

A Kinetic Study of Humate Extraction from Carbonaceous Waste using Alkaline Reagents

Maksat Kambatyrov

Mukhtar Auevov South Kazakhstan Research University, 160012 Shymkent, Kazakhstan
maksat-kambatyrov@mail.ru

Perizat Abdurazova

Zhanibekov University, 160012 Shymkent, Kazakhstan
abdurazova.perizat@okmpu.kz

Ulzhalgas Nazarbek

Mukhtar Auevov South Kazakhstan Research University, 160012 Shymkent, Kazakhstan
unazarbek@mail.ru

Yerkebulan Raiymbekov

Mukhtar Auevov South Kazakhstan Research University, 160012 Shymkent, Kazakhstan
eplusr@bk.ru (corresponding author)

Received: 13 February 2025 | Revised: 28 February 2025 | Accepted: 9 March 2025

Licensed under a CC-BY 4.0 license | Copyright (c) by the authors | DOI: <https://doi.org/10.48084/etasr.10564>

ABSTRACT

The purpose of this study was to investigate the leaching process of coal waste under various alkaline reagents (NaOH, KOH, and NH_4OH) to obtain humate compounds, and assess the impact of concentration and temperature on reaction kinetics. The Scanning Electron Microscopy with Energy Dispersive X-ray analysis (SEM-EDX), X-ray Diffraction (XRD), and Fourier-Transform Infrared spectroscopy (FTIR) methods were employed to study the physicochemical properties of carbon-containing waste. The Diffusion-Controlled Model (DCM) and Kramers Model (KM) were applied to calculate the reaction rate constants and activation energies. The results demonstrated that KOH exhibited the highest efficiency with a pH value of 13.59 at a 10 % concentration and 60 °C, while the activation energy for NaOH, KOH, and NH_4OH ranged from 11.90 to 15.60 kJ/mol. These findings focus on temperature impact and confirm the applicability of the proposed models for analyzing and predicting the leaching processes of coal waste.

Keywords-carbonaceous waste; humate-containing compounds; diffusion-controlled model; Kramers model; activation energy

I. INTRODUCTION

The concept of sustainable development in industry and agriculture in order to minimize the environmental impact of economic activities, has been widely recognized by scientists and world leaders [1]. A key principle of sustainability is the necessity to fully utilize all substances extracted during the development of deposits and the processing of minerals. The more comprehensively raw materials are employed, the lower the environmental impact is. Coal mining and processing generate large volumes of waste, including overburden, mine rocks, and materials form gravitational and flotation beneficiation, as well as fly ash and slag [2]. The storage of coal waste involves significant capital and operational costs and often requires land that could be used for agriculture, raising serious environmental concerns [3]. Effective coal waste management involves measures to prevent the

spontaneous combustion of coal-containing rocks generated during mining and beneficiation, as well as the reclamation of spoil heaps and their further use. Typical coal waste processing methods include beneficiation, combustion, and gasification. Alternative approaches, such as coking and the production of thermoanthracite, carbon-graphite products, sorbents, and briquettes, virtually do not produce solid waste [4]. In some cases, the final stage of processing results in the production of synthetic motor fuels, chemicals, waxes, and humic preparations [5].

Brown coal waste can be characterized as one of the most promising solutions for coal waste utilization, serving as a secondary raw material for the production of humate-containing products with valuable agricultural applications.

In recent years, studies about humates have gained significant importance due to their various properties in a wide

range of applications, including an increase in agricultural productivity, depleted land restoration, and enhancement of the ecological situation. Particularly, authors in [6] observed that humate utilization in agriculture improved soil structure and increased its fertility and water retention capacity, which is an advancement against climate change and frequent droughts. Plant growth and strengthening plant resistance reinforcement were also promoted to tackle diseases and stresses, reducing the need for chemical fertilizers and pesticides. Authors in [7] focused on the extraction of humates from low-grade brown coal samples mined in the Malkara and Yatagan coal fields in Turkey. The specimens underwent a 72-hour leaching with nitric acid and then were first filtered to separate the insoluble solid particles, and a second filtration took place with Potassium hydroxide for alkalization, resulting in the formation of a nitrohumic acid solution with varying pH levels.

Authors in [8], examined humate extraction by processing lignite from the Kahramanmaraş Afşin-Elbistan region in Turkey. Polymer inclusion membranes were used, allowing for the successful extraction of small sodium humate molecules. Meanwhile, authors in [9] indicated that the colorimetric approach and the CDF method overestimated the humate content, compared to traditional approaches. Similarly, an alternative humate extraction method was developed in [10] using 0.5 M KOH, which exhibited faster processing times and improved efficiency. Authors in [11] applied a hydrothermal method with potassium hydroxide, achieving high humate yields and improved properties, while researchers from China [12] identified the optimal conditions for humate extraction from lignite using Response Surface Methodology (RSM), studying the effects of time, alkali concentration, and temperature. It is clear that processing coal waste and extracting compounds that contain humate is a possible solution in agriculture. More than 33 million tons of waste have been accumulated over the years due to coal mining and processing activities in Kazakhstan, which has substantial coal reserves of about 12 billion tons [13].

The present study aims to investigate the potential conversion of coal waste into humate-containing products that could be utilized in agriculture. The scientific novelty of the research is the examination of the kinetics of humate leaching from carbonaceous waste using DCM and KM, which allowed for the first-time determination of the reaction rate constants and activation energies for various alkalis and their concentrations.

