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**ABSTRACT**

of the dissertation for the degree of Doctor of Philosophy

**MODELING OF OIL SLUDGE UTILIZATION PROCESSES  
IN THE ABSHERON PENINSULA**

Specialty: 3303.01 – Chemical Technology and engineering

Field of Science: Technical Sciences

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The work was performed at the Institute of Catalysis and Inorganic Chemistry named after acad.M.F. Naghiyev of the Ministry of Science and Education Republic of Azerbaijan at the Laboratory of Physico-Chemical Technologies and Their Modelling of the Department of Modelling and Technology of Chemical and Environmental Processes.

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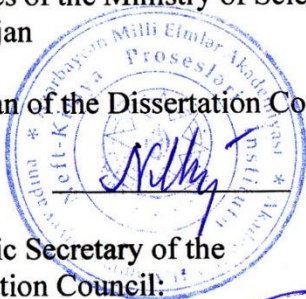
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## GENERAL CHARACTERISTICS OF THE WORK

**Relevance and level of development.** The rapid development of the oil and gas industry, while being one of the most important sectors of the global economy, has also caused serious environmental problems. In regions where long-term intensive oil extraction has taken place, as well as in areas where oil refineries and other industrial enterprises operate, the oil sludges formed have become a major source of ecological hazard. These sludges have a complex composition, contaminating soils, underground and surface water sources, thereby disturbing ecological balance and negatively affecting human health. According to available statistical data, millions of tons of oil sludge are generated annually in the oil industry, and the difficulties in managing them create not only economic losses but also pose a serious threat to the sustainable development of the environment.

The history of the oil industry in Azerbaijan is linked to the Absheron Peninsula, where long-standing oil extraction, refining, and transportation activities have generated large amounts of oil sludge. A massive portion of these wastes has been stored in various open landfills, causing severe soil pollution and degradation of the ecological environment. Currently, traditional approaches to the utilization of these wastes in the Absheron Peninsula do not ensure full compliance with environmental standards, economic efficiency, or safe reuse of sludges. Therefore, the development of environmentally safe, economically efficient, and technologically modern innovative methods for the effective management of oil sludges is considered both urgent and necessary <sup>1</sup>.

In global practice, various physical, chemical, and biological methods are used for the utilization of oil sludges. However, when applied individually, each method has certain limitations. Physical methods only allow partial cleaning of sludges, chemical methods may

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<sup>1</sup>Bakhonina, E. I. Modern technologies of processing and utilization of hydrocarbon-containing waste. // Message 1. Thermal methods of utilization and neutralization of carbon-containing waste. Bashkir Chemical Journal, 2015, – 22(1), p.20-29

create additional environmental risks, and biological methods are not effective for all types of sludge and require long processing times. In this regard, the combined application of existing methods and the determination of their optimal regimes are significant. To increase the efficiency and optimization of such combined methods, it is necessary to use modern scientific approaches, especially mathematical modelling, and optimization methods.

The application of mathematical modelling makes it possible to determine effective regimes for combined technologies, optimize technological parameters, and predict outcomes with precision in advance. Thus, by modelling oil sludge utilization processes, it becomes possible to minimize negative environmental impacts and to identify more economically advantageous technological solutions<sup>2</sup>.

The relevance of these issues demonstrates the importance of developing effective technologies for the utilization of oil sludges in the Absheron Peninsula and optimizing these processes through mathematical methods. The research conducted in the dissertation is aimed at solving the existing problems in this field and at obtaining corresponding scientific results. This, in turn, contributes to ensuring environmental safety, reducing economic costs, and obtaining products suitable for reuse. Therefore, the proposed dissertation topic is relevant from ecological, economic, and scientific-technical perspectives and can make an important contribution to solving the problem on a scientific basis.

**Object and subject of research.** The object of the research is the oil sludges formed in the Bibiheybat, Balakhani, Surakhani, and Ramana fields of the Absheron Peninsula. These sludges have a complex physicochemical composition, containing high amounts of heavy metals and hydrocarbons, and are considered hazardous wastes both ecologically and economically.

The subject of the research is the study of the physicochemical

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<sup>2</sup> Велиев, Э. Ф. Аскеров, В. М. Алиев, А. А. Методы увеличения нефтеотдачи пластов высоковязкой нефти, основанные на внутрислоеистой модификации ее физико-химических свойств. SOCAR Proceedings, 2022, – №2, с.144-152.

and structural properties of these sludges, their utilization through combined technological methods, and the mathematical modelling and optimization of these processes. Particular attention is given to the description of the drying, extraction, adsorption, and distillation stages based on differential equations, as well as to the selection of the most efficient technological regimes.

**Goals and objectives of the study.** The main purpose of the dissertation is to develop mathematical models based on the application of combined technological methods to increase the efficiency of oil sludge management and utilization formed as a result of long-term oil industry activities in the Absheron Peninsula, to optimize these models, and to determine the prospects for industrial application of the proposed technologies by testing them under laboratory conditions. Achieving this purpose aims to provide both scientific and practical contributions to environmental protection and to the improvement of economic efficiency.

To achieve the main purpose, the following specific tasks were set and solved step by step in the dissertation:

1. A comprehensive study of the formation mechanisms, physicochemical and structural characteristics of oil sludges generated from various sources in the Absheron Peninsula, with detailed analysis of their composition, properties, and classification.

2. Investigation of the advantages and shortcomings of existing traditional methods (physical, chemical, thermal, and biological) for the treatment and utilization of oil sludges, and identification of the problems of low-efficiency methods.

3. Theoretical and experimental research on the possibilities of combining different utilization methods, and determination of the most optimal combined technologies to increase technological efficiency.

4. Development of new mathematical models for describing effective oil sludge utilization processes, and verification of the accuracy and reliability of these models through laboratory experiments.

