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Mathematical modeling and ecological assessment of fluoride release in a mixture of mineralized phosphorite waste and wastewater from the fat and oil industry

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ABSTRACT

This study investigates fluoride loss in a mixture of mineralized mass (MM) extracted from the Central Kyzylkum phosphorite deposits and acidic wastewater (AWW) generated by the fat-and-oil industry. The research aimed to evaluate fluoride release and its retention stability under various conditions. Experimental trials were conducted using AWW:MM mass ratios ranging from 100:10 to 100:40. The experiments were carried out at 333 K for 30 minutes, employing ionometric analysis. The theoretical fluoride content varied from 1.23 g to 4.90 g, while the experimental values ranged from 0.88 g to 3.68 g. The lowest fluoride loss was observed at the 100:20 ratio, amounting to 0.34 g. The highest loss, 1.22 g, was recorded at the 100:40 ratio. The 100:25 ratio (pH 5.90), with a fluoride loss of 0.40 g and an experimental retention of 2.66 g, was identified as optimal. At pH values between 6.33 and 7.30, fluoride levels stabilized between 3.08 g and 3.68 g. An exponential regression model demonstrated a high degree of correlation (R^2 = 0.9767). The standard deviation ranged from ±0.002 g to ±0.008 g. Ions in AWW (SO_4^{2-}: 48,145 mg/L and Cl^-: 38,116 mg/L) significantly accelerated fluoride volatilization. The emission of HF gas contributed to atmospheric pollution; however, the 100:25 ratio minimized environmental impact. The results aligned with literature-reported fluoride loss ranges of 0.3–1.5 g. This research contributes to the development of effective and environmentally safe approaches to waste reutilization.

Keywords: fluoride loss, pH value, Ionometric analysis, exponential regression, mineralized mass, acidic wastewater.

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Introduction

Extensive mining and processing of phosphorite rock produce a substantial amount of waste. This waste material also has strong biological capacity and does not convert into a passive substance for a rather extended period of time. Acid wastewater from the fat and oil industry is highly ionized, creating a real danger of pollution of soils and water sources. If the wastewater and mineral waste are separated, the interaction of the combined chemical properties of the two is not understood. This

approach to waste utilization is presently changing in the direction of processing individual wastes together in order to be able to treat the interaction of the two. It is important to investigate the amount of fluoride fixed and liberated into the combined waste products. The physicochemical properties of fluoride are highly sensitive to the components of ionic agents and pH conditions [[1], [2], [3], [4], [5]].

The Central Kyzylkum phosphorite ores have been generating significant low-grade phosphorite waste over the years. Although these wastes appear to be physically stable, they still contain reactive substances such as fluoride, sulfates, and carbonates that can potentially vary through natural weathering. Reaction to rainwater, wind, and solar exposure alters the topological geochemistry of the waste, and geochemical analysis has shown that the concentration of fluoride is high around the waste storage areas [[6], [7], [8], [9]]. Moreover, the presence of finer dust particles in dry environments leads to aerial suspension of the dust particles that is potentially inhalable by the nearby population. These waste substances should therefore not be classified as non-reactive but as potentially reactive technogenic waste that warrants regulation and follow-up treatment strategies [[10], [11], [12]].

In the processes of neutralization and saponification, the fat and oil industry produces a strongly acidic soapstock wastewater (AWW), which always has a pH level below 4 [[13], [14], [15]] The resulting wastewater is rich in anions (SO_4^{2-}, Cl^-, NO_3^-) and cations (Na^+, Mg^{2+}, NH_4^+, Ca^{2+}), a fact that makes it a complex electroactive solution [[16], [17], [18]]. Due to its acidity and higher ions concentration, AWW strongly reacts with other wastes rich in phosphates: Ion exchange, dissolution, and surface-related adsorption phenomena can release fluoride ions, which were unavailable prior to the interaction [[19], [20], [21]]. Generally, the soapstock wastewater can be seen as a reactive effluent rather than a passive one, and it can alter the physicochemical conditions of other wastewaters produced by the industry. In fact, a comprehensive understanding of the soapstock wastewater chemistry is very important for the precise modeling of the behavior of the complex samples of industrial wastes [[22], [23]].

When mineralized mass (MM) and AWW are combined, an intensely reactive dispersion is formed, wherein chemical transformations proceed rapidly. The high acidity of AWW—driven by ions such as H^+, SO_4^{2-}, and Cl^-—can disrupt the ionic balance of structurally bound inorganic fluoride compounds in MM. Fluoride in MM typically exists in relatively stable crystalline phases, such as fluorapatite and cryolite, but their stability decreases sharply at low pH. Under protonation conditions, fluoride minerals undergo partial decomposition, thereby facilitating the conversion of fluoride into ionic or gaseous forms such as *HF* [[6], [12]] (Figure 1).

This process is kinetically governed by acidity level, temperature, and the ionic strength of the reactive medium. Notably, the ion-exchange capacity and complexation potential of sulfate and chloride anions significantly enhance the system's reactivity. The mineralized structure of the MM (mineralized mass) undergoes transformation in acidic environments, particularly in terms of porosity and surface activity. Under such conditions, fluoride components dissociate from the crystalline lattice and transition into mobile forms. The phase recrystallization and surface ion migration induced by interaction with AWW directly influence the residual fluoride content in the final product. In such