II. MATERIALS AND METHODS

A. Research Objectives

Carbonaceous waste from brown coal mining at the Maikuben deposit (Central Kazakhstan) was utilized as the raw material. The coal waste was collected from the slag heaps near the Shoptikol section of the Maikuben deposit, as displayed in Figure 1. The primary material was preliminarily crushed and ground using a laboratory mill. Sodium, potassium, and ammonium hydroxides (AppliChem GmbH, Germany) were employed as alkaline reagents.



Fig. 1. Map of the location of carbonaceous waste from brown coal mining at the Maikuben Deposit in Central Kazakhstan (Image ©2025 Airbus, CNES/Airbus, Landsat/Copermicus, Maxar Technologies, Map data ©2025).

B. Research Setup

Humate extraction under laboratory conditions was carried out in a reactor equipped with a magnetic stirrer, as shown in Figure 2, and a connected ITAN brand pH meter.

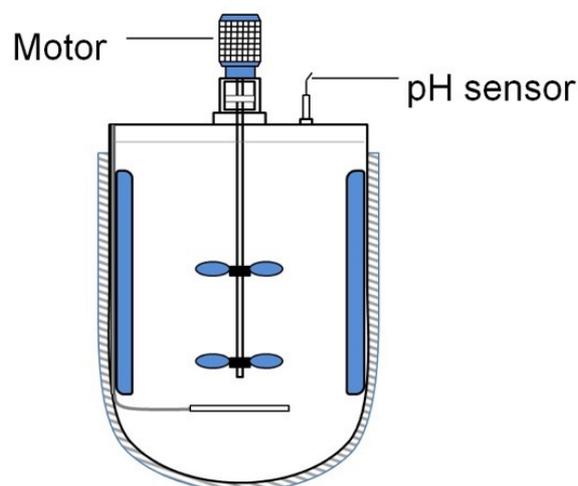


Fig. 2. Experimental setup.

The sample was stirred in a reactor with an alkaline solution for 2-6 hours at a temperature of 30-60 °C. The suspension was then centrifuged at 210 s⁻¹ for 15 minutes, decanted into another container and washed twice with an alkaline solution. The efficiency of the process was evaluated based on the pH indicators of the slurry.

C. Chemical and Instrumental Analysis Methods

The organic composition was measured using a CHN-628 analyzer, by loading the samples into an autosampler in a capsule. After the removal of atmospheric gases, the sample was combusted in a furnace, the remaining gases were passed through a thermoelectric cooler in order to remove moisture, and collected in a ballast container. Equal gas quantities were extracted, with the carrier gas transferring them to infrared cells to determine carbon and hydrogen content, followed by a thermal conductivity cell for nitrogen analysis.

A JSM6490 LV instrument (Japan) was utilized for Energy Dispersive X-ray (EDX) analysis in order to determine the chemical composition of raw materials and products. This method releases energy in the form of X-ray quanta by bombarding the sample with an electron beam, causing the ejection of electrons from the inner shells of the atoms. These photons are then detected and analyzed by energy and intensity.

FTIR spectroscopy was performed using the SHIMADZU IR PRESTIGE-21 (Japan).

XRD analysis was performed on a D8 Advance diffractometer (Bruker, Germany), and the phase composition was determined using EVA software and the PDF-2 database. For statistical data processing, the "Statista" program was utilized.

D. Kinetic Analysis

To examine the kinetic behavior of the alkaline leaching process for coal waste, the DCM (1) and the KM (2) were chosen:

$$1 - \frac{3}{2}(1 - X)^{\frac{2}{3}} + \frac{1}{2}(1 - X) = kt \quad (1)$$

$$X = 1 - \exp\left(-\frac{kt}{\tau}\right) \quad (2)$$

where X is the degree of leaching, k is the reaction rate constant, and t is the time.

The X value was calculated based on the change in pH using:

$$X = \frac{pH_{final}}{pH_{initial}} \cdot 100\% \quad (3)$$

DCM is applied when the rate of the process is limited by the diffusion of reactants through the pores or external layers of

the material. This choice is justified by the fact that in the process of leaching coal waste, the reaction rate may be restricted due to the slow diffusion of alkali through the solid phase of the waste, making the model useful for describing such systems. KM is deployed to describe processes that involve overcoming energy barriers and are characterized by slow kinetics. It is applicable in systems where particle movement or reactions occur through potential barriers under the influence of temperature.

III. RESULTS AND DISCUSSION

A. Composition and Structure of Carbonaceous Waste

The organic composition of carbonaceous waste from the Maikube lignite deposit on a dry, ash-free basis is presented in Table I.

TABLE I. ORGANIC COMPOSITION OF CARBONACEOUS WASTE

C ^{daf}	H ^{daf}	S ^{daf}	N ^{daf}	O ^{daf}
52.53%	3.41%	0.74%	0.89%	42.41%

The elemental composition of lignite is characterized by high carbon content (around 60-70%), hydrogen (approximately 5-6%), and oxygen (20-30%) [14]. Compared to coal mining waste, carbon content is lower (52.5%), which probably means a reduced calorific value and increased mineral impurities or oxidation products. The oxygen is much higher (42.47%), differing from traditional lignites, while the hydrogen content (3.73%) exhibits similar values. The oxygen content is quite high, which may demonstrate a lower calorific value and potentially higher environmental safety.