5. Selection of optimal regimes for combined utilization technologies based on the developed mathematical models,

improvement of technological parameters through the application of optimization methods, and enhancement of economic efficiency.

6. Comprehensive evaluation of the environmental safety of the proposed technological solutions, and development of necessary measures to minimize environmental impact.

7. Preparation of appropriate technological schemes and proposals to assess the feasibility and techno-economic justification of applying the developed optimal combined technologies in industrial conditions.

**Methods of Research.** In the dissertation, ASTM and EPA standard methods were used to study the physicochemical properties of oil sludges. The elemental composition was determined using an Agilent Technologies ICP-OES 5810 spectrometer, while the molecular structure was investigated with a Cary 630 FTIR spectrometer. For developing the theoretical foundations of the processes, mathematical modelling based on differential equations and mass and heat balances was applied. The numerical solution and optimization of the models were carried out using the Runge-Kutta method (RK4) and modern computational methods such as Evolutionary Algorithms. At the same time, special laboratory experiments were conducted, and the tangible results of the processes were compared with theoretical models to ensure the optimization of technological parameters.

**The main provisions put forward for defence:**

- Development of new mathematical models for the combined utilization of oil sludges;
- Increase of technological efficiency through the combination of physical and chemical methods;
- Improvement of technological and economic indicators as a result of optimization;
- Assessment and minimization of environmental impacts based on mathematical models.

**Scientific novelty of the research.** The scientific novelty of the conducted research is substantiated by the following results:

- For the first time, considering the specific conditions of the Absheron Peninsula, new and improved mathematical models for the

modeling of combined oil sludge utilization methods have been developed, enabling precise and effective control of processes.

- The scientific basis for combining various methods for the effective utilization of oil sludges has been established, and the technological efficiency and economic advantages of such an approach have been experimentally proven.

- Based on the proposed mathematical models, optimal operating regimes of combined technologies have been determined, and the improvement of technological efficiency and economic performance has been scientifically justified through optimization results.

- To minimize the environmental impacts of the proposed combined utilization methods, a system of comprehensive measures has been developed, and environmental safety indicators have been evaluated for the first time using mathematical models.

**Theoretical and practical significance of the study.** The combined technologies developed for the utilization of oil sludges in the Absheron Peninsula have been substantiated through mathematical modelling methods. For this purpose, new differential equations were formulated for drying, extraction, adsorption, and distillation processes based on mass and heat balances, hydrodynamic laws, and kinetic dependencies. The Runge-Kutta method was applied for the numerical solution of the models, while modern optimization methods such as Evolutionary Algorithms were used for selecting optimal parameters. Thus, the dissertation not only contributes to the practical resolution of the oil sludge utilization problem but also introduces new scientific approaches to the theory of mathematical modelling and process optimization.

The practical significance of the work lies in the possibility of applying the developed models and technological solutions under real conditions. Thanks to the proposed combined methods, the ecological impact of oil sludges can be minimized, waste can be reused, and as a result, both economic losses are reduced and environmental safety indicators in industrial enterprises are improved. Laboratory tests have shown that the developed technologies enable the recovery of valuable hydrocarbons from oil sludges and the separation of heavy metals and

harmful components. As a result, it is possible to obtain both purified material and reusable products.

In addition, the proposed technologies can be applied not only to the Absheron Peninsula but also to other regions facing similar ecological problems. This gives the dissertation broad application prospects. Overall, the theoretical results of the work provide added value to science, while its practical applications make a significant contribution to industry and environmental management.

**Approval and implementation.** A total of 11 scientific papers have been published on the main scientific results and practical recommendations of the dissertation. Of these, 8 are articles and 3 are conference materials and theses.

The materials of the dissertation have been discussed at the following conferences:

The 66th Scientific and Technical Conference of Students dedicated to the 135th anniversary of Agha Akhundov (Baku, 2017); The VIII International Competition-Conference of Student Scientific Works named after A.A. Yakovkin “*Physical Chemistry – the Basis of New Technologies and Materials*” (Saint Petersburg, 2019); The V International Scientific Conference of Researchers dedicated to the 101st anniversary of Heydar Aliyev (Baku, 2024).

**Name of the organization where the dissertation work was performed.** The presented dissertation was carried out at the Institute of Catalysis and Inorganic Chemistry named after acad. M.F. Naghiyev of the Ministry of Science and Education of the Republic of Azerbaijan.

**Personal participation of the author.** The author personally participated in the formulation of the issues included in the dissertation, the generalization and interpretation of the experimental results obtained, the conduct of tests, and the writing of scientific works.

The volume of the structural sections of the dissertation and the total volume in characters

The dissertation consists of an introduction, four chapters, a conclusion, a list of references comprising 123 sources, and includes 20 tables, 25 figures, 3 graphs, and 1 scheme, making up a total of 133

pages. Excluding tables, figures, graphs, schemes, and the reference list, the dissertation contains a total of 194113 characters, distributed as follows: Introduction – 14939 characters; Chapter I – 46268 characters; Chapter II – 66126 characters; Chapter III – 38385 characters; Chapter IV – 25830 characters; and Conclusion – 2565 characters.

In the **introduction**, the general state of the problem is analysed, the relevance of the dissertation topic is justified, and the objectives and tasks of the research are defined. At the same time, the scientific novelty, direction, and practical significance of the work are highlighted, and the main theses for defence are formulated.

In **Chapter I**, the existing literature on the causes of oil sludge formation, their composition, and classification has been thoroughly analysed. It has been shown that the accumulation of sludges over many years as a result of extraction and processing activities in the Absheron Peninsula has caused environmental problems. The physicochemical properties of sludges formed from various sources were comparatively studied, and it was determined that they contain high concentrations of heavy metals, hydrocarbons, and other pollutants.

