifer, a trench is dug in the air pump area, removing the vegetation layer and snow cover. This increases the depth of soil freezing and ensures the reliable operation of the underground reservoir.

Method of regulating groundwater reserves (patent RU 2244785, Figure 7) involves creating an impermeable barrage across the river valley, which partially or completely blocks the aquifer, reduces groundwater flow beyond the barrage, and stores groundwater during high-water periods. During low-water periods, water is released according to demand. Air pumps are installed within the intake zone to control the reservoir's level, and in winter, if necessary, measures are taken to increase soil freezing to maintain water storage capacity.

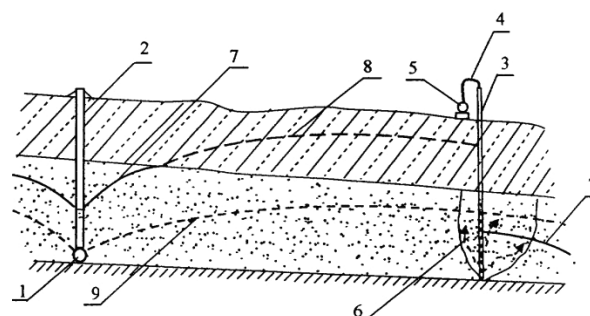


Figure 7. Device for regulating groundwater reserves

The use of such devices allows for the regulation of underground reserves, ensuring a stable water supply for settlements and industrial facilities, and creating strategic water reserves for agricultural irrigation. The process flow is adjusted depending on natural, climatic, and hydrogeological conditions.

For example, at the Zhartas groundwater deposit (Sherubay-Nura River valley), aquifer replenishment is achieved through the filtration of surface runoff, a reservoir, and flood discharges, while water intake capacity is increased by periodically flooding the central section of the infiltration water intake. Similarly, the water intake near Karaganda uses a 13 million m³ infiltration basin fed from the Tonarskoye Reservoir, designed for long-term flow regulation on the Sherubay-Nura River. In the Karaganda region, a 13 million m³ reservoir, functioning as an infiltration basin, is used for artificial groundwater recharge at a water intake used for municipal and industrial water supply. The reservoir is replenished by periodic water releases from the large Tonarskoye Reservoir, a long-term regulated reservoir on the Sherubai-Nura River.

In addition to river valleys, areas of carbonate structures, which are widespread in Central Kazakhstan, particularly in the southwestern part of the region, are promising for artificial groundwater recharge. Most of these structures are located near residential and industrial facilities requiring domestic and drinking water. Many structures have been explored, and their groundwater reserves have been confirmed by the State and Territorial Cadastre of Reserves. For example, the total exploitable reserves of 24 aquifers near the city of Zhezkazgan amount to 441 million m³/year, of which 145 million m³/year are approved by the State Reserves Committee.

The high filtration properties of carbonate rocks ensure efficient groundwater accumulation and flushing, making them suitable for water supply to large facilities. Geological

and hydrogeological studies allow us to accurately determine the marginal boundaries of these structures and calculate the volume of their reservoirs. Aquifer complexes of carbonate and terrigenous rocks of the Devonian-Carboniferous period are identified within the brachyanticline, synclinal, and more complex structures of the Zhezkazgan-Ulatau, Niyaz-Yerementau, and other districts [10]. The areas of aquifers vary from 60 km² (Saryopan) to 850 km² (Zhailmen), with a thickness of water-bearing deposits of 30-50 m, in places reaching 150-200 m.

Groundwater in carbonate structures occurs at depths ranging from 5-10 m at the periphery to 40-50 m in the center of the basins. Groundwater pressure can reach 4-30 m, with piezometric levels ranging from 0.6 to 18 m above the surface. The main reserves are located in the karst zone and limestone fractures, forming subartesian basins with unconfined and confined waters.

The carbonate structures of the Zhezkazgan region are of particular economic importance. Studies on the Aidos brachyanticline, cut by the Karakengir River valley, have shown high filtration of the bottom of the reaches, composed of coarse gravel, crushed rock, and pebbles. The hydraulic relationship between groundwater in alluvial deposits and the surface waters of the river is significant. The Karakengir aquifer and the fissure-karst waters of carbonate rocks provide a replenishment rate of up to $2.75 \cdot 10^6$ m³/day at the Aidos water intake site. Similar results are observed at 12 aquifers near the city of Zhezkazgan, where the total groundwater replenishment volume exceeds 30 million m³/year (≈ 1000 dm³/s).

For the creation of large underground reservoirs, it is recommended to use open, gravity-fed artificial groundwater replenishment systems (Type I) with artificial reservoirs to accumulate flood runoff and recharge groundwater. Direct withdrawal of water from reservoirs for domestic and drinking purposes is impractical due to the high content of suspended solids and the unstable sanitary and bacteriological condition of the water, which requires preliminary treatment. The most suitable for artificial groundwater replenishment are closed brachyanticline basins, such as the Eskulin, Zhanai, Aidos, Sarybulak, Mashuran, and Alaigyr structures, composed of permeable rocks capable of retaining significant volumes of water. Groundwater replenishment can be achieved by using surface water from the Zhezda, Kengir, Sarybulak, Sherubai-Nura, and other rivers.

For type II aquifers, closed process systems employing infiltration wells at depths of up to 15-20 meters and absorption wells at greater depths are rational. These systems can also be used to dilute brackish groundwater in limestone structures. The process system includes preliminary treatment and preparation of river water before injection to improve drinking water quality and reduce suspended solids and microorganisms.

4. Conclusions

In conclusion, the study emphasizes that Central Kazakhstan possesses significant and largely underutilized potential for the implementation of artificial groundwater replenishment technologies. This is due to a combination of favorable hydrogeological conditions, geomorphological features, and the region's arid and semi-arid climate. The conducted

zoning of the territory allowed us to substantiate the identification of zones of varying potential, forming a scientific and practical basis for a differentiated approach to the design and placement of artificial groundwater replenishment systems.