The results of energy-dispersive analysis are portrayed in Figure 3 and Table II.

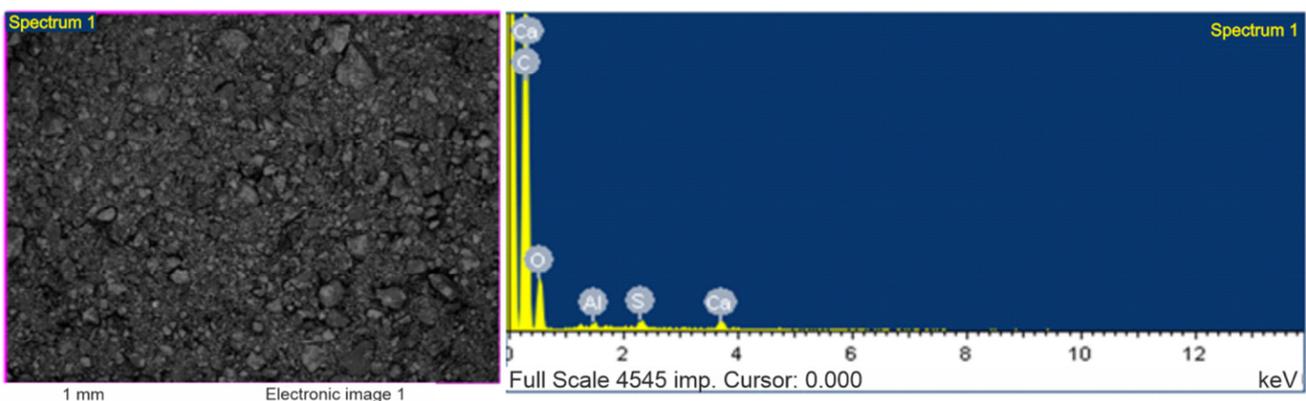


Fig. 3. SEM image and EDX spectra of carbonaceous waste samples.

TABLE II. CHEMICAL COMPOSITION OF THE MINERAL PART OF THE CARBONACEOUS WASTE

C	O	Al	S	Ca
75.11%	23.31%	0.32%	0.57%	0.70%

Figure 3 illustrates the SEM image and EDX spectra of the carbonaceous waste. It is observed that the coal waste samples

have a coarse-grained structure with different mineral fragments. In EDX spectrum, carbon (C) and oxygen (O) are detected as the main elements, with a composition of 75.11% and 23.31%, respectively, suggesting a high level of organic compounds. Additionally, the presence of aluminum (Al) at 0.32%, sulfur (S) at 0.57%, and calcium (Ca) at 0.70% indicates little impurities of mineral components. The XRD

analysis was performed for a more detailed study of the mineral composition of brown coal waste, as illustrated in Figure 4. XRD revealed that the primary mineral phase is quartz (89.3%), as implied by the leading peaks on the diffractogram (e.g., at an angle of 26.67° and a d-value of 3.339 \AA). The

presence of kaolinite (6.9%) and muscovite (3.8%) was also identified by XRD, revealing the existence of aluminosilicates in the samples.

The organic part was analyzed employing FTIR spectroscopy, with the results being displayed in Figure 5.

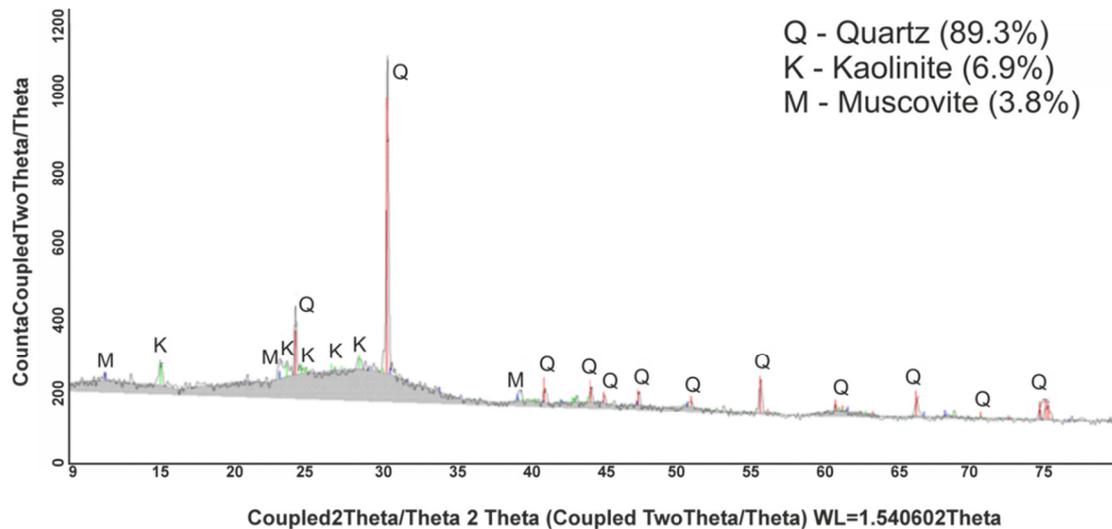


Fig. 4. XRD analysis of carbonaceous waste samples.

