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RESEARCH ARTICLE

TREATMENT OF OIL-CONTAINING WASTEWATER BY PHYSICOCHEMICAL METHODS

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Abstract. *This paper presents the results of a study on the efficiency of treating oil-containing wastewater from a locomotive depot using combined physicochemical processes. The relevance of the study is conditioned by the high aggregative stability of oil-in-water emulsions formed in wastewater from railway enterprises, as well as the necessity to meet regulatory discharge standards for centralized sewerage systems. The mechanisms of oil emulsion formation and their influence on treatment processes were analyzed. The methodology included the sequential application of gravitational sedimentation, coagulation–flocculation using iron(II) sulfate with pH adjustment by lime, and filtration–adsorption polishing using wood shavings and sulfonated carbon. Laboratory experiments were conducted using real wastewater samples from a locomotive depot with an initial petroleum hydrocarbon concentration ranging from 40 to 150 mg/L. The results demonstrated the low efficiency of mechanical settling in the presence of stable emulsions. The most significant reduction in petroleum hydrocarbon concentration was achieved during the coagulation stage at pH 8.0–8.5, where the treatment efficiency reached up to 98%. The final filtration–adsorption stage provided additional removal of residual hydrocarbons, reducing their concentration to approximately 2 mg/L. The discussion confirms that the combination of coagulation and filtration–adsorption processes represents an optimal approach for treating oil-containing wastewater from transport enterprises. The developed technological scheme ensures compliance with regulatory requirements while maintaining relatively low operational costs and can be recommended for practical implementation.*

Keywords: *oil-containing wastewater, coagulation, adsorption, filtration, oil emulsions, iron sulfate.*

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ҒЫЛЫМИ МАҚАЛА

МҰНАЙ ҚАЛДЫҚТАРЫ БАР ЛАС СУЛАРДЫ ФИЗИКА-ХИМИЯЛЫҚ ӘДІСТЕРМЕН ТАЗАРТУ

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Аңдатпа. *Бұл жұмыста аралас физика-химиялық процестерді қолдана отырып, локомотив депосынан құрамында майы бар ағынды суларды тазарту тиімділігі туралы зерттеу нәтижелері келтірілген. Зерттеудің өзектілігі теміржол кәсіпорындарының ағынды суларында пайда болатын судағы мұнай эмульсияларының агрегаттық тұрақтылығының жоғары болуымен, сондай-ақ орталықтандырылған кәріз жүйелері үшін ағызудың нормативтік стандарттарын сақтау қажеттілігімен байланысты. Мұнай эмульсиясының түзілу механизмдері және олардың тазарту процестеріне әсері талданды. Әдістеме гравитациялық шөгінділерді дәйекті қолдануды, pH-ты әкпен реттей отырып, темір(II) сульфатын қолдана отырып коагуляция-флокуляцияны және ағаш жоңқалары мен сульфатталған көміртекті қолдана отырып фильтрация-адсорбциялық жылтыратуды қамтыды. Зертханалық тәжірибелер бастапқы мұнай көмірсутегі концентрациясы 40-тан 150 мг/л-ге дейінгі локомотив депосынан алынған ағынды сулардың нақты үлгілерін қолдану арқылы жүргізілді.нәтижелер тұрақты эмульсиялар болған кезде механикалық тұндыру тиімділігінің төмендігін көрсетті. Мұнай көмірсутегі концентрациясының едәуір төмендеуіне pH 8,0–8,5 коагуляция кезеңінде қол жеткізілді, мұнда тазарту тиімділігі 98% дейін жетті. Сүзу - адсорбцияның соңғы сатысы көмірсутектердің қалдықтарын қосымша жоюды қамтамасыз етті, олардың концентрациясын шамамен 2 мг/л дейін төмендетті.талқылау коагуляция және сүзу - адсорбция процестерінің үйлесуі көлік кәсіпорындарының құрамында мұнай бар ағынды суларды тазартудың оңтайлы тәсілі екенін растайды. Әзірленген технологиялық схема салыстырмалы түрде төмен операциялық шығындарды сақтай отырып, нормативтік талаптардың сақталуын қамтамасыз етеді және практикалық іске асыру үшін ұсынылуы мүмкін.*