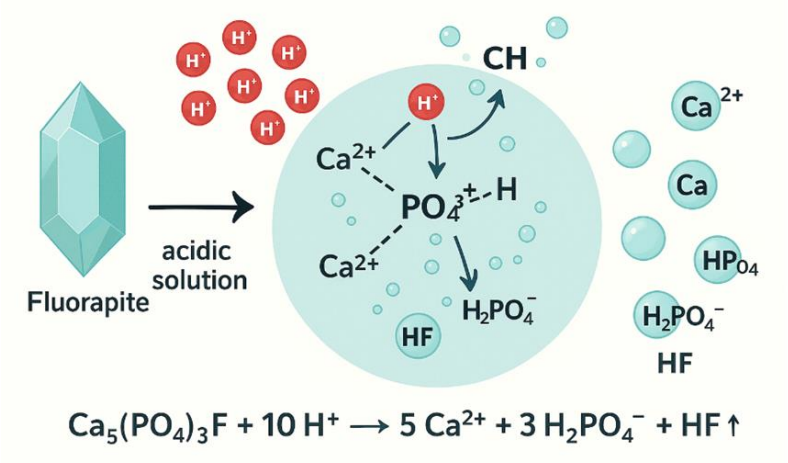

Figure 1 - The decomposition process of fluorapatite ($Ca_5(PO_4)_3F$) in acidic solution

mixed systems, the retention or mobilization of fluoride depends functionally on ionic strength, pH of the medium, and reaction duration. Mathematical modeling enables theoretical interpretation of these conditions and introduces a predictive approach to managing the transformation process. Furthermore, the reactions occurring in AWW-MM mixtures should not be viewed as simple physical interactions, but rather as complex, thermodynamically and kinetically controlled phase transformations. The portion of fluoride retained in the product—without volatilizing into the gaseous phase—can be determined based on mass changes, pH gradients, and the kinetics of dissociation. Such combined systems transition waste into an activated reactive structure, thus enabling controlled environmental risk management. The reactive integration of MM and AWW represents a scientifically grounded direction for the development of alternative waste neutralization technologies [[24], [25], [26], [27]].

The primary objective of this study was to experimentally determine the amount of fluoride retained in the final product derived from MM and AWW mixtures, and to evaluate its loss by comparing experimental results with theoretical calculations. The theoretical amount of fluoride was calculated from the original chemical composition of the waste, and the gap between this value and the measured content in the final product indicated the degree of fluoride release or transfer. In the experiments, mixtures of mineralized mass (MM) and acidic wastewater (AWW) were exposed to controlled conditions of temperature, duration, and mass ratio to reproduce a reactive environment. After processing, the fluoride concentration in the material was determined through analytical techniques and used as a key parameter in modeling. This approach made it possible to identify the main chemical factors influencing whether fluoride was retained or lost in the system. Within the modeling framework, variations in fluoride levels were mathematically related to pH, ionic strength, and mixing proportions. The findings offered a clearer understanding of how fluoride-containing waste undergoes reactive transformations under environmentally relevant conditions.

This research systematically examined ion exchange, phase structure alteration, and component mobility within a reactive medium generated through combined treatment of industrial waste streams. The methodology was grounded in a concept of transforming dual-source waste into an environmentally safe form via chemically activated transformation. This approach redefined the waste materials not as passive inert residues but as chemically reactive substrates. The behavior of fluoride-containing compounds—particularly the dynamic changes arising from pH gradients and ionic strength—was mathematically described through modeling. The methods of conversion of stable fluoride forms into free ions and further retention or release of the ions within the system have been examined using analytical methods. Thus, it has become possible to develop a model based on the physicochemical properties of the substance in relation to ecological risk levels to make technological waste management even more sustainable.

Experimental part

The main focus of this study was on industrial wastes characterized by varied chemical compositions and a high tendency to react.

The first object was MM obtained from the phosphorite deposits of the Central Kyzylkum region. Its composition includes 15.09% P_2O_5, 43.17% CaO, 1.22% Al_2O_3, 1.34% Fe_2O_3, and 1.21% MgO. Additionally, the material contains 1.7% fluoride, 14.01% carbonate compounds, and 2.17% sulfates. The fluoride is primarily bound in the form of fluorapatite, which is highly reactive in acidic environments [[15], [16], [17], [18], [19]].

The second object was AWW generated from technological processes at the “Urganch yog-moy” JSC. The AWW contained 100 mg/L H^+, 43,158 mg/L Na^+, 38,116 mg/L Cl^-, 48,145 mg/L SO_4^{2-}, 1,824 mg/L Mg^{2+}, and 300 mg/L Ca^{2+}. In addition, it included 20.01 mg/L NO_2^-, 840 mg/L NO_3^-, 3,446 mg/L HCO_3^-, 100 mg/L NH_4^+, 30 mg/L Fe^{2+}, and 0.3 mg/L Fe^{3+}. This solution formed a strongly acidic medium with a total ionic strength of 2,148.08 mg-equiv/L and a pH range of 2.1–2.5. The ionic composition of AWW triggers stepwise ion-exchange reactions with the structurally bound fluoride in MM [[15], [16], [17], [18], [19]].

Mixtures of AWW and MM were prepared in mass ratios ranging from 100:10 to 100:40, mixed under a reaction medium at 333 K for 30 minutes. Each mixture was subsequently dried at 353 K to form a solid phase, crushed into powder, and analyzed for residual fluoride content. The interaction of acidic ions with fluoride components in MM promotes fluoride migration and

decomposition in the reactive medium. Furthermore, the increase in pH from 4.10 to 7.30 following the reaction indicates the occurrence of partial neutralization. Owing to their chemical complexity and high reactivity, these two waste streams serve as an excellent laboratory model system for studies on waste recycling, environmental safety, and mathematical modeling. Within such systems, fluoride transformation behavior, decomposition kinetics, and ion equilibrium parameters can be thoroughly investigated.

After drying, the residual fluoride content in powder samples of AWW–MM mixtures was measured using an ion-selective electrode method with a portable ionometer device, calibrated in accordance with the manufacturer's instructions (produced in the Russian Federation).

To enable solubilization of fluoride ions, each powder sample was extracted in a 1:10 ratio with distilled water. The prepared solutions were kept at 20–25 °C for a minimum of 30 minutes to allow the ion balance to reach stability. Subsequent measurements were performed in a buffered medium with a pH of about 5.0–5.5, ensuring that only free and reactive forms of fluoride were detected. The ionometer was calibrated prior to each measurement using standard fluoride solutions of 0.1, 1.0, and 10 mg/L concentrations.

During analysis, the actual fluoride concentration in mg/L was displayed directly on the device screen. Each sample was measured in triplicate, and the arithmetic mean was calculated along with standard deviation to assess analytical precision.