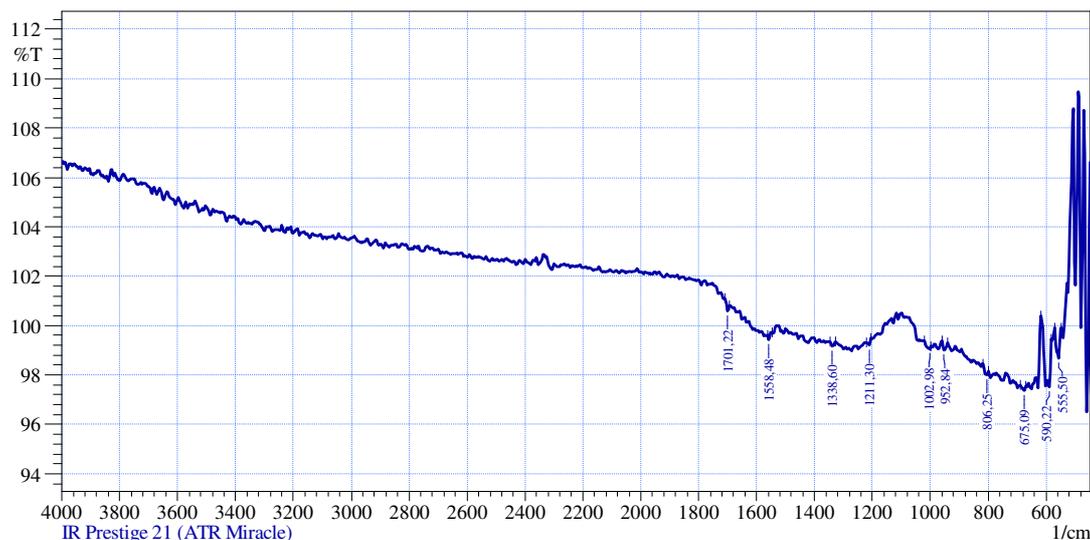


Fig. 5. FTIR analysis of carbonaceous waste samples.

The FTIR analysis revealed carbonyl groups ($\text{C}=\text{O}$) at 1701.22 cm^{-1} and aromatic $\text{C}=\text{C}$ bonds at 1558.46 cm^{-1} (organic substances) [15-16]. The additional peaks at 1338.60 cm^{-1} and 1211.30 cm^{-1} confirm the $\text{C}-\text{O}$ stretching [17]. The peaks at 675.09 cm^{-1} and 590.22 cm^{-1} are related to the inorganic component, like the mineral phases confirmed by the XRD analysis. It is evident that the FTIR results, supplemented by XRD and EDX data, demonstrate both organic and

inorganic components of waste, which is important for the further processing stage.

B. Study of the Leaching Process

The pH value was the primary parameter used to evaluate process efficiency. The key results are presented in Figure 6, demonstrating an effect of alkalis concentration and temperature on the solution pH during the extraction of humates.