The most promising areas, located along the valleys of major rivers (Nura, Sherubay-Nura, Taldy, Zharly, Tunduk, Kengir, Sarysu, etc.), are characterized by thick alluvial deposits with high filtration properties. These conditions create the preconditions for the formation of significant underground reservoirs, effectively replenished by flood runoff. In turn, type II carbonate structures (Zhezkazgan-Ulatau and Niyaz-Yerementau districts) possess high potential due to their extensive fracturing and karstification, which facilitates intensive infiltration and accumulation of groundwater.

The technological schemes for artificial groundwater replenishment, both open and closed, developed as part of the study allow for the flexible adaptation of engineering solutions to specific environmental conditions. The use of infiltration basins, regulated water intake structures, and absorption wells not only increases groundwater reserves but also manages their regime. Technologies using absorption wells are particularly important for carbonate formations, where targeted dilution of brackish water by injecting fresh surface water is possible.

Furthermore, ensuring high quality of the injected water is a key condition for the effective implementation of artificial groundwater replenishment. The need for preliminary water treatment and preparation is driven by the unstable hydrochemical and sanitary-bacteriological conditions of surface water. The implementation of modern treatment facilities and water quality control systems should be considered a mandatory element of the entire process chain.

Equally important are the organizational and environmental aspects: the successful operation of artificial groundwater recharge systems requires continuous monitoring of the hydrogeological regime, control of filtration and mixing processes, and an assessment of potential aquifer contamination risks. Only by meeting these conditions can the environmental safety and long-term sustainability of water management systems be ensured.

Thus, the study results confirm that the integrated application of artificial groundwater recharge technologies, based on consideration of natural conditions, the use of modern engineering solutions, and strict adherence to environmental requirements, is one of the most promising areas for water supply development in Central Kazakhstan. The implementation of the proposed approaches will improve the reliability of water supply, ensure the rational use of water resources, and create a sustainable basis for the socio-economic development of the region in the context of increasing freshwater shortages.

Author contributions

Conceptualization: AMY, AZZ; Data curation: AMJ; Formal analysis: AMJ; Funding acquisition: AMY; Investigation: AMY; Methodology: AMY; Project administration: AMY; Resources: AZZ; Software: GET, AKA; Supervision: GET, AKA; Validation: AMY, AZZ; Visualization: GET, AKA; Writing – original draft: AMY, AMJ; Writing – review & editing: AZZ. All authors have read and agreed to the published version of the manuscript.

Funding

This research was carried out within the framework of grant funding for scientific and (or) scientific-technical projects for 2024-2026 (Ministry of Science and Higher Education of the Republic of Kazakhstan) No. AP23490816 «Development of technologies for artificial replenishment of groundwater for water supply of settlements, industrial enterprises and irrigation of pastures in small-hill areas of Central Kazakhstan, Republic of Kazakhstan».

Acknowledgements

The authors gratefully acknowledge the editor and reviewers for their insightful comments and constructive suggestions, which contributed to improving the manuscript.

Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Орталық Қазақстанда жасанды толықтыру әдістерін қолдана отырып, ірі жер асты су қоймаларын құрудың негіздемесі

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Андатпа. Бұл мақалада Орталық Қазақстандағы ірі жер асты су қоймаларының физикалық, географиялық және гидрогеологиялық жағдайларын ескере отырып, жасанды жер асты суларын қайта толтырудың типтік схемаларының негіздемесі келтірілген. Мақаланың мақсаты - су қоймаларының сипаттамаларына, су көздерінің қолжетімділігіне және аймақтың суға деген сұранысына негізделген қазіргі заманғы сулы қабаттарды қайта толтыру әдістерін талдау және олардың тиімділігі мен қолданылуын бағалау. Мақалада жасанды жер асты суларын қайта толтырудың әртүрлі технологиялық схемалары және сүзу процестерін реттеу шаралары қарастырылады, олардың техникалық және экономикалық мүмкіндігі бағаланады. Алынған нәтижелер аймақтың су ресурстарын оңтайлы пайдалану, тұрақты сумен жабдықтауды қамтамасыз ету және табиғи экожүйелерге теріс әсерді азайту бойынша ұсыныстар әзірлеуге мүмкіндік береді. Сонымен қатар, мақалада геологиялық және әлеуметтік-экономикалық факторларды ескеретін суды пайдалануды жоспарлауға кешенді тәсілдің маңыздылығы атап өтілген.

Негізгі сөздер: жер асты сулары, жасанды қайта толтыру, сулы қабаттар, технологиялық схемалар, Орталық Қазақстан, гидрогеология, суға деген сұраныс.

Обоснование создания крупных подземных водохранилищ в Центральном Казахстане методами искусственного восполнения запасов

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Аннотация. В работе представлено обоснование типовых схем искусственного восполнения подземных вод с учётом физико-географических и гидрогеологических условий крупных подземных водохранилищ Центрального Казахстана. Цель работы заключается в анализе современных методов восполнения водоносных горизонтов, оценке их эффективности и применимости в зависимости от характеристик коллекторов, наличия источников воды и водопотребности региона. В работе рассмотрены различные технологические схемы искусственного восполнения подземных вод и мероприятия по регулированию фильтрационных процессов, с оценкой их технической и экономической целесообразности. Полученные результаты позволяют разработать рекомендации по оптимальному использованию водных ресурсов региона, обеспечению устойчивого водоснабжения и снижению негативного воздействия на природные экосистемы. Кроме того, работа подчеркивает значимость интегрированного подхода к планированию водопользования, учитывающего как геологические, так и социально-экономические факторы.

Ключевые слова: подземные воды, искусственное восполнение, водоносные горизонты, технологические схемы, Центральный Казахстан, гидрогеология, водопотребность.