To complete the fluorine material balance and experimentally confirm the transition of fluoride into the gas phase, an additional set of experiments was conducted using a gas absorption method. The experimental setup was supplemented with a fluoride gas trapping system designed to capture hydrogen fluoride (HF) released during the interaction between acidic wastewater (AWW) and mineralized mass (MM).

The reaction was carried out in a sealed glass reactor equipped with a gas outlet. The outlet was connected to a two-stage absorption unit. The first absorber contained 0.1 M NaOH solution, intended for quantitative absorption of HF according to the reaction:

$$HF + NaOH \rightarrow NaF + H_2O$$

The second absorber contained distilled water to capture residual fluoride species and possible aerosol-bound fluorine. All connections were made using chemically resistant tubing to prevent fluoride losses.

Blends of AWW and MM were also synthesized at mass ratios of 100:10 to 100:40. These mixtures were then allowed to react for 30 minutes at 333 K, the same as those in the main experiment. During the reaction process, the gas produced was channeled through the absorption system under natural gas pressure without forced gas flow. Once the experiment was completed, the absorber solution was allowed to stabilize for 30 minutes under room temperature.

The concentration of fluoride in the absorption solutions was analyzed using an ion-selective electrode analysis technique. Before carrying out the test, the NaOH absorber solution was first made to have a pH of 5.0 to 5.5 using a diluted hydrochloric acid. The calibration was carried out using a standard fluoride solution with a concentration of 0.1, 1.0, and 10.0 mg/L. The experiment was done in triple replication.

The amount of fluorine transferred to the gas phase, F_{gas}, was calculated using the measured fluorine concentration, as well as the volume of the absorption solution. This amount was then employed to calculate a complete fluorine material balance via the equation:

$$F_{total} = F_{solid} + F_{liquid} + F_{gas}$$

Where: F_{solid} = residual fluoride in dried solid product, F_{liquid} = fluoride in liquid phase, F_{gas} = fluoride captured in absorption system.

This allowed an experimental distinction to be made between loss of fluoride due to volatilization of HF gas and losses retained within the solid phase or carrier liquid. In addition, gas absorption, as a quantitative gas capture process, ensured that gas phase fluoride was quantified accurately, and this had an impact on improving calculations related to fluorine balance.

This method is distinguished by its rapidity, sensitivity, and low measurement error. The ion-selective electrode approach offers a reliable means of quantifying reactive fluoride, evaluating its retention, and assessing ecological risk levels.

The theoretical fluoride content in MM was calculated based on the mass fraction of structurally bound fluoride. In this study, calculations were performed assuming complete presence of fluoride in the form of fluorapatite ($Ca_5(PO_4)_3F$). For each mixture with a defined mass of MM (m_{MM}), the

theoretical mass of fluoride (m_F) was determined using the following equation:

$$m_F = m_{MM} \cdot \frac{\omega_F}{100}$$

Where:

m_F — theoretical fluoride mass (g),

m_{MM} — mass of mineralized mass used in the mixture (g),

ω_F — mass fraction of fluoride in the mineralized mass (%).

The amount of substance (n_F) of fluoride corresponding to the theoretical mass was then calculated using the molar mass of fluoride:

$$n_F = \frac{m_F}{M_F}$$

Where:

n_F — amount of substance of fluoride (mol),

M_F— molar mass of fluoride (19.00 g/mol).

In all experimental combinations (i.e., varying AWW:MM mass ratios), the theoretical fluoride content was calculated individually based on the above formulas. For each calculation, a reaction efficiency of 100% was assumed, representing an ideal condition. Subsequently, to compare with the experimentally determined values, the mass of fluoride loss was estimated using the following relationship:

$$\Delta m_F = m_F^{theoretical} - m_F^{practical}$$

The above model serves as a basis for theoretically assessing the probability of fluoride decomposition, the reactivity level of acidic components in the environment, and the kinetics of structural breakdown. This mathematical approach, developed based on formulas, is used to model the degree of retention or loss of fluoride in waste materials.

The degree of fluoride loss is expressed through a mathematical model based on the difference between theoretical and practical quantities after the reaction with the waste mixture. In this case, the mass of lost fluoride (*ΔF*) is determined by the following equation:

$$\Delta F = F_{theoretical} - F_{practical}$$

Here,

ΔF — amount of fluoride loss (g or mg),

$F_{theoretical}$ — theoretically calculated fluoride content,

$F_{practical}$— experimentally determined fluoride content.

To evaluate the loss in percentage terms, the following expression is used:

$$P_{loss} = \left(\frac{\Delta F}{F_{theoretical}}\right) \cdot 100 =$$

$$= \left(\frac{F_{theoretical} - F_{practical}}{F_{theoretical}}\right) \cdot 100$$

Using these formulas, the degree of fluoride loss for each AWW:MM mass ratio is quantitatively assessed. Thus, the impact of the acidic medium on fluoride breakdown, the ionic balance of the reactive system, and the overall mechanism of fluoride release can be represented through mathematical modeling. Thanks to its high sensitivity, this model provides predictive insights into the process and serves as a reliable tool for assessing the environmental risks associated with the waste system.

To further assess the scale of fluoride release and the ion balance in AWW:MM mixtures, a modeling approach incorporating differential analysis, empirical coefficients, and regression methods was applied. The decline in fluoride concentration within the mixtures was described as a function of the AWW:MM mass ratios.This relationship was further clarified using an exponential regression model. The general mathematical expression adopted for the modeling is as follows [[28], [29], [30]]:

$$C_F = C_o \cdot e^{-kx}$$

Here,

C_F — final fluoride concentration in the dried powder sample (% or mg/g),

C_o — initial (theoretical) fluoride concentration,

k — exponential decay coefficient of the reaction (experimentally determined),

x — mass of mineralized mass (MM) in the AWW:MM ratio (g or %).

In this model, the value of kkk is determined from actual experimental results, and its fit is statistically evaluated using the coefficient of determination R^2. Additionally, changes in equilibrium caused by ionic interactions in the reactive medium are assessed using the Le Chatelier principle. The dynamic equilibrium shift *ΔQ* is modeled according to the following equation:

$$\Delta Q = f\,(C_{H^+}, C_{F^-}, pH, t)$$

Here,

C_{H^+}, C_{F^-} — concentrations of key ions (hydrogen and fluoride) in the reaction medium,

pH — the acidity level of the reaction environment,

t — temperature in Kelvin (K).