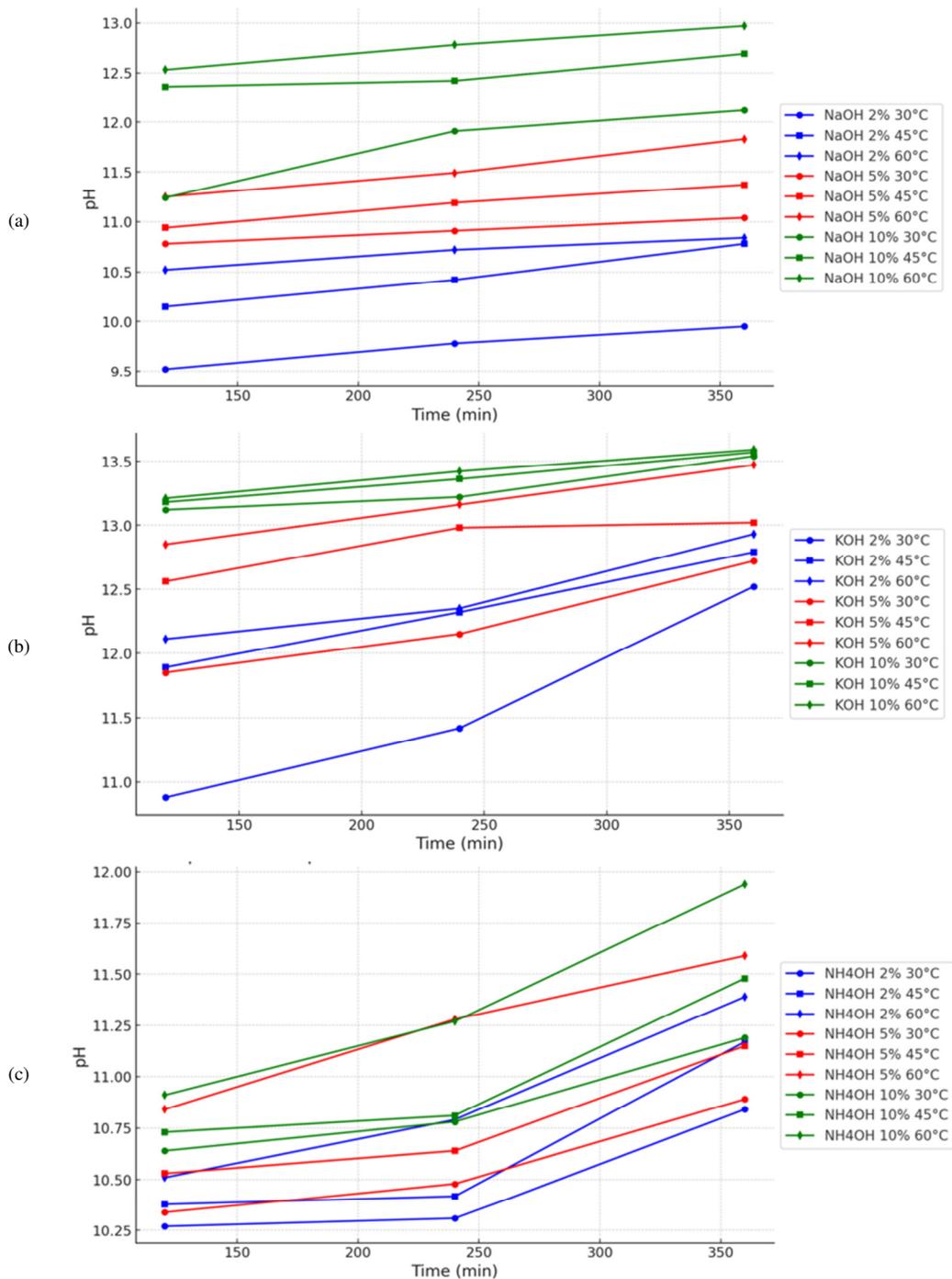


Fig. 6. pH changes during alkaline leaching with: (a) NaOH, (b) KOH, and (c) NH₄OH at different concentrations and temperatures.

Specifically, for NaOH at a 2% concentration, a moderate increase in pH is observed, reaching a maximum value of 10.84 at 60 °C and 360 minutes, implying sufficient but not important alkalinity improvement, as evidenced in Figure 6(a). With the concentration of NaOH being raised to 5%, pH continues to increase, reaching 11.83 under the same conditions, suggesting a stronger alkaline environment, which is beneficial for humate extraction. At 10% NaOH, a pH value of 12.97 at 60 °C and

360 minutes was observed, representing the maximum impact of alkali on the extraction process. These findings reveal that the higher the alkali concentration and temperature are, the more the efficiency of humate extraction is enhanced. This can be explained by the fact that a higher alkalinity promotes more breakdowns of organic components, leading to an increase in the yield of humate-containing compounds [18].

KOH exhibits similar patterns to NaOH, but with higher pH values under comparable conditions, as depicted in Figure 6(b). At a 2% KOH concentration, pH increases to 12.93 at 60 °C and 360 minutes, which is significantly higher compared to NaOH. When the KOH concentration increases to 5%, the pH reaches 13.47, showing further enhancement in alkalinity. The maximum value is observed at 10% KOH (pH = 13.59) under the same conditions. This indicates a more pronounced alkaline effect of KOH, even at a low concentration, which may be attributed to the higher dissociation of hydroxide ions in the KOH solution compared to NaOH [19]. As for NH₄OH, despite an increase in pH with higher concentration and temperature values, its alkaline effect was less obvious compared to NaOH and KOH. At a 2% NH₄OH concentration, as can be seen in Figure 6(c), the pH reaches 11.39 at 60 °C

and 360 minutes (noticeably lower). This may be due to the ammonium nature, which provides weaker alkalinity compared to stronger bases, like sodium and potassium hydroxides. At 5% NH₄OH, the pH increases to 11.59, indicating its limited effectiveness in developing a stable alkaline environment. Once more, the maximum pH values are observed at 10% NH₄OH at 60 °C and 360 minutes, leading to the conclusion that while NH₄OH can increase the solution's alkalinity, its impact is still less significant compared to NaOH and KOH.

C. Study of Kinetic Patterns

The kinetics of the processes were investigated deploying DCM and KM. The reaction rate constants were calculated using (2) and (3), respectively. The obtained results are presented in Tables III–V.

TABLE III. REACTION RATE CONSTANTS FOR SODIUM HYDROXIDE (min⁻¹)

Time (min)	NAOH 2%			NAOH 5%			NAOH 10%		
	30 °C	45 °C	60 °C	30 °C	45 °C	60 °C	30 °C	45 °C	60 °C
DCM									
120	0.0620	0.0661	0.0685	0.0702	0.0713	0.0733	0.0732	0.0805	0.0817
240	0.0450	0.0480	0.0494	0.0503	0.0515	0.0529	0.0549	0.0572	0.0589
360	0.0374	0.0405	0.0408	0.0415	0.0428	0.0445	0.0456	0.0477	0.0488
KM									
120	0.0094	0.0107	0.0116	0.0122	0.0126	0.0135	0.0135	0.0178	0.0187
240	0.0049	0.0056	0.0060	0.0062	0.0066	0.0071	0.0079	0.0090	0.0101
360	0.0034	0.0040	0.0041	0.0043	0.0046	0.0051	0.0055	0.0065	0.0072

TABLE IV. REACTION RATE CONSTANTS FOR POTASSIUM HYDROXIDE (min⁻¹)