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<https://doi.org/10.51301/ejsu.2026.i4.06>

Paleothermicity and hydrocarbons generation modelization in the eastern part of the Precaspian Basin and Pre-Uralian Basin (Kazakhstan)

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Abstract. The Precaspian basin is the main oil province in Kazakhstan, where there are such giant fields as Tengiz, Karachaganak, Astrakhan and Kashagan. In previous works have been identified source rocks associated mainly with the sub-salt complex. However, the issue of such parameters as the depth of the oil window remains unresolved, because the geothermal gradient is low and the studied source rocks have a low maturity. By the study of the organic matter in these sediments and simulation of genesis of hydrocarbons by Petromod 1D software (IES GmbH; now SLB), we wanted to determine the depth range of oil window for essential source rocks. This area is composed of three parts from Devonian to late Carboniferous: the Precaspian Basin subdivided into a basin (claystones, mudstones and calciturbidites) and a platform (limestone and storm sandstones), and the Pre-Uralian Basin (turbidite sandstones). For the studied sector the values of the R_o are low and varies from 0.4 to 0.7 and T_{max} lies between 420 and 445°C. The simulation of the heat flow was calibrated by Vitrinite reflectance with different kinetics according to the type of organic matter – Vandenbroucke et al. (1999)'s model was chosen for the type III (Brent) and for the type II (KCF). The low value of the heat gradient can be compensated by the geological duration during which source rock undergoes the transformation. In the sector studied the phase of generation of oil can correspond to the level of evaluation, corresponding to value 0.5% of R_o and even 0.4% for the algal type or mixed OM II/III. For the studied formations, the major part of hydrocarbons was generated from the maximal phase of burial. We can distinguish four zones in which the depths of the beginning and end of the oil window are different: the western zone (basin) from 4-4.5 km to 7-9 km, the zone of slope and border from 3-3.7 km to 4.5-5 km, the zone of Preuralian basin from 2.8-3.3 to 4.5-5 km, and the eastern zone under the thrust of Ural (Izembet) from 2-2.8 to 3.5-4 km.

Keywords: Precaspian basin, Pre-Uralian Basin, organic matter, simulation, heat flow, petroleum system, maturity, calibration.

Received: 15 April 2026

Received in revised form: 08 August 2026

Accepted: 17 August 2026

Available online: 31 August 2026

1. Introduction

The Precaspian Basin contains substantial prospective hydrocarbon resources, estimated at 10-12 billion tonnes of oil and condensate and 5-6 trillion cubic metres of natural gas. However, the origin of these hydrocarbons remains insufficiently understood because the basin is characterized by a low geothermal gradient and generally low source-rock maturity. Therefore, this study examines the organic matter in the sedimentary succession to identify the principal source rocks and assess their thermal maturity.

The study area comprises three principal geological domains developed from the Devonian to the Late Carboniferous: the basinal zone of the Precaspian Basin, composed predominantly of claystones, mudstones, and calciturbidites; its platform zone, represented by limestones and storm-generated sandstones; and the Pre-Uralian Basin, dominated by turbiditic sandstones. From the Asselian to the Artinskian,

turbidites and claystones accumulated throughout the eastern Precaspian Basin and the Pre-Uralian Basin, followed by evaporite deposition during the Kungurian [1]. These sedimentary successions occur at depths ranging from 1700 to 4500 m.

The samples were analyzed using organic petrography, including maceral analysis and vitrinite reflectance measurements; geochemical methods, including Rock-Eval pyrolysis and extract analysis; and molecular analysis by gas chromatography-mass spectrometry (GC-MS).

To investigate hydrocarbon generation and migration, one-dimensional (1D) basin modeling was performed to reconstruct the evolution of the sedimentary basin during subsidence. This approach enables the positions of the oil and gas windows to be reconstructed throughout the basin's geological history. The modeling was conducted for five wells representing five distinct tectonic zones using version 9 of PetroMod 1D, developed by IES GmbH (now SLB).

The models integrate geological and geochemical data, subsidence and thermal histories, the kinetics of organic matter transformation, and hydrocarbon generation and expulsion. Together, these parameters define the physical framework for simulating the basin's thermal evolution and hydrocarbon generation history. To obtain an acceptable agreement between the modeled and measured thermal indicators, the heat-flow history of each well was calibrated using vitrinite reflectance data, present-day temperatures, and paleotemperatures derived from fluid inclusion microthermometry.

2. Materials and methods

2.1. Principles and background

2.1.1. Model parameters

1D modeling was performed for wells representing different tectonic zones: the western part of the basin, the slope, the platform zone of the Caspian basin, the Cis-Ural zone, and the reverse-thrust junction zone with the Urals under cover, respectively.

The calculations were performed using the PetroMod 1D model. This model was used to reconstruct the subsidence history, thermal evolution of the basin, and hydrocarbon generation. The model was calibrated by changing the heat flow and the degree of erosion until an acceptable agreement between the modeled and actual thermal indicators was achieved.

2.1.2. Physical parameters

The thicknesses and lithologies of the various geological formations were specified for each well. The lithologies used in the calculations were defined as mixtures of pure components with specified volume percentages.

The geological history of the eastern Caspian Basin has been dominated by subsidence, but there were also isolated periods of tectonic inversion at the end of the Bashkirian, the end of the Carboniferous, and the end of the Asselian-Artinskian. The thicknesses and lithologies of the various geological formations were specified for each well (an example of the well representing the middle position within the territory under consideration is given in Table 1).