In **Chapter II**, the methodological basis of the research and the analytical methods used are presented. For this purpose, oil sludge samples were taken from the Bibiheybat, Balakhani, Surakhani, and Ramana fields of the Absheron Peninsula. The physicochemical properties of the samples were studied using ASTM and EPA standard methods, their elemental composition was determined with an Agilent ICP-OES 5810 instrument, and their molecular structure was studied using a Cary 630 FTIR spectrometer.

The analyses revealed that the sludges contained excessive amounts of heavy metals and harmful organic compounds. In addition, based on the obtained data, the hazard level of the sludges was assessed, and the necessity of complex treatment measures was determined. Thus, Chapter II demonstrated the real properties of the oil sludges and provided a strong experimental basis for building mathematical models for their utilization.

In **Chapter III**, the step-by-step mathematical modelling of the

oil sludge utilization processes was carried out. For the stages of drying, extraction, adsorption, and distillation, differential equations were formulated based on mass and heat balances, kinetic dependencies, and hydrodynamic parameters. The process parameters of each stage were considered, and their dynamics were solved numerically using the Runge-Kutta method.

At the same time, Evolutionary Algorithms were applied for process optimization, and the most favourable regimes of technological parameters were selected. The results of the models were compared with laboratory experiments, confirming their reliability. Thus, Chapter III created a theoretical and methodological basis for the phased treatment of oil sludges and provided a scientifically substantiated approach directed toward practical application.

In **Chapter IV**, the possibilities, and prospects for industrial-scale application of the proposed complex utilization technology were evaluated. The technological schemes developed based on modelling and laboratory experiments were adapted to industrial conditions, and their economic and ecological advantages were analysed.

Potential technical problems during application — such as raw material variability, equipment wear, and energy balance management — were identified, and solutions were proposed.

The dissertation concludes with the results of the conducted research, a list of references, and appendices.

## MAIN CONTENT OF THE WORK

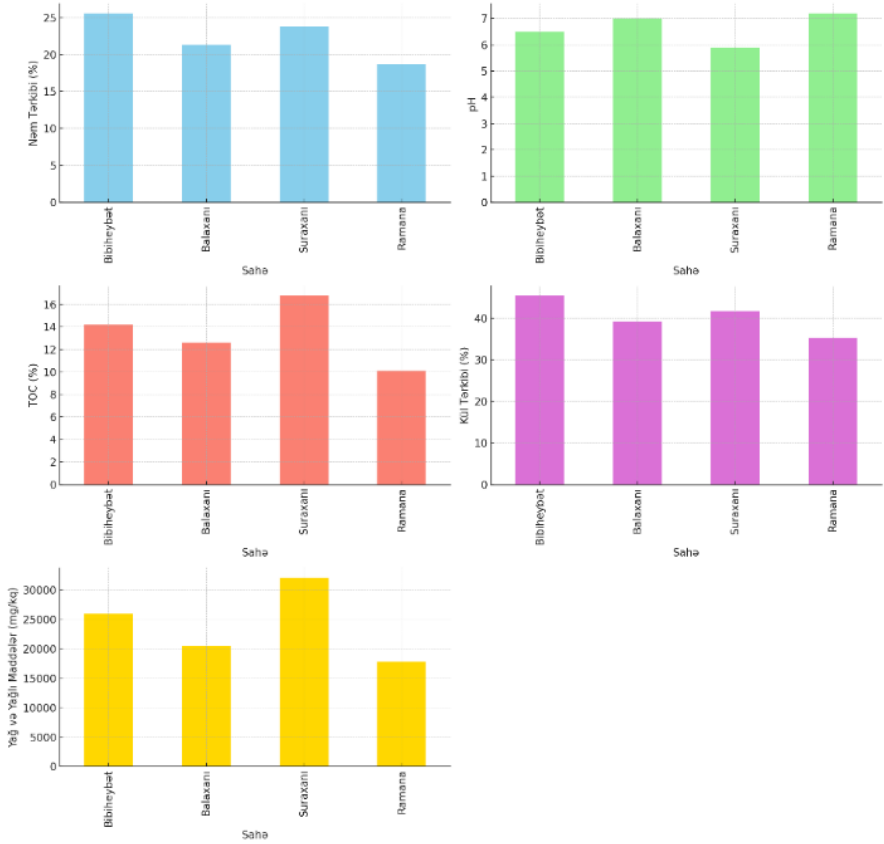
### **Collection of Oil Sludge Samples from the Absheron Peninsula and Application of Analytical Methods for Determining Physicochemical Properties**

Oil sludges collected from various oil fields and industrial enterprises of the Absheron Peninsula have been thoroughly studied. As the main objects of the study, oil sludges accumulated in the four major oil fields of the Absheron Peninsula — Bibiheybat, Balakhani, Surakhani, and Ramana — were selected. During sampling, a total of 12 samples were collected from three different zones in each field, including open sludge pits, drilling sites, and historical sludge deposits, in order to take into account different ecological conditions and anthropogenic impacts.

For the determination of the physicochemical characteristics of oil sludges, internationally recognized ASTM and EPA standard methods were used. Moisture content was determined by drying at 105 °C according to ASTM D2216; pH was measured with a digital pH meter using ASTM D1293; total organic carbon (TOC) was determined by the Walkley-Black method; ash content was measured using ASTM D2974; density was determined according to ASTM D7263; and particle size distribution was measured by laboratory sieve analysis in accordance with ASTM D422. The concentration of oil and grease was determined by EPA 9071B, using Soxhlet extraction followed by gravimetric analysis.

Based on the obtained results, the Bibiheybat and Balakhani fields showed relatively higher moisture and ash content, while lower values were recorded in the Ramana and Surakhani fields. The TOC and oil/grease content were found to be higher in the Surakhani area and lower in the Ramana area. The pH values were acidic in Surakhani samples, while in other fields they were closer to neutral. Regarding particle size distribution, finer fractions dominated in the Surakhani samples.