Time (min)	KOH 2%			KOH 5%			KOH 10%		
	30 °C	45 °C	60 °C	30 °C	45 °C	60 °C	30 °C	45 °C	60 °C
DCM									
120	0.0709	0.0775	0.0789	0.0772	0.0818	0.0837	0.0855	0.0859	0.0861
240	0.0526	0.0568	0.0569	0.0560	0.0598	0.0606	0.0609	0.0615	0.0618
360	0.0471	0.0481	0.0486	0.0478	0.0490	0.0507	0.0509	0.0510	0.0511
KM									
120	0.0777	0.0849	0.0865	0.0846	0.0897	0.0917	0.0937	0.0941	0.0943
240	0.0815	0.0880	0.0882	0.0867	0.0927	0.0941	0.0944	0.0954	0.0958
360	0.0894	0.0913	0.0923	0.0908	0.0930	0.0962	0.0967	0.0969	0.0970

TABLE V. REACTION RATE CONSTANTS FOR AMMONIUM HYDROXIDE (min⁻¹)

Time (min)	NH ₄ OH 2%			NH ₄ OH 5%			NH ₄ OH 10%		
	30 °C	45 °C	60 °C	30 °C	45 °C	60 °C	30 °C	45 °C	60 °C
DCM									
120	0.0669	0.0676	0.0685	0.0674	0.0686	0.0706	0.0693	0.0699	0.0711
240	0.0475	0.0480	0.0497	0.0483	0.0490	0.0520	0.0497	0.0498	0.0519
360	0.0408	0.0420	0.0428	0.0409	0.0419	0.0436	0.0421	0.0432	0.0449
KM									
120	0.0733	0.0741	0.0750	0.0738	0.0752	0.0774	0.0760	0.0766	0.0779
240	0.0736	0.0744	0.0770	0.0748	0.0761	0.0805	0.0769	0.0772	0.0805
360	0.0774	0.0797	0.0813	0.0777	0.0796	0.0827	0.0799	0.0821	0.0852

Based on the data outlined in Table III, it is evident that for both models, reaction rate constants increase with a rising temperature and alkali concentration. This confirms that both temperature and alkali concentration are crucial factors, affecting the kinetics of the leaching process. In DCM, the reaction rate constants reach maximum values at all time intervals at a temperature of 60 °C for all NaOH concentrations (2%, 5%, 10%). This observation can be related to a more active diffusion process and the release of ions into the solution. For instance, for 10% NaOH at 360 minutes and 60 °C, the reaction rate constant is 0.0488 min⁻¹, which is much

higher than that of 30 °C and 45 °C. Similarly, KM demonstrates an increase in reaction rate constants as the temperature and concentration of NaOH rise, reflecting more intense alkali interaction with coal waste. The highest values are observed at 60 °C, reaching 0.0187 min⁻¹ after 120 minutes, corresponding to the maximum alkaline activity under these conditions.

The same trend is observed for KOH with a rising temperature and alkali concentration, as showcased in Table IV. When compared to NaOH, KOH demonstrates higher

reaction rate constants. For instance, at 120 minutes and a temperature of 60 °C, the reaction rate constant is 0.0861 min⁻¹ (DCM), which exceeds the value for NaOH under the same conditions (0.0817 min⁻¹). This confirms the more pronounced alkalinity of KOH and its higher efficiency in leaching reactions. In KM, the highest reaction rate constants are observed at 10% KOH at 60 °C, where after 360 minutes, a value of 0.0970 min⁻¹ is obtained. This may indicate that KOH provides a more intense interaction with coal waste and, consequently, a more effective release of humate-containing compounds.

The data for NH₄OH concentration are not as high compared to KOH and NaOH. For example, according to DCM at 10% NH₄OH and 60 °C (0.0711 min⁻¹ for 120 minutes), the values are lower than those for NaOH and KOH under similar conditions. This indicates a weaker influence of NH₄OH on the coal waste leaching process, likely due to the lower dissociation of hydroxide ions in the solution. In KM, a similar pattern is detected. The reaction rate constants for NH₄OH increase with a rising concentration and temperature, but they remain reduced compared to those for NaOH and KOH. The highest reaction rate constant for NH₄OH is 0.0852 min⁻¹ at 360 minutes and 60°C for 10% NH₄OH, which is still lower compared to KOH and NaOH. Thus, NH₄OH demonstrates weaker alkaline activity in the leaching process, as confirmed by the lower reaction rate constants calculated using both models.

Based on the obtained reaction rate constants, the activation energies for the three types of alkalis were calculated using the Arrhenius equation [20]. This method allowed determining the effect of temperature on the reaction rate, and evaluating which components most effectively enable the leaching of humate-containing compounds from carbon-containing waste. The results are presented in Table VI.

TABLE VI. CALCULATED VALUES OF ACTIVATION ENERGY

Type of reagent and concentrations	The calculated values of E_a , kJ/mol	
	DCM	KM
NaOH	2%	14.17
	5%	14.37
	10%	14.15
KOH	2%	12.85
	5%	13.98
	10%	14.63
NH ₄ OH	2%	13.52
	5%	13.82
	10%	13.50

DCM assumes that the reaction rate is determined by the diffusion of the reagent to the surface of solid particles, with mass transfer acting as the limiting step [21]. The reaction rate constants increase with a rising temperature and concentration of alkaline solution, as higher temperatures reduce the solution's viscosity. However, they increase the kinetic energy of molecules, enabling faster ions entry and exit. The activation energy values for NaOH, KOH, and NH₄OH, range from 12 to 15 kJ/mol, revealing mass transfer as the primary mechanism [22]. Carbonaceous waste has a porous structure, which can slow down the diffusion process, especially at initial stages.