Furthermore, an Excel-based graphical analysis was performed to illustrate the differences between the theoretical and experimental values of fluoride content at each test point. From these results, a correlation model with high accuracy was constructed. This mathematical framework makes it possible to explore the reaction mechanisms in the AWW:MM system in detail, supports predictive modeling of fluoride loss, and provides a quantitative basis for evaluating the ecological impact of the resulting waste mixtures.

Results and Discussion

In this study, the efforts were directed towards investigating the release and loss of fluoride in the mixture of mineralized mass (MM with 1.7% of fluoride content), mined at the Central Kyzylkum phosphorite deposits and the acidic wastewater (AWW of the fat and oil industry), as well as discussing environmental issues associated with them. Experimental tests were conducted at AWW:MM mass ratios of 100:10 to 100:40 at 333 K for 30 minutes. Tests of the solid residues obtained were conducted through the ionometric method.

** In addition, gaseous fluoride released during the interaction was experimentally captured using an absorption system, allowing the completion of a full fluorine material balance across solid, liquid, and gas phases.*

In this chapter, results are presented with supporting tables and figures, together with statistical analysis and a discussion of the involved aspects of the loss of fluoride and relevant scientific observations and recommendations for further studies [[31], [32], [33], [34]].

The results provided data about the theoretical and experimental values of fluoride content in grams, as well as the amount of fluoride loss. Table 1 summarizes the values obtained for each AWW:MM mass ratio (100:10–100:40), showing that the theoretical fluoride content ranged from 1.23 g to 4.90 g, while the experimental values ranged from 0.88 g to 3.68 g. The lowest fluoride loss (0.34 g) was recorded at the 100:20 ratio, whereas the highest loss (1.22 g) occurred at the 100:40 ratio.

Table 2 presents pH values (4.10-7.30) and practical fluoride amounts (0.88 g-3.68 g). The highest amount was observed at pH 5.90 (2.66 g), while at pH 6.33-7.30, it stabilized in the range of 3.08-3.68 g. The standard deviation varied from ±0.002 g to ±0.008 g.

Table 1 - Theoretical and practical fluoride quantities and fluoride losses in AWW:MM mixtures

AWW:MM mass ratio	Theoretical fluoride amount (g)	Practical fluoride amount (g)	Fluoride loss (g)	Standard deviation (g)
100:10	1.23	0.88	0.35	±0.002
100:15	1.84	1.42	0.42	±0.003
100:20	2.45	2.11	0.34	±0.004
100:25	3.06	2.66	0.40	±0.005
100:30	3.68	3.08	0.60	±0.006
100:35	4.29	3.39	0.90	±0.007
100:40	4.90	3.68	1.22	±0.008

Table 2 - pH and fluoride content in AWW:MM mixtures

AWW:MM mass ratio	pH	Practical fluoride amount (g)	Standard deviation (g)
100:10	4.10	0.88	±0.002
100:15	4.81	1.42	±0.003
100:20	5.62	2.11	±0.004
100:25	5.90	2.66	±0.005
100:30	6.33	3.08	±0.006
100:35	6.74	3.39	±0.007
100:40	7.30	3.68	±0.008