Abşeron Yarımadasındaki Neft Şamlarının Fiziki-Kimyevi Xüsusiyyətləri



**Graph 1. Graphical Representation of the Relevant Indicators of Samples Collected from Oil Fields**

For the determination of elemental composition, an Agilent Technologies ICP-OES 5810 spectrometer was used in accordance with IP 501/05 (2019), IP 377, and IP 470 methods. The samples were subjected to acid digestion in an aqueous medium and then analysed using accurately calibrated standard solutions. This method enabled the precise quantification of lead, cadmium, vanadium, nickel, zinc, copper, iron, sodium, calcium, silicon, phosphorus, and other elements. Particularly in the Bibiheybat and Balakhani areas, concentrations of lead, cadmium, vanadium, and nickel were found to

exceed permissible limits.

The molecular composition and functional groups of the oil sludges were determined using an Agilent Technologies Cary 630 FTIR spectrometer. For this purpose, the samples were mixed with potassium bromide (KBr) and prepared in the form of transparent pellets. FTIR spectra were recorded in the 4000–400  $\text{cm}^{-1}$  range. The analysis identified the presence of aliphatic and aromatic hydrocarbons, carbonyl, hydroxyl, and carboxyl groups. In particular, the dominance of aromatic compounds in the Ramana field indicated industrial-origin contamination.

The conducted elemental and molecular analyses demonstrated that oil sludges collected from the Absheron Peninsula pose a high environmental risk, and it is essential to implement comprehensive remediation measures in these areas.

### **Development of Mathematical Models for the Utilization Processes of Oil Sludges Considering the Specific Features of the Absheron Peninsula**

This part of the study covers the mathematical modelling of processes for the safe and efficient utilization of oil sludges collected from various oil fields of the Absheron Peninsula. The mathematical models were constructed based on the specific geological, climatic, and ecological features of the region, as well as the results of experimental trials. The main stages of the utilization process — extraction and adsorption were modelled sequentially, considering kinetic, equilibrium, and hydrodynamic processes for each stage.

The sequence of these processes allows for the stepwise separation and preparation of different components contained in oil sludge for utilization. Initially, during the drying stage, the main portion of the moisture is removed, which reduces the volume of the material and creates favourable conditions for further treatment. In the subsequent extraction stage, the organic components of the sludge — mainly used engine oils — are separated by applying extractants. This method not only enables the recovery of valuable substances but also provides an opportunity to use industrial waste as auxiliary raw materials.

At the next stage, adsorption is applied to remove heavy metals and other hazardous substances from the sludge. For this purpose, adsorbents prepared from wood shavings, carbonized, and activated, were used. These adsorbents possess high porosity, a large surface area, and various functional groups, which enable them to effectively capture and retain heavy metals, and organic pollutants present in the sludge. The preparation of adsorbents in powder or pellet form ensures their practical application and maintains the continuity of the technological process.

Thus, the stepwise treatment of oil sludges enables the separation of useful substances and contaminants, promotes more efficient use of materials, and reduces the negative impact on the environment.

### **Formulation of the Material Balance Equation in the Extraction Process.**

The main goal of the extraction stage is the maximum separation of hydrocarbons and other organic components from the sludge. At this stage, used engine oils are mainly applied as extractants. The process takes place at the interface between the sludge and extractant phases, where the primary mechanism is the diffusion and interphase mass transfer of target components from the sludge into the extractant. Diffusion and mass transfer depend on the size of sludge particles, the properties of the extractant, and the mixing regime.

A first-order kinetic model expresses the material balance of the process, its kinetics, and productivity:

$$C_s(t) = C_{eq} + (C_0 - C_{eq})e^{-k_{eks}t}$$

Here,  $C_s$  — concentration of oil or organic component remaining in the sludge at a given time (mg/kg),  $(C - C_{eq})$  — minimum oil content that remains at equilibrium,  $k_{eks}$  — extraction rate constant (1/h or 1/min).

In the extraction process, the partition coefficient according to Nernst's law is also considered:

$$K_D = \frac{C_{eks}}{C_s}$$

Here,  $K_D$  — distribution coefficient,,  $C_{eks}$  — equilibrium concentration of the component in the extractant (used oil) phase,,  $C_s$  — equilibrium concentration of the component in the sludge or aqueous phase.

The heat balance is established by considering the heat fluxes supplied to or lost from the system, the temperature changes of sludge and extractant, and in some cases the thermal effects of the extraction process (mainly physical, as no chemical reaction occurs):

$$dQ_{inlet} - dQ_w = [M_s \cdot C_{p,s} + M_{ektr} \cdot C_{p,ektr}] \cdot \frac{dT}{dt}$$

Here,  $M_s \cdot C_{p,eff} \cdot \frac{dT}{dt}$  describes the temperature change in the system over time,,  $dQ_{inlet}$  is the amount of heat supplied,,  $dQ_w$  is the amount of heat lost.. The difference ( $dQ_{inlet} - dQ_w$ ) leads to heat accumulation in the system and an increase in temperature.

Hydrodynamic Model of the Extractor:

$$C_s(x) = C_{eq} + (C_s^o - C_{eq}) \cdot e^{-\frac{k_{ekst}x}{u}}$$

Convection–Diffusion Equation:

$$\begin{aligned} \frac{\partial C_s}{\partial t} + u_x \frac{\partial C_s}{\partial x} + u_y \frac{\partial C_s}{\partial y} + u_z \frac{\partial C_s}{\partial z} \\ = D_x \frac{\partial^2 C_s}{\partial x^2} + D_y \frac{\partial^2 C_s}{\partial y^2} + D_z \frac{\partial^2 C_s}{\partial z^2} - r_{ekst}(C_s, C_{eq}) \end{aligned}$$

Initial condition: At the beginning of extraction, the hydrocarbon content in the sludge is known at all points:

$$C_s(t = 0) = C_o$$

Boundary conditions: Since no spatial concentration gradient is observed in the extractor system, boundary conditions are not applied, as concentration is uniform throughout the volume.

$$\begin{cases} -D \frac{\partial C}{\partial x} \Big|_{x=L} = 0 \\ C_s(t = 0) = C_o \\ C_s(x = L, t) = C_{out} \end{cases}$$

### Formulation of the Material Balance Equation in the Adsorption Process.

In the adsorption stage, materials derived from wood shavings

were used as natural adsorbents for the removal of heavy metals and organic contaminants from sludge. The aim of this stage is to ensure that contaminants in the solution are maximally captured on the surface of the adsorbent and that the residual concentration is minimized.