NaOH and KOH provide a higher rate of diffusion and faster leaching process, while NH₄OH shows lower reaction rate constants and activation energies, resulting in a less efficient diffusion process compared to sodium- and potassium-based alkalis.

On the other hand, the KM mechanism focuses on the probability of overcoming activation barriers in chemical reactions [23]. In the case of leaching humates from coal waste using alkalis, the reaction rate constants increase with a rising temperature and concentration of the solution. This suggests that the likelihood of overcoming the activation barrier increases in the system, leading to a faster reaction with increasing temperature. The activation energy values for NaOH, KOH, and NH₄OH range from 11.90 to 15.60 kJ/mol. For KOH, the activation energy is lower (11.90-13.02 kJ/mol), indicating an easier activation process and faster chemical reactions compared to NaOH. Within this model, the mechanism of humate leaching from coal waste can be described as a process involving an activation barrier, which is determined by the interaction of hydroxide ions (OH⁻) with the surface of the coal waste and the release of humate-containing compounds. In the chemical reaction, overcoming the activation barrier is necessary for breaking bonds in the solid material (coal waste) and forming the products (humates). The higher the temperature is, the more molecules possess sufficient energy to overcome the barrier, and the faster the reaction proceeds [24]. As alkali concentration raises, the number of hydroxide ions increases, enabling diffusion and interaction with active sites on the coal waste surface. This leads to faster activation and higher reaction rate constants. In a similar study [25], an activation energy of 7.69 kJ/mol was identified using Pavlyuchenko's formula, which is notably lower than in the current experiments. This result may suggest that the mechanisms described in involve simpler and faster chemical interactions or possibly occur under different conditions including higher solution concentrations or other temperature regimes that contributed to the acceleration of the processes.

IV. CONCLUSION

The aim of this study was to evaluate coal waste leaching procedures at different alkalis concentrations and temperatures, focusing on the effect of pH. The Scanning Electron Microscopy with Energy Dispersive X-ray analysis (SEM-EDX), X-ray Diffraction (XRD), and Fourier-Transform Infrared spectroscopy (FTIR) methods were employed to examine the physicochemical properties of carbon-containing waste, while two models -the Diffusion-Controlled Model (DCM) and the Kramers Model (KM)- were utilized to observe the reaction kinetics. The experimental results demonstrated that the pH is related to an increasing temperature and alkali concentrations, as it also rises, suggesting a higher rate of leaching and strengthened chemical activity of the alkalis. Additionally, both temperature and alkali concentrations raised the reaction rate constants, indicating that reactions are accelerated with high temperatures. KOH exhibited the highest efficiency with a pH value of 13.59 at a 10 % concentration and 60 °C, while the activation energy for NaOH, KOH, and NH₄OH ranged from 11.90 to 15.60 kJ/mol, which

corresponds to the typical values for diffusion-controlled processes. KM, used to calculate kinetic parameters, also produced reliable results, proving its capability in describing the coal waste leaching processes.

FUNDING

This research is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan, grant number AP19174296.