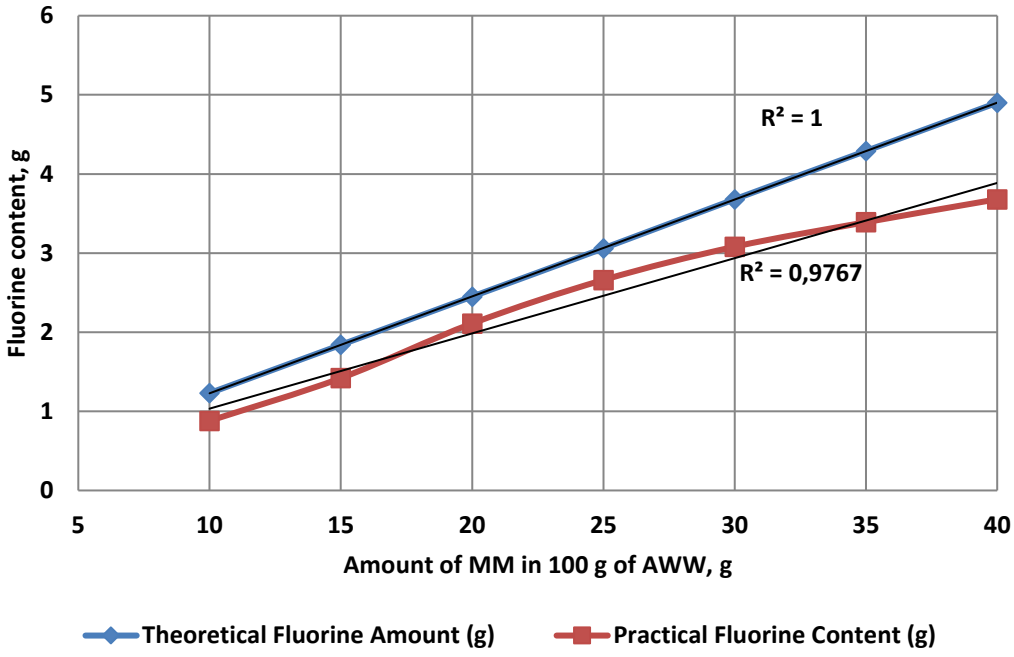

Figure 2 - Theoretical and practical comparison of fluoride quantity

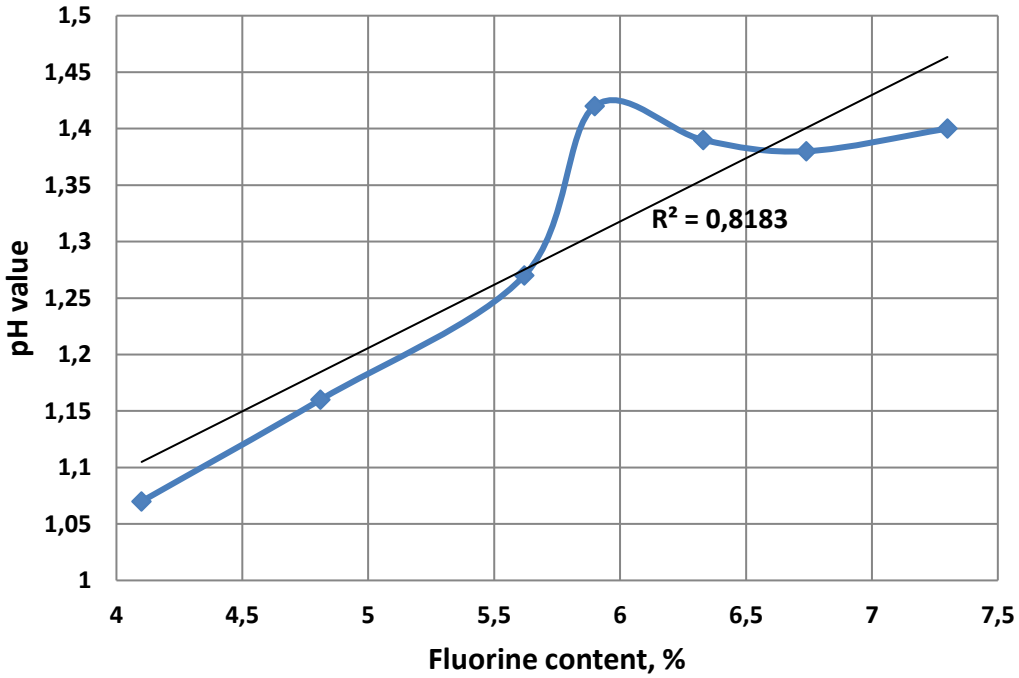

Figure 3 - The relationship between pH and fluoride content

Figure 2 (line graph), comparing the theoretical and practical amounts of fluoride, showed the highest practical amount (2.66 g) at a ratio of 100:25.

Figure 3 (scatter graph) illustrates the relationship between pH and the practical amount of fluoride, showing the highest amount (2.66 g) at pH 5.90 and stabilization in the pH range of 6.33-7.30.

In this study, Figure 2 compares the theoretical (1.23 g–4.90 g) and experimental (0.88 g–3.68 g) amounts of fluoride at various AWW:MM mass ratios (100:10–100:40) using a line graph. The highest experimental fluoride content was observed at the 100:25 ratio with a value of 2.66 g, while the lowest was recorded at the 100:10 ratio with 0.88 g. Fluoride loss ranged from 0.34 g (100:20) to 1.22 g (100:40). Figure 3 presents a scatter plot of pH values (4.10–7.30) versus experimental fluoride content (0.88 g–3.68 g). The peak fluoride retention occurred at pH 5.90, corresponding to 2.66 g. In the

pH range of 6.33 to 7.30, fluoride levels stabilized between 3.08 g and 3.68 g. In both graphs, the standard deviation of ionometric analysis ranged from ±0.002 g to ±0.008 g. These graphs clearly demonstrate the dependence of fluoride content on both mass ratio and pH, confirming the reliability of the experimental conditions.

The fluoride loss (0.34–1.22 g) was evaluated based on a complete fluorine material balance, including experimentally determined fluoride contents in the solid and liquid phases as well as gaseous fluoride captured using an absorption system, and subsequently analyzed using an exponential regression model (R^2 = 0.9767).

Each ionometric measurement was repeated three times, with standard deviations ranging from ±0.002 g to ±0.008 g. The minimum fluoride loss was recorded at the 100:20 ratio (0.34 g), and the maximum at 100:40 (1.22 g). The 100:25 ratio (0.40 g loss and 2.66 g retained fluoride) was identified as the most balanced condition. The correlation between pH (4.10–7.30) and experimental fluoride content (0.88 g–3.68 g) showed a strong relationship. Statistical results confirmed the reliability of data obtained at 333 K and a reaction time of 30 minutes. This analysis allowed accurate evaluation of fluoride behavior in response to varying mass ratios and pH values. The low standard deviation highlighted the high reproducibility of results. The exponential model effectively explained the variability in fluoride loss and provided a robust foundation for subsequent chemical and environmental discussions.

From a chemical standpoint, fluoride loss (0.34 g–1.22 g) was evaluated as a function of pH. At the 100:10 ratio (pH 4.10), the highest loss (0.35 g) was attributed to the formation of hydrogen fluoride (HF) gas. The 100:25 ratio (pH 5.90) provided optimal conditions with the lowest fluoride loss (0.40 g) and highest experimental fluoride retention (2.66 g). In the pH range 6.33–7.30 (ratios 100:30–100:40), fluoride content stabilized between 3.08 g and 3.68 g, attributed to the decreased acidity of the medium. The high ionic strength of AWW, particularly SO_4^{2-} (48,145 mg/L) and Cl^- (38,116 mg/L), accelerated fluoride release under low pH conditions. Environmentally, the release of HF gas (notably at 100:10) contributed to air pollution and posed health risks. Ratios of 100:20 (0.34 g loss) and 100:25 (0.40 g loss) minimized soil and water contamination. The treatment of MM and AWW mixtures promoted stable fluoride retention, making the process an effective waste neutralization strategy. The findings demonstrated the significance of this method in reducing environmental impact and provided a scientific basis for managing fluoride behavior and associated ecological risks [[35], [36], [37]].

Conclusion

This study investigated fluoride loss in a mixture of MM obtained from the Central Kyzylkum phosphorite deposits and AWW from the fat-and-oil industry, yielding several significant findings. The theoretical fluoride content across AWW:MM ratios (100:10–100:40) ranged from 1.23 g to 4.90 g, while the experimental content varied from 0.88 g to 3.68 g. The minimum fluoride loss was observed at the 100:20 ratio (0.34 g), whereas the maximum was recorded at 100:40 (1.22 g). The 100:25 ratio (pH 5.90) demonstrated optimal conditions with only 0.40 g of loss and 2.66 g of retained fluoride. At pH values between 6.33 and 7.30, fluoride content stabilized within the range of 3.08 g to 3.68 g. Ionometric analysis showed high reproducibility, with a standard deviation between ±0.002 g and ±0.008 g.