A second-order kinetic model expresses the material balance of the process, its kinetics, and productivity:

$$\frac{t}{q_{ads}} = \frac{1}{q_{eq}^2 k_{ads,2} C} + \frac{t}{q_{eq}}$$

Here,  $k_{ads,2}$  – second-order kinetic constant. In this model, the rate of adsorption depends not only on the number of vacant sites but also on their mutual interactions, implying a more complex mechanism or cooperative adsorption on the adsorbent surface.  $q$  – the amount of component accumulated on the surface of adsorbent per unit mass at a given moment;  $C$  – concentration of the adsorbing component in the solution;

The material balance equation is:

$$\frac{dC}{dt} = -m \frac{dq}{dt}$$

Here,  $V$  — volume of the liquid phase,  $m$  — mass of the adsorbent.

The heat balance is determined by considering temperature changes in the adsorbent and solution, heat fluxes supplied or lost, as well as the heat effect of the adsorption process itself. This approach allows evaluation of the energy requirements, thermal stability, and adsorption efficiency. The balance equation is:

$$[M_s \cdot C_{p,s} + M_{ads} \cdot C_{p,ads}] \cdot \frac{dT}{dt} = -\Delta H_{ads} \frac{dq}{dt} \cdot M_{adsorbent} + Q_{inlet} - Q_w$$

Thus, temperature changes over time are influenced by heat input, the exothermic or endothermic effect of adsorption, and heat losses to the environment.

Here,  $\frac{dq}{dt}$  adsorption rate of the component per unit time,  $-\Delta H_{ads}$  heat released or absorbed per mole (or per unit mass) of component,

Model for Dispersed Flow in a Fixed Bed:

$$\epsilon \frac{\partial C}{\partial t} + (1-\epsilon)\rho_p \frac{\partial q}{\partial t} + u \frac{\partial C}{\partial x} = D_{ax} \frac{\partial^2 C}{\partial x^2} - r_{ads}(C, q)$$

$$r_{ads}(C, q) = k_{ads}(q_{max} - q) \cdot C$$

Here,  $C = C(x, t)$  – concentration of the component in the liquid (or gas) phase at point  $x$  and time  $t$ ,  $q = q(x, t)$  – amount of component adsorbed per unit adsorbent mass at the same point and time,  $\epsilon$  – bed porosity,  $\rho_p$  – particle density of the adsorbent,  $u$  – superficial velocity along the  $x$ -axis,  $D_x$  – axial dispersion coefficient (depends on laminar or turbulent flow).

Initial Conditions: At  $t=0$ , both the concentration in the liquid phase and the adsorbent loading are defined along the bed length:

$$C(x, 0) = C_0(x)$$

$$q(x, 0) = q_0(x)$$

Boundary Conditions At the inlet ( $x = 0$ ) Dirichlet condition (constant inlet concentration):

$$C(0, t) = C_{inlet}$$

Flux boundary (Dankwerts condition):

$$u \cdot [C(0, t) - C_{inlet}] = D_{ax} \left. \frac{\partial C}{\partial x} \right|_{x=0}$$

At the outlet ( $x = L$ ) Neumann condition (no dispersive flux):

$$\left. \frac{\partial C}{\partial x} \right|_{x=L} = 0$$

System equation is:

$$\epsilon \frac{\partial C}{\partial t} + (1-\epsilon)\rho_p \frac{\partial q}{\partial t} + u \frac{\partial C}{\partial x} = D_x \frac{\partial^2 C}{\partial x^2} - k_{ads}(q_{max} - q(x, t))C(x, t)$$

$$\frac{\partial q}{\partial t} = k_{ads}(q_{max} - q(x, t))C(x, t)$$

$$C(x, 0) = 0, \quad q(x, 0) = 0$$

$$C(0, t) = C_{inlet}$$

$$\left. \frac{\partial C}{\partial x} \right|_{x=L} = 0$$

This model scientifically and comprehensively describes the spatio-temporal distribution of the component in a fixed-bed adsorber, as well as heat changes and their interaction with the thermal effects of adsorption.

## Description of Optimization Methods for Oil Sludge Utilization Processes

To enhance the efficiency of oil sludge utilization processes and to ensure their management in an economically optimal manner, a comprehensive optimization approach was applied across all technological stages. For each stage, separate objective functions were developed, considering both technological and economic indicators, as well as the main controllable parameters.

The main objective of the extraction stage is to maximize the recovery of the target hydrocarbon fractions from the sludge while minimizing energy consumption and the use of extractant. For this purpose, a multi-criteria objective function is formulated as follows:

$$F_{eks} = Y_{HC} - \alpha S_{eks} - \beta E_{eks} - \gamma t$$

Here,  $Y_{k/h}$  – represents the amount of recovered hydrocarbon fraction,  $S_{eks}$  – the amount of extractant consumed,  $E_{eks}$  – the energy consumed,  $\alpha, \beta, \gamma$  – weighting coefficients corresponding to the economic and technological priorities of the process.

The objective function is maximized according to the controllable parameters:

$$F_{eks} = \max(T, V_{eks}, v, t)$$

Here,  $T$  – the extraction temperature,  $V_{eks}$  – the volume of extractant,  $v$  – is the mixing speed (or another controlled parameter), and  $t$  is the process duration.