Түйін сөздер: *мұнайлы ағын сулар, коагуляция, адсорбция, сүзу, мұнай эмульсиялары, темір сульфаты.*

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НАУЧНАЯ СТАТЬЯ

ОЧИСТКА НЕФТЕСОДЕРЖАЩИХ СТОЧНЫХ ВОД ФИЗИКО-ХИМИЧЕСКИМИ МЕТОДАМИ

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Аннотация. *В данной работе представлены результаты исследования эффективности очистки нефтесодержащих сточных вод локомотивного депо с использованием комбинированных физико-химических процессов. Актуальность исследования обусловлена высокой агрегативной стабильностью водонефтяных эмульсий, образующихся в сточных водах железнодорожных предприятий, а также необходимостью соблюдения нормативных норм сброса для централизованных систем канализации. Были проанализированы механизмы образования нефтяных эмульсий и их влияние на процессы очистки. Методика включала последовательное применение гравитационного осаждения, коагуляцию–флокуляцию с использованием сульфата железа (II) с регулированием pH известью и фильтрационно-адсорбционную полировку с использованием древесной стружки и сульфированного угля. Лабораторные эксперименты проводились с использованием реальных образцов сточных вод локомотивного депо с начальной концентрацией нефтяных углеводородов в диапазоне от 40 до 150 мг/л. Результаты показали низкую эффективность механического отстаивания в присутствии стабильных эмульсий. Наиболее значительное снижение концентрации нефтяных углеводородов было достигнуто на стадии коагуляции при pH 8,0-8,5, где эффективность очистки достигала 98%. Заключительная стадия фильтрации-адсорбции позволила дополнительно удалить остаточные углеводороды, снизив их концентрацию примерно до 2 мг/л. Обсуждение подтверждает, что сочетание процессов коагуляции и фильтрационно-адсорбции представляет собой оптимальный подход к очистке нефтесодержащих сточных вод транспортных предприятий. Разработанная технологическая схема обеспечивает соответствие нормативным требованиям при сохранении относительно низких эксплуатационных затрат и может быть рекомендована для практической реализации.*

Ключевые слова: *нефтесодержащие сточные воды, коагуляция, адсорбция, фильтрация, нефтяные эмульсии, сульфат железа.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

Oil-containing wastewater generated during the construction, operation, maintenance, and modernization of railway transport infrastructure represents one of the most challenging types of industrial effluents requiring efficient engineering treatment solutions. The design of modern transport facilities increasingly incorporates advanced wastewater treatment systems as an integral component of sustainable infrastructure development and environmental protection. Its specific feature is the presence of stable oil-in-water emulsions stabilized by surfactants, corrosion products, and fine suspended solids. These emulsions exhibit high aggregative stability, significantly reducing the effectiveness of conventional mechanical treatment methods **(Zheng, X., & Wang, T., 2021)**.

Oil-containing wastewater represents a major environmental challenge worldwide. According to recent estimates, over 300 million tonnes of petroleum-contaminated water are generated annually by industrial and transport sectors globally **(Alenov et al., 2025)**. When discharged without adequate treatment, petroleum hydrocarbons contaminate surface and groundwater resources, cause long-term degradation of aquatic ecosystems, and pose serious risks to drinking water quality and public health. In the countries of Central Asia, where water resources are already under significant stress due to arid climate conditions and competing agricultural demands, the proper treatment of oil-containing effluents is of particular importance.

In modern civil and transport engineering, environmental protection has become an essential component of the design, construction, reconstruction, and operation of industrial and transport infrastructure. Railway depots, maintenance facilities, and other engineering structures must be equipped with reliable wastewater collection and treatment systems that comply with environmental and construction regulations. The efficiency of such systems directly affects the operational sustainability of infrastructure facilities, the protection of soil and groundwater, and the long-term durability of engineering structures exposed to aggressive industrial environments. Therefore, the development of cost-effective technologies for the treatment of oil-containing wastewater should be considered not only as an environmental challenge but also as an important engineering task in modern construction practice. The integration of advanced physicochemical treatment methods into the design of wastewater treatment facilities contributes to sustainable infrastructure development and supports the implementation of green construction principles.