An exponential regression model (R^2 = 0.9767) confirmed the reliability of fluoride loss predictions. High concentrations of ions in AWW (SO_4^{2-}: 48,145 mg/L; Cl^-: 38,116 mg/L) accelerated fluoride release. At a 100:10 ratio (pH 4.10), the emission of hydrogen fluoride (*HF*) gas contributed to air pollution. In contrast, the 100:20 and 100:25 ratios effectively minimized soil and water contamination. The co-treatment of MM and AWW ensured stable fluoride retention, supporting its application as a waste-neutralization strategy. Statistical findings aligned with literature data indicating fluoride losses in the range of 0.3–1.5 g. A key limitation of the study was the inability to directly measure *HF* gas emissions. Nevertheless, the results support the strategy's effectiveness in mitigating environmental risks. Reducing fluoride loss significantly contributes to lowering ecological impact and provides a foundation for developing advanced waste treatment technologies. These findings offer practical implications for industrial waste management and play a critical role in enhancing environmental safety. Moreover, the study contributes to the advancement of innovative approaches in fluoride control.

Conflicts of interest. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Минералданған фосфорит қалдықтары мен май-май өнеркәсібінің ақаба сулары қоспасындағы фтордың бөлінуін математикалық модельдеу және экологиялық бағалау

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АННОТАЦИЯ

Бұл зерттеу Орталық Қызылқұм фосфорит кен орындарынан алынған минералданған масса (ММ) мен май-және май өнеркәсібінде түзілетін қышқыл ағынды сулардың (ҚАС) қоспасындағы фтордың жоғалуын зерттеуге бағытталған. Жұмыстың мақсаты фтордың бөлінуін және оның тұрақты сақталуын әртүрлі жағдайларда бағалау. Эксперименттер ҚАС:ММ масса арақатынасы 100:10-нан 100:40-қа дейінгі аралықта, 333 К температурада, 30 минут бойы ионометриялық талдау әдісімен жүргізілді. Теориялық фтор мөлшері 1.23 г-дан 4.90 г-ға дейін, ал тәжірибелік нәтижелер 0.88 г-дан 3.68 г-ға дейін өзгерді. Ең аз фтор жоғалуы 100:20 қатынасында — 0.34 г, ал ең жоғары жоғалту — 1.22 г — 100:40 қатынасында анықталды. Оптималды жағдай 100:25 қатынасында (pH 5.90) байқалып, фтордың жоғалуы 0.40 г, ал қалдық мөлшері 2.66 г болды. pH 6.33–7.30 аралығында фтор мөлшері 3.08 г–3.68 г деңгейінде тұрақтанды. Экспоненциалды регрессия моделі жоғары корреляцияны көрсетті (R^2 = 0.9767). Стандартты ауытқу ±0.002 г–дан ±0.008 г–ға дейін болды. ҚАС құрамындағы иондар (SO_4^{2-}: 48145 мг/л, Cl^-: 38116 мг/л) фтордың ұшуын едәуір жеделдетті. HF газының бөлінуі атмосфераның ластануына әкелді, алайда 100:25 қатынасы экологиялық әсерді барынша азайтты. Алынған нәтижелер әдеби деректердегі фтор жоғалу ауқымына (0.3–1.5 г) сәйкес келеді. Бұл зерттеу өнеркәсіптік қалдықтарды тиімді әрі экологиялық қауіпсіз қайта өңдеуге арналған жаңа тәсілдердің дамуына үлес қосады.

Түйін сөздер: фторидтің жоғалуы, pH көрсеткіші, ионометриялық талдау, экспоненциалды регрессия, минералданған масса, қышқылды ағынды сулар.

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Математическое моделирование и экологическая оценка высвобождения фтора в смеси минерализованных фосфоритных отходов и сточных вод масложировой промышленности

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АННОТАЦИЯ

В настоящем исследовании рассматриваются потери фтора в смеси минерализованной массы (ММ), извлечённой из фосфоритных месторождений Центрального Кызылкума, и кислых сточных вод (КСВ), образующихся в жировой и масложировой промышленности. Целью работы являлась оценка высвобождения фтора и устойчивости его удержания при различных условиях. Эксперименты проводились при массовых соотношениях КСВ:ММ от 100:10 до 100:40 при температуре 333 К в течение 30 минут с использованием ионометрического анализа. Теоретическое содержание фтора варьировало от 1,23 г до 4,90 г, тогда как экспериментальные значения находились в пределах от 0,88 г до 3,68 г. Минимальные потери фтора (0,34 г) наблюдались при соотношении 100:20, максимальные потери (1,22 г) — при 100:40. Оптимальным признано соотношение 100:25 (pH 5,90), при котором потери составили 0,40 г, а остаточное содержание — 2,66 г. При значениях pH от 6,33 до 7,30 концентрация фтора стабилизировалась в пределах 3,08–3,68 г. Модель экспоненциальной регрессии показала высокую степень корреляции (R^2 = 0,9767). Стандартное отклонение варьировало от ±0,002 г до ±0,008 г. Ионы в составе КСВ (SO_4^{2-}: 48145 мг/л и Cl^-: 38116 мг/л) значительно ускоряли испарение фтора. Выделение HF-газа способствовало загрязнению атмосферы, однако при соотношении 100:25 экологическое воздействие было минимальным. Полученные результаты согласуются с литературными данными, указывающими на диапазон потерь фтора от 0,3 до 1,5 г. Исследование вносит вклад в разработку эффективных и экологически безопасных подходов к утилизации промышленных отходов.

Ключевые слова: потеря фтора, значение pH, ионометрический анализ, экспоненциальная регрессия, минерализованная масса, кислые сточные воды.