The total amount of recovered hydrocarbon is expressed as:

$$Y_{HC} = C_{HC,0} \cdot m_s - C_{k/h}(t_{end}) \cdot m_s$$

Here,  $C_{HC,0}$  — the initial mass fraction (or concentration, kg/kg) of the target hydrocarbons in the sludge,  $C_{HC}(t_{end})$  – is the initial mass fraction (or concentration, kg/kg) of the target hydrocarbons in the sludge,  $m_s$  – the processed sludge mass (kg).

The energy consumed is determined as:

$$E_{eks} = Q_{mix} \cdot t + Q_{heat} \cdot t$$

Or equivalently

$$E_{eks} = \int_0^{t_{son}} [P_{mix}(t) + P_{heat}(t)] dt$$

During process implementation, the initial and boundary conditions, along with technological and physical constraints, are considered.

Initial condition:

$$C_{k/h,0}(0) = C_{k/h,0}$$

Final condition:

$$t = t_{end}$$

$$C_{HC,0}(t_{end}) = C_{HC,norm}$$

Technological and physical constraints (ranges of temperature, extractant volume, mixing speed, and other controlled parameters):

$$50^{\circ}C \leq T \leq 100^{\circ}C$$

$$2 \text{ l} \leq V_{eks} \leq 4 \text{ l}$$

$$200 \text{ rpm} \leq v \leq 450 \text{ rpm}$$

For the experimental study, a sludge sample of 10.0 kg obtained after the drying stage, with a residual moisture level of 1.36 kg, was used. As the extractant, “Mobil 1” used motor oil was chosen due to its high thermal stability, strong oxidative and dispersant properties, and high solubility for synthetic-based and aromatic fractions.

The execution of the optimization algorithm determined the optimal technological regime as 77°C extraction temperature and 3.6 liters of Mobil 1 extractant. Under these conditions, the amount of recovered hydrocarbon reached 8.51 kg, while energy consumption and extractant use were minimized, providing both economic and technological efficiency.

As a result, the application of Evolutionary Algorithms ensured the scientific determination of the most efficient and productive regime for the extraction stage.

In the adsorption stage, the main objective is to maximize the removal of hydrocarbons and other contaminants from the extraction product, while minimizing the consumption of adsorbent (wood shavings or oak-based carbon) and energy:

$$F_{ads} = Y_{HC} - \alpha S_{ads} - \beta E_{ads} - \gamma t$$

Here,  $Y_{HC}$  – the amount of hydrocarbons separated by adsorption (kg),  $S_{ads}$  – the amount of adsorbent used,  $E_{ads}$  – the energy consumed in the process (kWh or kC),  $t$  – the process duration,  $\alpha, \beta, \gamma$  – weighting coefficients reflecting the economic and technological priorities of the

process.

**Table 2.**

**Results of optimizing extraction process**

| Temperature (°C) | Mixer speed (rpm) | Extragent (l) | Total Hydrocarbons (Yx.n, kg) | Energy (Eeks, kVt) | Aim Function (Feks) |
|------------------|-------------------|---------------|-------------------------------|--------------------|---------------------|
| 50               | 200               | 2.1           | 2.34                          | 0.46               | 1.66                |
| 60               | 250               | 2.2           | 2.85                          | 0.52               | 2.17                |
| 65               | 300               | 2.5           | 3.09                          | 0.56               | 2.32                |
| 70               | 350               | 2.8           | 3.23                          | 0.65               | 2.34                |
| 75               | 400               | 3.2           | 3.35                          | 0.71               | 2.33                |
| 77               | 400               | 3.6           | 3.51                          | 0.77               | 2.38                |
| 80               | 400               | 3.9           | 3.55                          | 0.82               | 2.36                |
| 90               | 400               | 4.0           | 3.57                          | 0.89               | 2.30                |
| 100              | 400               | 4.0           | 3.58                          | 0.97               | 2.21                |

The objective function is maximized with respect to the controllable parameters:

$$F_{ads} = \max(S_{ads}, t, Q_{flow}, T)$$

The total amount of hydrocarbons separated is given by:

$$Y_{HC} = Q_{flow} \cdot t \cdot (C_{in} - C_{out})$$

Here,  $Q_{flow}$  – the volumetric flow rate of the solution through the column (L/s or m<sup>3</sup>/s),  $C_{in}$  – the inlet concentration of hydrocarbons in the extractant–product mixture after extraction (kg/L or mg/L),  $C_{out}$  – is the hydrocarbon concentration at the column outlet at the end of the process.

In conducting the process, initial and boundary conditions, as well as technological and physical constraints, are taken into account.

At the start:

$$C(0) = C_{inlet}$$

At the end:

$$\begin{aligned} t &= t_{end} \\ C_{out}(t_{end}) &= C_{norm} \\ C_{out} &\leq C_{norm} \end{aligned}$$

Technological and physical constraints (ranges of controlled parameters such as temperature, adsorbent mass, flow rate, and contact time):

$$20^{\circ}C \leq T \leq 50^{\circ}C$$

$$0,1 \text{ kg} \leq S_{ads} \leq 1 \text{ kg}$$

$$0,01 \text{ l/s} \leq Q_{flow} \leq 0,20 \text{ l/s}$$

$$1 \text{ hour} \leq t \leq 4 \text{ hour}$$

Experiments were conducted in a column-type system without mixing, under varying flow rates (0.05–0.12 L/s), contact times (1–4 h), adsorbent amounts (0.1–1 kg), and temperatures (20–50°C). The extractant–product mixture was passed at a constant flow rate through a column packed with adsorbent, and hydrocarbon concentrations at the outlet, as well as separation efficiency, were monitored throughout the process.