Table 1. Input table with stratigraphic data for the Loktybai 14G well (Case of a model with small amplitude erosion)

Age	Top, m	Bottom, m	Present thickness, m	Eroded thickness, m	Deposition age, MPa		Erosion age, MPa		Lithology
					from	to	From	to	
Quaternaire	0	10	10		65	0			
Cretaceous	10	500	490		135	65			Clastic
Jurassic	500	630	130		203	135			Clastic
Triassic	630	950	320		250	203			Clastic
Permian Sup.	950	1250	300		274	250			Clastic
Kungurian	1296	3442	2146		277	274			Salt-bearing rocks+clastic
Asselian-Artinskian	3442	3685	243		296	277			Clastic
Upper Carboniferous-Podolskian	0	0	0	130			305	296	Limestones+ evaporites
Myachkovian	3685	3721	36		307	305			Limestones
Lower Podolskian	3721	3813	92		308	307			
Upper Visean	3813	4005	192		337	308			Clastic
Lower Moscovian									
Lower-Middle Visean	4005	5250	1245		360	337 Middle-Devonian			Limestones
Middle-Upper Devonian	5250	6200	950		390	360 Devonian			Clastic
Lower Devonian	6200	6750	550		410	390			Limestones
Lower Paleozoic	6750	7500	750		540	410			Clastic
Basement	7500					540			Clastic-limestone
									Volcanic, metamorphic rocks

The lithologies used in the calculations were defined as mixtures of pure components with specified volume percentages. The geological history of the eastern Caspian Basin has been dominated by subsidence, but there were also isolated periods of tectonic inversion at the end of the Bashkirian, the end of the Carboniferous, and the end of the Asselian-Artinskian.

2.1.3. Thermal indicators of the model

The thermal markers used in this study are vitrinite reflectivity (VR), current temperatures and fluid inclusion entrapment temperatures.

Thermal history reconstructions are based on vitrinite reflectance measurements (VR, % Rr). The VR measurements were primarily performed on samples from potential source rocks of the Visean, Serpukhovian-Moscovian, and Asselian-Artinskian successions. In general, the measured VR values are consistent with previously reported data for the eastern

part of the Precaspian Basin [2]. The values are relatively low and generally do not exceed 0.7%. Only the reverse-thrust zone beneath the allochthonous strata shows VR values in the range of 1-1.25. Thermal history was reconstructed based on these parameters.

For one-dimensional modeling, wells with a sufficient number of vitrinite reflectance (VR) measurements over the investigated depth intervals were selected. Where direct VR measurements were unavailable, three types of maturity proxies were used: VR-equivalent values derived from non-vitrinite macerals, such as alginite and tasmanite; VR values estimated from the methylphenanthrene index (MPI-1); and VR values estimated from Rock-Eval T_{max} . The latter two were calculated using the corresponding empirical relationships between MPI-1 or T_{max} and vitrinite reflectance.

The measured VR values were plotted against depth for each well and compared with the corresponding vitrinite

reflectance profiles simulated using the Easy%Ro model

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2.1.4. Hydrocarbon genesis modeling

This study also considers the conditions of hydrocarbon formation. The model uses parallel-reaction kinetic models to simulate hydrocarbon generation (oil and gas) and includes the secondary cracking of compounds formed during primary cracking. These reactions are described by the Arrhenius Equation (1) and are assumed to follow first-order kinetics:

$$\frac{dX}{dt} = X A_0 \exp\left(-\frac{E_a}{RT}\right), \quad (1)$$

where X is the fraction of the substance reacted; A_0 is the pre-exponential factor, s^{-1} ; E_a is the activation energy, cal/mol; R is the universal gas constant; T is the absolute temperature, K; t is time, s.

Equation (1) can also be written in differential form as:

$$dX = X A_0 \exp\left(-\frac{E_a}{RT}\right) dt, \quad (2)$$

Knowing the change in temperature with time, this equation allows one to calculate the fraction of reacted substance in a given time interval. Most modern kinetic models use distributions of activation energies, but with a single pre-exponential factor. Each fraction is assigned a fraction of the original carbon (IH) determined for the reference sample.

Thus, for the same thermal history and a given activation energy, the fraction of reacted substance can be determined. Models with parallel reactions also allow the distribution of part of the IH to different compounds, which makes it possible to quantitatively estimate the number of compounds generated (oil, gas, etc.) during kerogen cracking.

Numerous kinetic models have been reported in the literature [4]. However, whenever possible, the model should incorporate kinetic parameters specific to the source rocks under investigation.

This study focuses on the different phases of hydrocarbon generation and the possibilities of secondary cracking. The quantitative aspect is considered only indicatively.

2.1.5. Thermal regime of the basin

According to **Ошибка! Источник ссылки не найден.** the threshold for the onset of oil formation depends on the geothermal gradient, depth and time of burial. The temperature at which oil begins to form varies from 50°C in Paleozoic basins to 115°C in Mio-Pliocene deposits. The time of oil generation also varies: the main phase may follow the deposition of source rocks with a delay of several million to 300 million years.

The temperature corresponding to the onset of the oil window decreases from approximately 120°C for 12-million-year-old deposits to 60-62°C for deposits aged 180-359 million years. This relationship is expressed as:

$$T = 164.4 - 19.39 \ln t, \quad (r = -0.89) \quad (3)$$

where T is the threshold temperature for oil generation, °C; t is geological time, million years; r is the correlation coefficient.

An alternative time-temperature relationship is given in [6]:

$$\log_{10} t = \frac{3014}{T} - 6.498 \quad (4)$$

where t is geological time, million years, and T is the absolute temperature, K.

These equations were used to determine the threshold temperature for the onset of oil generation in different source-rock series. For the Lower-Middle Visean rocks (345.5-334 Ma), the estimated temperatures are 50-51°C according to the Pigott model [7] and 60-61°C according to the Connan model [6]. For the Serpukhovian-Moscovian rocks (326.5-305 Ma), the corresponding temperatures are 52-54°C and 62-63°C, while for the Lower Permian rocks (296-278.5 Ma), they are 55-56°C and 64-65°C. These temperatures were used to estimate the depth of the onset of the oil window in the source rocks of the pre-salt complex. The resulting temperature and depth estimates helped to select the most appropriate kinetic model for the organic matter types and basin conditions.