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References

[1] Kurbaniiazov R K, Reimov A M, Namazov Sh S, & Beglov B M. Nitrogen-phosphoric fertilizers obtained by interaction of the concentrated solutions of ammonium nitrate with the mineralized mass of the phosphorites of Central Kyzylkum. Russian Journal of Applied Chemistry. Pleiades Publishing Ltd. 2009. https://doi.org/10.1134/s107042720906038x

[2] Sultonov B E, Nozimov E S, & Kholmatov D S. Recycling of Local Phosphate Waste - mineralized Mass into Activated Phosphorus Fertilizers. Chemical Science International Journal. Sciencedomain International. 2023. https://doi.org/10.9734/csji/2023/v32i6875

[3] Shamuratov S, Baltaev U, Achilova S, Alimov U, Namazov S, & Usanbaev N. Enhancement of availability of high calcareous phosphorite by neutralization of acid effluent and composting of cattle manure. (O. Tursunov, Ed.), E3S Web of Conferences. EDP Sciences. 2023. https://doi.org/10.1051/e3sconf/202337703004

[4] Shamuratov S, Alimov U, Rifky M, Baltaev U, Ibragimova M, Kurambaev S, & Radjabov M. Investigation of the Kinetics of Cotton Soapstock Saponification under Ultrasonic Illumination. Eurasian Chemico-Technological Journal. 2025; 27(4):323–335. https://doi.org/10.18321/ectj1679

[5] Hmidi K, Ksentini I, and Mansour L B. Treatment of Olive-Pomace Oil Refinery Wastewater Using Combined Coagulation-Electroflotation Process. Journal of Water Chemistry and Technology. Allerton Press. 2017. https://doi.org/10.3103/s1063455x17050046

[6] Halstead W D. The thermodynamics of fluoride loss during the chemical analysis of welding fluxes. Journal of Applied Chemistry and Biotechnology. Wiley. 1973. https://doi.org/10.1002/jctb.5020230308

[7] Doniyarov N A, & Tagayev I A. Obtaining a new kind of organic fertilizer on the basis of low-grade phosphorite of Central Kyzylkum. Materials and Geoenvironment. Walter de Gruyter GmbH. 2018. https://doi.org/10.2478/rmzmag-2018-0016

[8] Tagayev I, Doniyarov N, Asrorov A, & Murodov I. The Role of Medium Condition for Uranium Separation from Central Kyzylkum's Low-grade Phosphorite after Sulfuric Acid Treatment. International Journal on Advanced Science, Engineering and Information Technology. Insight Society. 2022. https://doi.org/10.18517/ijaseit.12.2.14060

[9] Juneja A, Kurambhatti C, Kumar D, & Singh V. Techno-Economic Evaluation of Phosphorous Recovery in Soybean Biodiesel Process. Processes. MDPI AG. 2022. https://doi.org/10.3390/pr10081512

[10] Sultonov BE, Kholmatov DS, Rasulov AA, and Temirov USh. Treatment of Phosphate Waste Generated during Thermal Processing of Phosphorites of the Central Kyzylkum. Obogashchenie Rud. Ore and Metals Publishing House. 2024. https://doi.org/10.17580/or.2024.04.06

[11] Shaymardanova Mokhichekhra, Kholtura Mirzakulov, Gavkhar Melikulova, Sakhomiddin Khodjamkulov, Abror Nomozov, and Oybek Toshmamatov. Studying of The Process of Obtaining Monocalcium Phosphate Based on Extraction Phosphoric Acid from Phosphorites of Central Kyzylkum. Baghdad Science Journal. College of Science for Women, University of Baghdad. 2024. https://doi.org/10.21123/bsj.2024.9836

[12] Sidorina E, Isagulov A, Rabatuly M, & Yang Y. Technology of production of aluminosilicate refractories for units processing fluorinated waste. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2024; 335(4):89–95. https://doi.org/10.31643/2025/6445.43

[13] Borowski S, & Cieciura-Włoch W. Enzymatic Pretreatment of Byproducts from Soapstock Splitting and Glycerol Processing for Improvement of Biogas Production. Molecules. MDPI AG. 2021. https://doi.org/10.3390/molecules26226782

[14] de Pablos-Martín A, Contreras Jaimes AT, Wahl S, Meyer S, & Brauer DS. Fluoride loss determination in bioactive glasses by laser-induced breakdown spectroscopy (LIBS). International Journal of Applied Glass Science. Wiley. 2021. https://doi.org/10.1111/ijag.15867

[15] Shamuratov Sanzharbek, Umid Baltaev, Umarbek Alimov, Namazov Shafoat, Sherzod Kurambaev, and Bazar Ibadullaev. Utilization Process Research of the Soap Industry Acid Waste Water with High Carbonate Phosphorite of Central Kyzylkum. E3S Web of Conferences. EDP Sciences. 2021. https://doi.org/10.1051/e3sconf/202126404079

[16] Shamuratov Sanjarbek, Umid Baltaev, Olga Myachina, Umarbek Alimov, Elyor Atashev, and Tokhir Kuramboev. Agrochemical Efficiency of Slow Release Phosphate Fertilizers Derived on the Base of Phosphorite Activation. E3S Web of Conferences. EDP Sciences. 2023. https://doi.org/10.1051/e3sconf/202343403014

[17] Sotimboev Ilgizarbek, Umidbek Baltaev, Sanjarbek Shamuratov, Ruzimov Shamsiddin, Umarbek Alimov, and Mirzabek Saporboyev. Technical and Economic Efficiency of Processing Acidic Wastewater from the Oil and Fat Industry into Necessary Agricultural Products. E3S Web of Conferences. EDP Sciences. 2024. https://doi.org/10.1051/e3sconf/202456303072

[18] Turatbekova Aidai, Malokhat Abdukadirova, Sanjarbek Shamuratov, Bakhodir Latipov, Mirzabek Saporboyev, Jafar Shamshiyev, and Yusuf Makhmudov. Investigation of the Effect of Fertilizers on the Biochemical and Physical Characteristics of Carrots (Daucus Carota L.). E3S Web of Conferences. EDP Sciences. 2024. https://doi.org/10.1051/e3sconf/202456303074

[19] Yuldasheva A, Shamuratov S, Kurambayev S, & Radjabov M. Mathematical Analysis of CaO Content Variation in Acidic Wastewater and Mineralized Mass Mixture from Central Kyzylkum Phosphorite Based on Exponential Decay Model. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2025; 339(4):79–86. https://doi.org/10.31643/2026/6445.42