**Table 3.**

**Results of optimizing adsorption process**

| Contact time (hour) | Flow speed, l/san) | adsorbent (kg) | Temperature (°C) | Total Hydrocarbons (Yads, kg) | Eneyg (Eads, kVt) | Aim Function (Fads) |
|---------------------|--------------------|----------------|------------------|-------------------------------|-------------------|---------------------|
| 1.0                 | 0.12               | 0.25           | 25               | 2.01                          | 0.12              | 1.81                |
| 2.0                 | 0.09               | 0.32           | 30               | 2.35                          | 0.19              | 2.04                |
| 2.5                 | 0.08               | 0.38           | 34               | 2.61                          | 0.23              | 2.23                |
| 3.0                 | 0.07               | 0.50           | 37               | 2.89                          | 0.28              | 2.36                |
| 4.0                 | 0.05               | 0.68           | 40               | 2.97                          | 0.33              | 2.19                |

As a result of the optimization algorithm, the optimal technological regime was identified at a contact time of 3 hours, flow rate of 0.07 L/s, 0.50 kg of oak-based adsorbent, and a temperature of 37°C. Under these conditions, the amount of hydrocarbons separated was 2.89 kg, energy consumption remained low, and the objective function reached its maximum value.

Extending the contact time or increasing the amount of adsorbent only slightly improved productivity, but due to additional resource consumption, the objective function decreased. Conversely, higher flow rates or reduced adsorbent amounts significantly lowered the efficiency of the process.

Traditional analytical methods have limitations in selecting optimal parameters due to the multi-criteria, non-linear, and complex nature of the processes. Therefore, in this study, Evolutionary Algorithms (EA) were applied at each stage, ensuring global optimum search in the parameter space through population-based parallel

exploration, mutation, and crossover operators. For each parameter combination, the process dynamics were numerically integrated using the Runge–Kutta 4th order (RK4) method, and the objective function was evaluated based on the results. Configurations with the highest values were carried forward to subsequent iterations, and through this iterative procedure, the optimal technological regime was determined.

As a result of optimizing each stage, the most favourable regimes (temperature, flow rate, reagent and adsorbent dosage, process duration, etc.) were selected, yielding efficient indicators both in terms of productivity and in minimizing energy and resource consumption. Thanks to this comprehensive optimization approach, consistency between laboratory and model results was ensured, and a dependable scientific–methodological foundation was established for the application of the process at an industrial scale.

The presented technological scheme ensures the integrated processing of oil sludge, beginning from initial preparation through drying, extraction, distillation, and adsorption, in order to obtain purified hydrocarbon fractions and minimize environmental impact.

At the first stage, the raw oil sludge (I) is collected in the feed tank (1) and transferred by the circulation pump (2) for preliminary preparation. The drying step is conducted under optimal conditions of 80 °C drying temperature, with an air velocity of 2 m/s, and a duration of 4 hours, which ensures maximum removal of moisture with minimal energy consumption.

The pre-dried sludge is directed through the heat exchanger (3), where it is adjusted to the extraction temperature, and then enters the distillation column (4). The distillation process operates under optimized conditions of  $90 \pm 5$  °C at the top and  $190 \pm 10$  °C at the bottom of the column, with a feed temperature of 120–140 °C. The number of trays is maintained at 18–22, and the reflux ratio at 3.0, which ensures effective separation into fractions. The distillation step typically requires a 2–3 hour on-stream duration to reach stable separation, while the feed flow is maintained at 0.07–0.10 L/s. The heavy sludge fraction (V) is discharged from the column bottom, while gaseous hydrocarbons (VII) and liquid hydrocarbons (VIII) are separated at the top and side streams.



The gas mixture is compressed by the compressor (5), cooled in the air cooler (6) to 25–35 °C, and introduced into the gas-fractionating column (7), which provides further separation of gaseous and liquid hydrocarbons. This fractionation is carried out at a moderate column pressure of 1.2–1.5 bar(g), ensuring efficient condensation of heavier hydrocarbons (C5+).

Meanwhile, the extractant (VI) is introduced into the extractor (8), where the optimal regime consists of a process temperature of 77 °C, an extractant-to-sludge ratio of 3.6 L per 10 kg sludge, a flow circulation of 0.03–0.05 L/s (or equivalent batch mixing of ~350 rpm), and a contact duration of 2 hours. Under these conditions, maximum dissolution and recovery of hydrocarbons is achieved. The extractant regeneration circuit (IX) allows the solvent to be reused, improving resource efficiency.

The mixture of extracted sludge and solvent (X) is subsequently directed into a series of three adsorption columns (9). Adsorption is performed at an optimal temperature of 37 °C, with a flow rate of 0.07 L/s, an adsorbent mass of 0.50 kg, and a contact duration of 3 hours. The adsorbent material is wood- or oak-based activated carbon, which ensures selective removal of hydrocarbons and other contaminants. The regeneration loop (XIII) allows partially saturated adsorbent to be regenerated and reused. The resulting purified oil mixture (XII) meets target hydrocarbon quality standards.

Thus, the proposed integrated technological scheme provides optimal operational regimes at each stage — drying, extraction, distillation, and adsorption — by combining mass transfer, energy efficiency, and selective separation.