2.1.6. Kinetic model

Several kinetic models are available in PetroMod 1D. The following criteria were used to select the most suitable models. First, models related to type II or type III organic matter (OM) were selected. PetroMod 1D includes 27 models for type II OM and 10 models for type III OM.

A comparison of the hydrocarbon generation phases obtained using different models showed that the T2(KCF)-CS model of Vandenbroucke et al. (1999) [8] best meets the selection criteria. According to this model, the temperature of oil generation onset varies from 72°C in the Devonian to 63°C at present. The PRV value remains relatively stable from the Devonian to the present (0.45-0.49%). The present-day depth of the onset of the oil window is approximately 2800-3000 m.

The T2(KCF)-CS model of Vandenbroucke et al. (1999) [8] was developed for the Portlandian-Berriasian Elgin Field in the North Sea. The studied Kimmeridge Clay Formation is characterized by the following parameters: type II OM; TOC – 8.2%; HI – 567 mg hydrocarbons/g TOC; T_{max} – 420°C.

In the Kumsai well, type III organic matter occurs in the Sakmarian-Artinskian sediments, whereas mixed type II/III organic matter occurs in the Asselian sediments. The Sakmarian sediments are characterized by TOC – 1.13%, HI – 49 mg/g TOC, and T_{max} – 425°C, indicating type III OM. The Asselian sediments are characterized by TOC – 3.49%, HI – 512 mg/g TOC, and T_{max} – 441°C, indicating type II or mixed type II/III OM.

2.1.7. Current heat flow

Heat flows from the Cenozoic to the present were determined by calibration against present-day temperatures. The results show that the temperature curve in the PetroMod 1D depth-temperature plot depends exclusively on the heat flow during the latest stratigraphic period, which corresponds to the Cenozoic in the present models. The present-day heat flow of 35-37 mW/m² was used as a reference for the paleo-heat-flow evolution curve.

3. Results and discussion

The Rock-Eval analysis identified two groups of kerogen in the slope and basin sediments: type III (humic) kerogen with a low HI (<150 mg/g TOC) in the Permian and Visean sediments, and type II (algal) kerogen with a high HI (>250 mg/g TOC) in the Serpukhovian-Moscovian sediments. Type III kerogen has the lowest oil-generation potential, whereas type II kerogen has the highest.

The Visean, Serpukhovian-Moscovian, and Asselian-Artinskian samples generally show low thermal maturity, with vitrinite reflectance (VR) values below 0.65% and $T_{\max}$ values below 435°C. The VR-depth diagrams show three types of gradients: the lowest in the western part and platform zone of the Precaspian Basin (Figure 1a), intermediate in the Pre-Uralian Basin, and the highest in the eastern suture zone overthrust by the Ural nappes (Figure 1b).

The heat-flow model was calibrated using vitrinite reflectance data. Three periods of erosion were identified in the study area: at the end of the Bashkirian, at the end of the Carboniferous, and before the Kungurian. The estimated erosion thickness ranges from 100 to 700 m. In the suture zone, the thickness of the nappes thrust over the autochthonous deposits of the Pre-Uralian Basin is approximately 4500 m.

The simulated heat-flow values are low in the western part of the Precaspian Basin (15-25 mW/m²) and increase to 40-50 mW/m² in the eastern part of the Pre-Uralian Basin within the suture zone. The maximum heat flow occurred during the period of maximum burial in the Early Permian, reaching 30 mW/m² in the west and 65 mW/m² in the east.

Hydrocarbon generation in the source rocks was simulated using different kinetic models according to the type of organic matter. The models of Vandenbroucke et al. (1999) [8] were selected for type III (Brent) and type II (KCF) organic matter.

The majority of hydrocarbons were generated during burial without any additional thermal event. In the eastern part of the Precaspian Basin (Akjar well), the low heat flow explains why the source rocks are either immature or within the oil window, from the Devonian to the base of the Permian succession (Figure 2).