REFERENCES

- [1] Y. Kassem, H. Camur, and E. G. Ghoshouni, "Assessment of a Hybrid (Wind-Solar) System at High-Altitude Agriculture Regions for achieving Sustainable Development Goals," *Engineering, Technology & Applied Science Research*, vol. 14, no. 1, pp. 12595–12607, Feb. 2024, <https://doi.org/10.48084/etasr.6494>.
- [2] M. Mohanty, D. R. Biswal, and S. S. Mohapatra, "A systematic review exploring the utilization of coal mining and processing wastes as secondary aggregate in sub-base and base layers of pavement," *Construction and Building Materials*, vol. 368, Mar. 2023, Art. no. 130408, <https://doi.org/10.1016/j.conbuildmat.2023.130408>.
- [3] M. Dutta *et al.*, "Environmental assessment and nano-mineralogical characterization of coal, overburden and sediment from Indian coal mining acid drainage," *Geoscience Frontiers*, vol. 8, no. 6, pp. 1285–1297, Nov. 2017, <https://doi.org/10.1016/j.gsf.2016.11.014>.
- [4] B. Smailov and U. Aravind, "Synthesis of humic acid with the obtaining of potassium humate based on coal waste from the Lenger deposit, Kazakhstan," *Green Processing and Synthesis*, vol. 13, no. 1, Jan. 2024, Art. no. 20230150, <https://doi.org/10.1515/gps-2023-0150>.
- [5] A. H. Tchapda and S. V. Pisupati, "A Review of Thermal Co-Conversion of Coal and Biomass/Waste," *Energies*, vol. 7, no. 3, pp. 1098–1148, Mar. 2014, <https://doi.org/10.3390/en7031098>.
- [6] G. Lyons and Y. Genc, "Commercial Humates in Agriculture: Real Substance or Smoke and Mirrors?," *Agronomy*, vol. 6, no. 4, Dec. 2016, Art. no. 50, <https://doi.org/10.3390/agronomy6040050>.
- [7] S. Ozkan and S. G. Ozkan, "Investigation of Humate Extraction from Lignites," *International Journal of Coal Preparation and Utilization*, vol. 37, no. 6, pp. 285–292, Nov. 2017, <https://doi.org/10.1080/19392699.2016.1171761>.
- [8] A. Manzak, C. Kurşun, and Y. Yıldız, "Characterization of humic acid extracted from aqueous solutions with polymer inclusion membranes," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 81, pp. 14–20, Dec. 2017, <https://doi.org/10.1016/j.jtice.2017.10.024>.
- [9] R. T. Lamar and K. H. Talbot, "Critical Comparison of Humic Acid Test Methods," *Communications in Soil Science and Plant Analysis*, vol. 40, no. 15–16, pp. 2309–2322, Sep. 2009, <https://doi.org/10.1080/00103620903111251>.
- [10] J. C. Rocha, A. H. Rosa, and M. Furlan, "An Alternative Methodology for the Extraction of Humic Substances from Organic Soils," *Journal of the Brazilian Chemical Society*, vol. 9, pp. 51–56, Feb. 1998, <https://doi.org/10.1590/S0103-50531998000100010>.
- [11] G. Cheng, Z. Niu, C. Zhang, X. Zhang, and X. Li, "Extraction of Humic Acid from Lignite by KOH-Hydrothermal Method," *Applied Sciences*, vol. 9, no. 7, Jan. 2019, Art. no. 1356, <https://doi.org/10.3390/app9071356>.
- [12] P. R. Wang, H. X. Dai, G. Y. Xu, and B. L. Xu, "Optimization of Research on the Extraction of Humic Acid from Lignite Using Response Surface Methodology," *Advanced Materials Research*, vol. 588–589, pp. 75–79, 2012, <https://doi.org/10.4028/www.scientific.net/AMR.588-589.75>.
- [13] "Coal production in Kazakhstan and major projects," *Mining Technology*, Apr. 06, 2023, <https://www.mining-technology.com/data-insights/coal-in-kazakhstan>.
- [14] B. N. Bowen and M. W. Irwin, "Coal Characteristics," Purdue University, Center for Coal Technology Research, West Lafayette, IN, USA, Oct. 2018.
- [15] M. Giovanela *et al.*, "Chemical and spectroscopic characterization of humic acids extracted from the bottom sediments of a Brazilian subtropical microbasin," *Journal of Molecular Structure*, vol. 981, no. 1–3, pp. 111–119, Sep. 2010, <https://doi.org/10.1016/j.molstruc.2010.07.038>.
- [16] M. Giovanela, E. Parlanti, E. J. Soriano-Sierra, M. S. Soldi, and M. M. D. Sierra, "Elemental compositions, FT-IR spectra and thermal behavior of sedimentary fulvic and humic acids from aquatic and terrestrial environments," *Geochemical Journal*, vol. 38, no. 3, pp. 255–264, 2004, <https://doi.org/10.2343/geochemj.38.255>.
- [17] J. Krumins, M. Klavins, and R. Krukovskis, "Characterisation of humic acids in fen peat," *International Journal of Agricultural Resources, Governance and Ecology*, vol. 16, no. 1, pp. 74–89, Jan. 2020, <https://doi.org/10.1504/IJARGE.2020.107066>.
- [18] T. Rashid *et al.*, "Parametric optimization and structural feature analysis of humic acid extraction from lignite," *Environmental Research*, vol. 220, Mar. 2023, Art. no. 115160, <https://doi.org/10.1016/j.envres.2022.115160>.
- [19] D. W. Smith, "Ionic hydration enthalpies," *Journal of Chemical Education*, vol. 54, no. 9, Sep. 1977, Art. no. 540, <https://doi.org/10.1021/ed054p540>.
- [20] S. A. Ashter, "6 - Mechanics of Materials," in *Thermoforming of Single and Multilayer Laminates*, Amsterdam, Netherlands: Elsevier, 2014, pp. 123–145.
- [21] D. S. Grebenkov, "Diffusion-Controlled Reactions: An Overview," *Molecules*, vol. 28, no. 22, Jan. 2023, Art. no. 7570, <https://doi.org/10.3390/molecules28227570>.
- [22] U. Germgård, "The Arrhenius Equation is Still a Useful Tool in Chemical Engineering," *Nordic Pulp & Paper Research Journal*, vol. 32, no. 1, pp. 21–24, Jan. 2017, <https://doi.org/10.3183/npprj-2017-32-01-p021-024>.
- [23] K. K. Likharev, "The Kramers problem and the Smoluchowski equation." LibreTexts Physics. [https://phys.libretexts.org/Bookshelves/Thermodynamics_and_Statistical_Mechanics/Essential_Graduate_Physics_-_Statistical_Mechanics_\(Likharev\)/05%3A_Fluctuations/5.06%3A_The_Kramers_problem_and_the_Smoluchowski_equation](https://phys.libretexts.org/Bookshelves/Thermodynamics_and_Statistical_Mechanics/Essential_Graduate_Physics_-_Statistical_Mechanics_(Likharev)/05%3A_Fluctuations/5.06%3A_The_Kramers_problem_and_the_Smoluchowski_equation).
- [24] "Effect of Temperature Change on Reaction Rate." JoVE Core. <https://app.jove.com/science-education/11698>.
- [25] B. M. Smailov *et al.*, "Kinetic research and mathematical planning on the obtaining of potassium humate from brown coal of the Lenger deposit," *Rasayan Journal of Chemistry*, vol. 13, no. 3, pp. 1899–1905, 2021.