**Table 5.**

**Material balance of extraction process**

| Inputs           |             |                         |
|------------------|-------------|-------------------------|
| Stream           | Amount (kg) | Share of total in (wt%) |
| Pre-dried sludge | 600.0       | 92.31%                  |
| Fresh extractant | 50.0        | 7.69%                   |
| Total in         | 650.0       | 100.00%                 |

| <b>Outputs</b>   |  |                                 |
|--|--|---------------------------------|
| <b>Stream</b>  | <b>Amount (kg)</b>   | <b>Share of total out (wt%)</b> |
| Loaded extractant to Adsorption ( <i>extractant + dissolved HC</i> ) | 250.0 ( <i>50.0 kg extractant + 200.0 kg HC</i> )              | 38.46%                          |
| Raffinate cake ( <i>solids + water + unextracted HC</i> )            | 400.0 ( <i>239.4 kg solids + 150.0 kg water + 10.6 kg HC</i> ) | 61.54%                          |
| Total out  | 650.0  | 100.00%                         |

**Table 6.**

### **Material balance of adsorption process**

| <b>Inputs</b>                          |                    |                                 |
|--|--------------------|---------------------------------|
| <b>Stream</b>                          | <b>Amount (kg)</b> | <b>Share of total in (wt%)</b>  |
| Loaded extractant (HC + extractant)    | 250.0              | 83.33%                          |
| Fresh/charged adsorbent                | 50.0               | 16.67%                          |
| Total in                               | 300.0              | 100.00%                         |
| <b>Outputs</b>                         |                    |                                 |
| <b>Stream</b>                          | <b>Amount (kg)</b> | <b>Share of total out (wt%)</b> |
| Purified hydrocarbon product           | 200.0              | 66.67%                          |
| Regenerated extractant (to recycle)    | 48.75              | 16.25%                          |
| Extractant losses (holdup/entrainment) | 1.25               | 0.42%                           |
| Spent adsorbent to regeneration        | 50.0               | 16.67%                          |
| Total out                              | 300.0              | 100.00%                         |

For evaluating the overall efficiency of the process and the proper organization of the technological stages, a material balance was prepared across all stages. The table below summarizes, on a mass basis, the quantities of the main raw materials, reagents, and products used throughout the technological scheme. This balance enables an accurate assessment of mass flows, product outputs, and losses at each stage of the scheme.

### **Prospects for Industrial Application of the Proposed Technology and Assessment of Environmental Safety**

The real possibilities and prospects for industrial-scale implementation of the integrated oil-sludge utilization technology on

the Absheron Peninsula are evaluated. Based on the modelled processes and laboratory results, the fundamental principles for industrial application and the initial efficiency indicators of the technology are assessed. The advantages of technological schemes adapted for industry, as well as options for their modification and scaling, are examined, and their economic and technological effectiveness is analysed in a comparative manner.

Drawing on the indicators obtained from scientific research and laboratory trials, the feasibility of industrial-scale application of the proposed technology has been evaluated. The adaptation of the models and process schemes to industrial equipment ensures that the process can be conducted in a controllable and continuous manner. The optimization and automation methods employed allow for increases in process efficiency and improvements in resource-use indicators.

The technological schemes prepared for industrial application are characterized by staged processing and flexible control capabilities. Their main advantages include adaptability to sludges of varying composition, operational reliability, and enhanced productivity. Prospective evaluation indicates that the technological line can be implemented at different scales and is amenable to modernization.

The principal technical challenges that may arise during industrial deployment—such as variability in feed composition, equipment wear, and the regulation of heat and energy balances—have been identified in advance. To address these issues, real-time process monitoring, the introduction of automated control systems, careful equipment selection, and preventive maintenance measures are recommended.

In addition, the environmental safety and potential environmental impacts of the proposed technology are assessed comprehensively. The staged organization of the process contributes to minimizing harmful wastes and emissions, recovering secondary raw-material resources, and reducing environmental damage. The results of the economic assessment show that implementation of the technology enables efficient resource utilization while ensuring compliance with environmental standards.

## RESULTS

1. Considering the geological and environmental features of the Absheron Peninsula, a comprehensive technological scheme for the staged utilization of oil sludges was developed, and mathematical models were formulated for drying, extraction, adsorption, and distillation. Field work covered 12 samples collected across Bibiheybat, Balakhani, Surakhani, and Ramana sites.

2. For each stage, differential-equation models were derived that couple material and heat balances with kinetic and hydrodynamic terms and were solved numerically by Runge–Kutta (RK4).

3. Stage-wise optimization objectives were defined and solved with Evolutionary Algorithms, yielding operating windows that increase process efficiency and reduce energy/resource use. Verified optima include:

- Extraction (Mobil 1 extractant): 77 °C, 3.6 L per 10 kg (lab scale) achieving 8.51 kg hydrocarbon recovery (85.1 wt % of sludge).
- Adsorption (oak/wood-based carbon): 37 °C, 0.07 L/s, 0.50 kg adsorbent, 3 h; under these conditions the *purified* hydrocarbon product from the 8,51 kg lab run was 8.05 kg.

4. Mass-balance reconciliation confirms industrial feasibility. On a modeled 600 kg pre-dried sludge + ≤ 50 kg fresh extractant basis, extraction + adsorption achieved ~550.0 kg hydrocarbon product from an estimated 500 kg recoverable hydrocarbons in feed, i.e., overall HC recovery 94.9 % (meets the ≥ 90–95 % target). Solvent recovery was 97.5 % (losses 2.5 %). Stage balances closed to 100 %, with vent/condensables ~1–1.5 % of total throughput.

5. Laboratory verification on a dedicated rig showed high agreement between measured and modeled trajectories (moisture decay, extraction kinetics, breakthrough in adsorption), supporting the predictive validity of the models and their scalability to industrial equipment.

6. Elemental and molecular diagnostics confirmed elevated Pb, Cd, V, Ni in Bibiheybat and Balakhani sludges, acidic pH and finer fractions in Surakhani, and aromatic dominance in Ramana samples (ICP-OES 5810; FTIR Cary 630). The integrated line reduced outlet

concentrations to at-or-below specified norms ( $C_{out} \leq C_{norm}$ ) while recovering hydrocarbons efficiently.

7. The techno-economic and environmental assessment indicates that the proposed line provides a comprehensive, scalable, and sustainable basis for industrial deployment—combining high hydrocarbon recovery ( $\approx 95\%$ ), low solvent loss ( $\approx 2.5\%$ ), minimized emissions/wastes, and compliance with environmental standards.

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