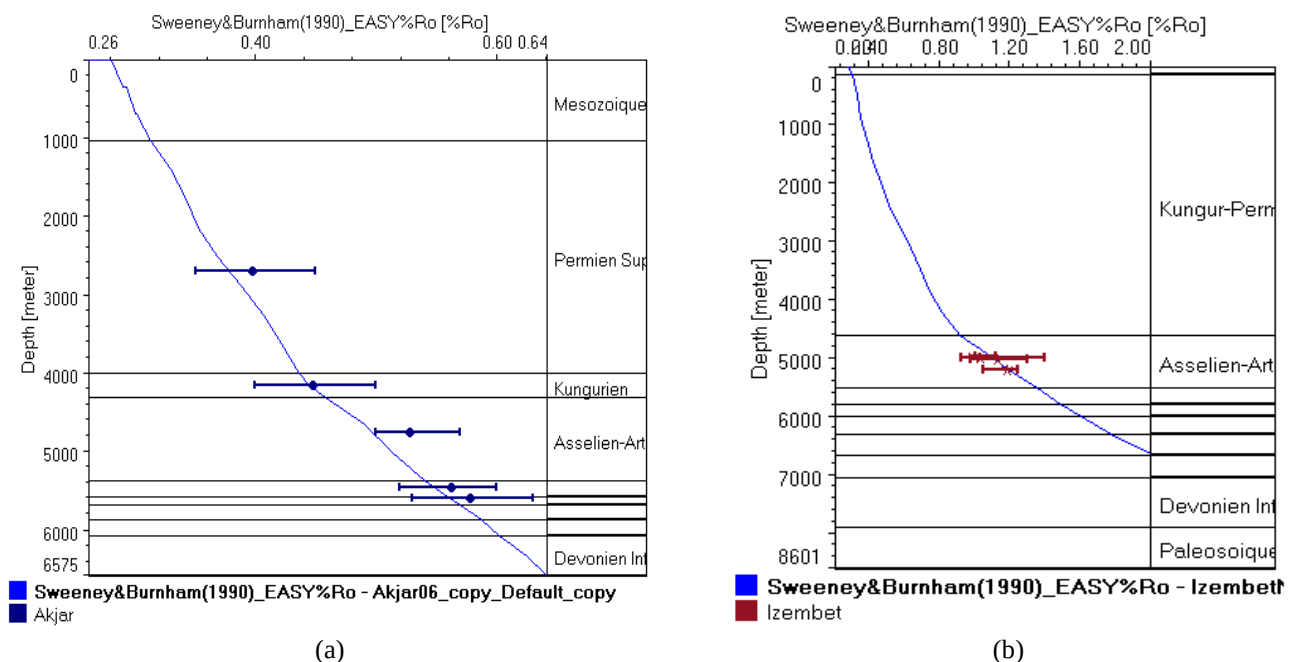


Figure 1. Calibration of the thermal history using vitrinite reflectance data for the: (a) – Akjar well; (b) – Izembet well

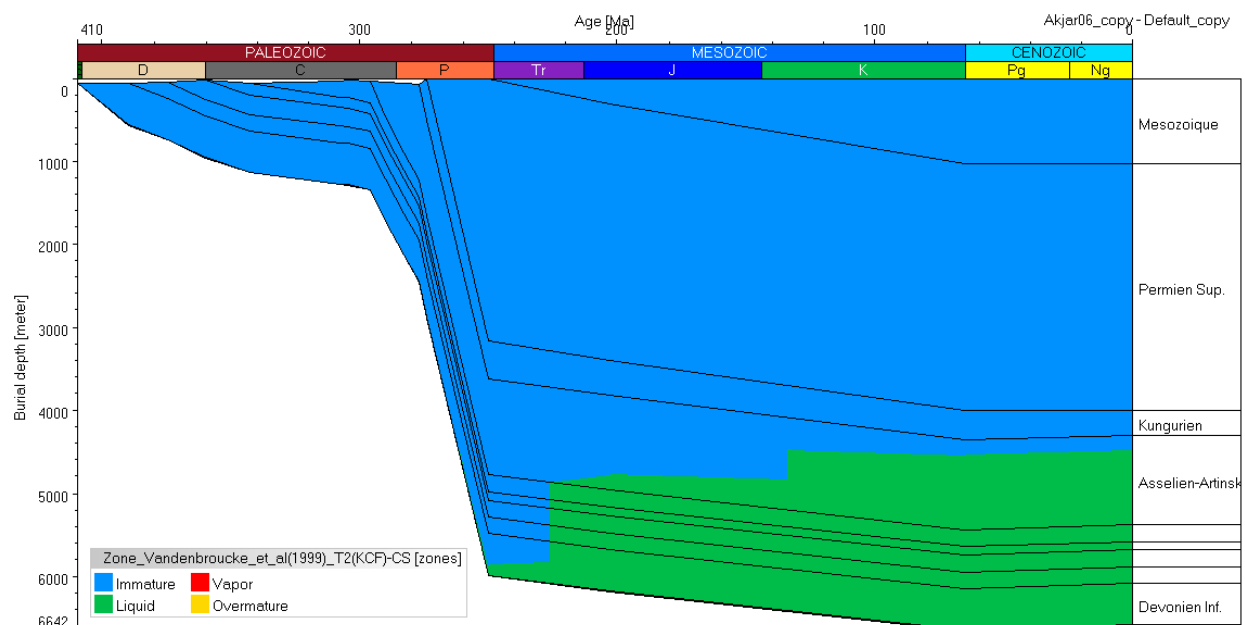


Figure 2. Simulation of hydrocarbon zones in the Akjar well (liquid represents oil)

In the suture zone of the Pre-Uralian Basin, the high heat flow explains the presence of the oil window in the Visean to Early Permian rocks and the wet-gas window in the Devonian rocks of the Izembet well (Figure 3), as well as the dry-

gas window in the Devonian rocks of the Belogorskaya well. The onset of the oil window occurs at depths of approximately 4000-5000 m in the basal part of the Precaspian Basin and 3500-4000 m in the suture zone.