[20] Shamuratov S, Baltayev U, Alimov U, Jabbarov M, & Madaminov A. Sigmoid Neutralization Response of Acidic Soapstock Waste by Mineralized Phosphorite Residues: A 4-Parameter Logistic Approach. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2026; 342(3):80–89. https://doi.org/10.31643/2027/6445.32

[21] Pintor Ariana MA, Andreia G Martins, Renata S Souza, Vítor JP Vilar, Cidália MS Botelho, and Rui AR Boaventura. Treatment of Vegetable Oil Refinery Wastewater by Sorption of Oil and Grease onto Regranulated Cork – A Study in Batch and Continuous Mode. Chemical Engineering Journal. Elsevier BV. 2015. https://doi.org/10.1016/j.cej.2015.01.025

[22] Mirshafiee Amir, Abbas Rezaee, and Rasol Sarraf Mamoory. A Clean Production Process for Edible Oil Removal from Wastewater Using an Electroflotation with Horizontal Arrangement of Mesh Electrodes. Journal of Cleaner Production. Elsevier BV. 2018. https://doi.org/10.1016/j.jclepro.2018.06.201

[23] Ahmad Talha, Rana Muhammad Aadil, Haassan Ahmed, Ubaid ur Rahman, Bruna CV Soares, Simone LQ Souza, Tatiana C Pimentel, et al. Treatment and Utilization of Dairy Industrial Waste: A Review. Trends in Food Science & Technology. Elsevier BV. 2019. https://doi.org/10.1016/j.tifs.2019.04.003

[24] Tadjiev SM, Atashev EA. Obtaining azosuperphosphate from low-grade phosphates of the central Kyzylkum. Journal of Critical Reviews. 2020; 7(5):472-477.

[25] Tadjiev SM, Atashev EA. Production of azosuperphosphate in the participation of Central Kyzylkum phospharites and ammonium sulphate. Journal of Critical Reviews. 2020; 7(7):358-362.

[26] De Leonardis A, Macciola V, Iftikhar A. Present and Future Perspectives on the Use of Olive-Oil Mill Wastewater in Food Applications. In: Souabi, S., Anouzla, A. (eds) Wastewater from Olive Oil Production. Springer Water. Springer, Cham. 2023. https://doi.org/10.1007/978-3-031-23449-1_4

[27] Jeba RH, Hemada HM, Nadir AA, et al. Improving stability of frying oils and food quality with addition of dried olive mill wastewater. npj Sci Food. 2025; 9:75. https://doi.org/10.1038/s41538-025-00430-x

[28] Fritz Matthew S. An Exponential Decay Model for Mediation. Prevention Science. Springer Science and Business Media LLC. 2013. https://doi.org/10.1007/s11121-013-0390-x

[29] Atashev E. Decomposition of Magnesite-Sparing Waste in Sulfuric Acid with a High Concentration: Empirical Modeling and Determination of Optimal Conditions. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2025; 339(4):71–78. https://doi.org/10.31643/2026/6445.41

[30] Baltayev U, Shamuratov S, Alimov U, Madaminov A, & Jabbarov M. Extraction of P_2O_5 from the mineralized mass of the Central Kyzylkum using acidic wastewater generated from cotton soapstock processing: scientific analysis based on equilibrium principles. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2025; 341(2):83–96. https://doi.org/10.31643/2027/6445.20

[31] Boyjanov N, Radjabov M, Serkayev Q, Boyjanov I, & Yaxshimuradov N. Activation and comparison of indicators of bentonite clay of the Navbakhor deposit. E3S Web of Conferences. 2024; 563:02018. https://doi.org/10.1051/e3sconf/202456302018

[32] Boyjanov NI, Rakhimov UB, Ataullaev ZM, Boltayev MA, Serkayev QP, Khamidova MO. Mathematical analysis of the linear increase in SIO2 content during the activation of Navbakhor alkaline bentonite with hydrochloric acid. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2027; 342(3):90-99. https://doi.org/10.31643/2027/6445.33

[33] Boyjanov NI, Otajonova GM, Kendjayev BB, Matyakubova MX, Sabirova NK, Masharipov AT, Boyjanov IR, Serkayev QP. Exponential modeling of Al_2O_3 reduction during activation of Navbahor alkaline-earth bentonite Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2027; 343(4):106-115. https://doi.org/10.31643/2027/6445.44

[34] Haidar Abbas, Sarmad Jaafar Mohammed Alrubaye, Ali Fawzi Al-Hussainy, Basim Mohammed Saadi, Mohannad Abdulrazzaq Gati, Talib Kh. Hussein, Boyjanov Nodirbek Ilxomovich, Nafaa Farhan Muften. Role of Carrageenan and Health Approach for Adsorption of Safranin-T Dye from Aqueous Solution by Using Polymer/CNT Surface. Journal Nanostruct. 2025; 15(4): 1798-1807. https://doi.org/10.22052/JNS.2025.04.027

[35] Hussein U A-R, Alalwan D H K, Qabel H A, Abid F M, Hamza H H, Ilxomovich B N, Aljeboree A M, & Alkaim A F. Green synthesis and characterization of guar gum/polyacrylamide/activated carbon hydrogel for efficient methylene blue removal. Journal of Nanostructures. 2025; 15(4):1849-1860. https://doi.org/10.22052/JNS.2025.04.028

[36] Kurayazov, Z., Ollaberganova, A., Jabbarov, M., Matnazarov, U., & Babajanova, R. (2026). Reduction of Fluoride in Central Kyzylkum Phosphate Waste in an Acidic Environment: Experimental and Mathematical Study Based on the Langmuir Model. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources, 343(4), 65–76. https://doi.org/10.31643/2027/6445.41

[37] Achilova, S., Saparbaeva, N., Matmuratov, A., Rustamova, N., & Karimboyev, O. (2026). Activation of the mineralized mass of Central Kyzylkum using acidic wastewater from the oil and fat industry: Freundlich-based adsorption kinetics for fluorine release. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources, 342(3), 65–79. https://doi.org/10.31643/2027/6445.31