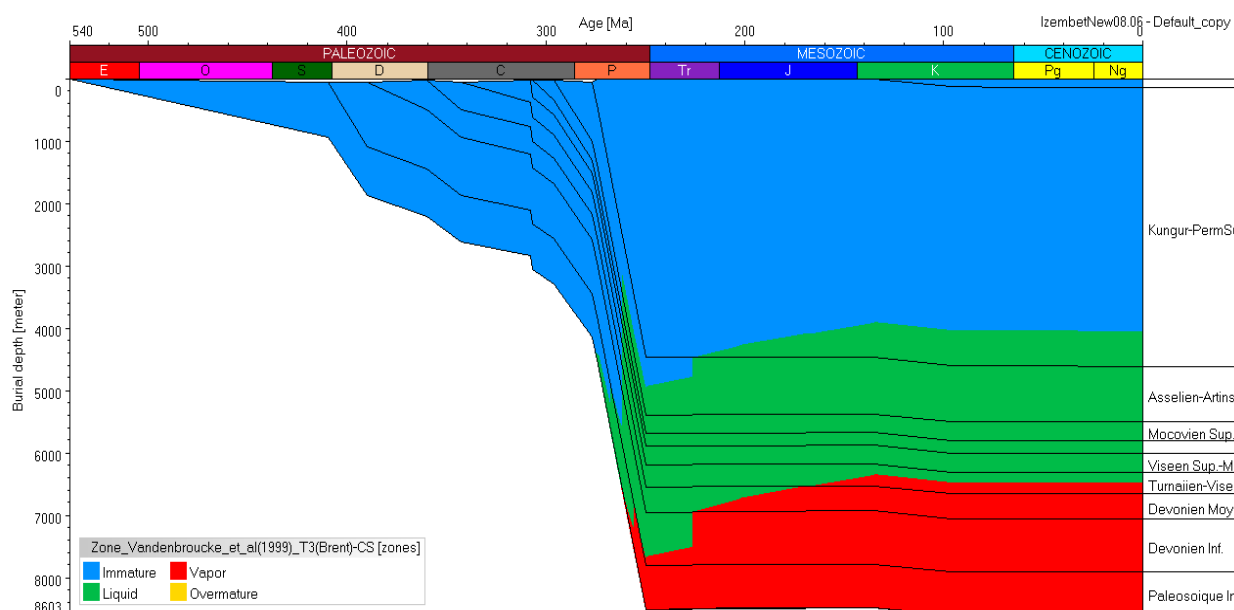


Figure 3. Simulation of hydrocarbon zones in the Izembet well (liquid represents oil; vapor represents wet gas)

The modeling results demonstrate that the thermal maturity and hydrocarbon generation history vary considerably between the tectonic zones of the study area. In the Akjar well, the low heat flow and thermal gradient resulted in the preservation of largely immature source rocks, while oil generation was restricted to the deepest parts of the sedimentary succession (Figure 2). By contrast, the higher heat flow in the Izembet well promoted more advanced organic matter transformation, resulting in oil generation within the Visean to Lower Permian rocks and gas generation within the deeper Devonian succession (Figure 3).

The depths of the oil window estimated from the PRV-depth relationships and the T2(KCF)-CS kinetic model [8] are generally comparable. Its onset is estimated at approximately 2100-3100 m in the overthrust zone (Izembet) and the Pre-Uralian Basin (Baijaryk), 3000-3700 m in the platform (Kumsai) and slope (Loktybai) zones, and 3800-4300 m in the western basal zone (Akjar). The greater depth of the oil window at Akjar is consistent with the lower thermal gradient of approximately 12-20°C/km.

The vertical extent of the oil window follows the same regional pattern. It is smallest in the eastern overthrust zone, increases in the Pre-Uralian, platform, and slope zones, and reaches 5000-5500 m in the western basal zone. Thus, the east-west differences in hydrocarbon generation can be explained primarily by spatial variations in heat flow, burial history, and tectonic setting, without requiring an additional regional thermal event.

4. Conclusions

The modeled heat flow decreases from the eastern overthrust zone toward the central and western parts of the Precaspian Basin. The lowest heat-flow values and thermal gradients were identified in the basal zone, whereas the highest values occurred in the suture zone of the Pre-Uralian Basin.

Thermal gradients within most of the Precaspian Basin generally do not exceed 23-25°C/km. Consequently, the studied source rocks are predominantly immature or within the oil window. This thermal regime is consistent with the predominance of oil and mixed oil-condensate-gas accumulations and the absence of known dry-gas fields in the central and western parts of the basin.

The PetroMod 1D simulations indicate maximum formation temperatures of 69-106°C, whereas fluid-inclusion trapping temperatures range from 82 to 138°C. This difference may reflect the circulation of hot hydrothermal fluids through relatively cooler formations. However, the discrepancy becomes considerably smaller if the fluid inclusions formed during the Kungurian-early Late Permian, when the modeled heat flow was higher.

The onset of the oil window varies from approximately 2100-3100 m in the eastern overthrust and Pre-Uralian zones to 3800-4300 m in the western basal zone, with intermediate depths of 3000-3700 m in the platform and slope zones. These results confirm that regional variations in heat flow and burial history controlled the spatial distribution of the oil and gas windows in the eastern Precaspian and Pre-Uralian basins. The developed models provide a basis for assessing source-rock maturity and identifying prospective hydrocarbon generation zones during further exploration of the region.

Author contributions

Conceptualization: TY, BK, MS; Data curation: TY; Formal analysis: TY, BK, MS; Funding acquisition: TY; Investigation: TY; Methodology: TY; Project administration: TY; Resources: BK, MS; Software: TY; Supervision: TY; Validation: TY; Visualization: TY, BK, MS; Writing – original draft: TY; Writing – review & editing: TY, BK, MS. All authors have read and agreed to the published version of the manuscript.

Funding

This research was carried out within the framework of grant funding from the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan for 2024-2026 project AP23489821 «Geological, geochemical, and microthermometric studies of oil and gas-generating formations and the prediction of new resources in the southeastern margin of the Pre-Caspian Syncline and the Ural Mugodzhazh region».

Acknowledgements

The authors sincerely thank the editor and anonymous reviewers for their time and careful evaluation of the manuscript. Their helpful comments, constructive suggestions, and valuable recommendations contributed to improving the structure, clarity, and overall quality of the paper. The authors also appreciate the reviewers' attention to the scientific content and presentation of the study.

Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Каспий маңы және Орал алды бассейндерінің шығыс бөлігіндегі палеотермиялық жағдайлар мен көмірсутектердің түзілуін модельдеу (Қазақстан)

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Андатпа. Каспий маңы бассейні Қазақстанның негізгі мұнай-газды провинциясы болып табылады, мұнда Теңіз, Қарашығанақ, Астрахан және Қашаған сияқты алып кен орындары орналасқан. Алдыңғы зерттеулерде негізінен тұзасты кешенімен байланысты мұнай түзуші жыныстар анықталған. Алайда мұнай терезесінің тереңдігі сияқты параметрлерді анықтау мәселесі әлі де толық шешілмеген, себебі геотермиялық градиент төмен, ал зерттелген мұнай түзуші жыныстардың жетілу дәрежесі төмен. Осы шөгінділердегі органикалық заттарды зерттеу және PetroMod 1D бағдарламалық жасақтамасы (IES GmbH; қазіргі уақытта SLB) көмегімен көмірсутектердің түзілуін модельдеу негізінде негізгі мұнай түзуші жыныстар үшін мұнай терезесінің тереңдік аралығын анықтау көзделді. Зерттелетін аумақ девоннан кейінгі карбонға дейін қалыптасқан үш құрылымдық-фациялық бөліктен тұрады: Каспий маңы бассейні, ол бассейндік бөлікке (сазды жыныстар, аргиллиттер және кальцитурбидиттер) және платформалық бөлікке (эктастар мен дауылдық құмтастар) бөлінеді, сондай-ақ турбидиттік құмтастардан тұратын Орал алды бассейні. Зерттелген секторда витриниттің шағылу қабілеті Ro төмен мәндермен сипатталып, 0.4-тен 0.7%-ға дейін өзгереді, ал Tmax 420-445°C аралығында болады. Жылу ағынын модельдеу органикалық заттың түріне байланысты әртүрлі кинетикалық модельдерді қолдана отырып, витриниттің шағылу қабілеті бойынша калибрленді: III типті органикалық зат (Brent) үшін Vandenbroucke et al. (1999) моделі, ал II тип үшін KCF моделі таңдалды. Геотермиялық градиенттің төмен мәні мұнай түзуші жыныстардың трансформацияға ұшырайтын геологиялық уақыт ұзақтығымен өтелуі мүмкін. Зерттелген секторда мұнай генерациясы фазасының басталуы шамамен 0.5% Ro жетілу деңгейіне, ал балдырлық немесе аралас II/III типті органикалық заттар үшін тіпті 0.4% Ro мәніне сәйкес келуі мүмкін. Зерттелген формациялар үшін көмірсутектердің негізгі бөлігі максималды көмілу кезеңінде түзілген. Мұнай терезесінің басталу және аяқталу тереңдіктері әртүрлі төрт аймақ бөлінді: батыс аймақ (бассейндік бөлік) – 4.0-4.5 км-ден 7-9 км-ге дейін; беткей және жиектік аймақ – 3.0-3.7 км-ден 4.5-5.0 км-ге дейін; Орал алды бассейні аймағы – 2.8-3.3 км-ден 4.5-5.0 км-ге дейін; Орал жапсарлы жылжуының астындағы шығыс аймақ (Изембет) – 2.0-2.8 км-ден 3.5-4.0 км-ге дейін.

Негізгі сөздер: Каспий маңы бассейні, Орал алды бассейні, органикалық зат, модельдеу, жылу ағыны, мұнай-газ жүйесі, жетілу дәрежесі, калибрлеу.

Палеотермичность и моделирование генерации углеводородов в восточной части Прикаспийского и Предуральского бассейнов (Казахстан)

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Аннотация. Прикаспийский бассейн является основной нефтегазоносной провинцией Казахстана, где расположены такие гигантские месторождения, как Тенгиз, Карачаганак, Астраханское и Кашаган. В предыдущих исследованиях были выявлены нефтематеринские породы, преимущественно связанные с подсолевым комплексом. Однако вопрос определения таких параметров, как глубина нефтяного окна, остается нерешенным, поскольку геотермический градиент здесь низкий, а изученные нефтематеринские породы характеризуются невысокой степенью зрелости. На основе изучения органического вещества в этих отложениях и моделирования генерации углеводородов с использованием программного обеспечения PetroMod 1D (IES GmbH; в настоящее время SLB) была предпринята попытка определить диапазон глубин нефтяного окна для основных нефтематеринских пород. Исследуемая территория включает три структурно-фациальные области, сформировавшиеся в период от девона до позднего карбона: Прикаспийский бассейн, подразделяемый на собственно бассейновую часть (глинистые породы, аргиллиты и кальцитурбидиты) и платформенную часть (известняки и штормовые песчаники), а также Предуральский бассейн, представленный турбидитовыми песчаниками. Для исследуемого участка значения отражательной способности витринита R_o являются низкими и варьируют от 0.4 до 0.7%, а T_{max} находится в диапазоне 420-445°C. Моделирование теплового потока было откалибровано по отражательной способности витринита с использованием различных кинетических моделей в зависимости от типа органического вещества: для органического вещества III типа (Brent) была выбрана модель Vandembroucke et al. (1999), а для II типа – модель KCF. Низкое значение геотермического градиента может компенсироваться продолжительностью геологического времени, в течение которого нефтематеринские породы подвергаются преобразованию. В исследуемом секторе начало фазы генерации нефти может соответствовать уровню зрелости около 0.5% R_o и даже 0.4% R_o для водородослевого либо смешанного органического вещества II/III типов. Для исследованных формаций основная часть углеводородов была сгенерирована в период максимального погружения. Выделены четыре зоны, различающиеся глубинами, начала и завершения нефтяного окна: западная зона (бассейновая часть) – от 4.0-4.5 до 7-9 км; зона склона и борта – от 3.0-3.7 до 4.5-5.0 км; зона Предуральского бассейна – от 2.8-3.3 до 4.5-5.0 км; восточная зона под Уральским надвигом (Изембет) – от 2.0-2.8 до 3.5-4.0 км.

Ключевые слова: Прикаспийский бассейн, Предуральский бассейн, органическое вещество, моделирование, тепловой поток, нефтегазовая система, зрелость, калибровка.

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Publisher: Satbayev University

Registration:

Ministry of Information and Social Development of the Republic of Kazakhstan
No. KZ19VPY00056529 dated 30 September 2022 (re-registration)

Official website: <https://vestnik.satbayev.university/index.php/journal/>

Established in August 1994. Published bimonthly

Editorial Office Address:

Satpayev St., 22, Almaty, Kazakhstan
Tel.: +7(727) 292-63-46