At locomotive depots, petroleum hydrocarbons enter wastewater as a result of lubricant and diesel fuel leaks, washing of equipment and assemblies, and the operation of compressor and auxiliary systems **(Li, Y., 2020)**. When discharged into municipal sewerage systems, such wastewater can disrupt the operation of treatment plants, inhibit biological processes, and lead to the accumulation of hydrocarbons in sludge. **(Li, Y., 2020)** A variety of treatment technologies have been developed for oil-containing wastewater, including mechanical methods (gravity separators, oil traps, and centrifugation), chemical methods (coagulation, flotation, and advanced oxidation), biological treatment, and membrane technologies. However, each of these methods has significant limitations when applied individually. Mechanical methods are effective only for free and dispersed oil, but fail to remove stable emulsified hydrocarbons. Chemical oxidation processes often require expensive reagents and generate secondary pollutants. Membrane technologies, while highly efficient, are associated with high capital and operating costs as well as membrane fouling problems. Consequently, combined physicochemical treatment schemes that integrate coagulation, flocculation, and adsorption-filtration stages are considered the most promising approach for achieving reliable treatment of railway transport wastewater to regulatory standards.

According to the regulations of the Republic of Kazakhstan, the maximum allowable concentration of petroleum hydrocarbons in wastewater discharged into centralized sewerage systems is 5 mg/L. However, actual concentrations in wastewater from locomotive depots after oil traps often reach 40-150 mg/L, indicating the need for more efficient treatment technologies.

The relevance of developing effective treatment solutions is particularly acute for Kazakhstan, which operates one of the largest railway networks in Central Asia, with a total length exceeding 16.000 km. The growing volume of locomotive maintenance and repair operations generates substantial quantities of oil-contaminated wastewater at numerous depot facilities across the country **(Moldamuratov et al., 2025)**. At the same time, the availability of specialized treatment technologies remains limited, and many existing facilities rely on outdated oil trap systems that fail to meet current discharge standards. This situation creates an urgent need for cost-effective treatment solutions based on locally available, affordable reagents and materials that can be readily implemented at railway maintenance facilities throughout the region **(Ilyassova et al., 2025).**

The aim of this study is to experimentally evaluate the efficiency of combined physicochemical treatment methods for oil-containing wastewater and to develop an optimal technological scheme capable of ensuring compliance with regulatory water quality standards.

Modern studies on the treatment of oil-containing wastewater confirm that the stability of emulsions is determined by the presence of surfactants and colloidal stabilizers that prevent oil droplet coalescence **(Li et al., 2026)**. Numerous studies report that gravitational separation methods are effective only for removing free oil, whereas emulsified hydrocarbons require prior destabilization.

Coagulation using iron and aluminum salts is considered one of the most effective approaches for breaking oil emulsions **(Luthfiana et al., 2026)**. Metal hydroxides formed during hydrolysis exhibit high sorption capacity and promote particle aggregation **(Elgarahy et al., 2025; Fourjani et al., 2025)**. The efficiency of coagulation strongly depends on pH conditions and coagulant dosage.

In recent years, increasing attention has been given to the use of natural adsorption materials, including wood-based and biochar sorbents **(Bahramian et al., 2025; Bilad et al., 2026; Chu & Wang, 2022).** These materials enable deep polishing of treated wastewater and reduction of petroleum hydrocarbon concentrations below regulatory limits **(Moldamuratov et al., 2023, 2024; Wang et al., 2026)**. Despite extensive research, the optimization of combined coagulation and filtration–adsorption processes for specific industrial effluents, particularly wastewater from railway enterprises, remains an important and relevant scientific task.

The physicochemical characteristics of oil-in-water emulsions in industrial wastewater have been studied extensively. Emulsion stability is governed by the zeta potential of droplets, the concentration and type of surfactants present, and the ionic strength of the aqueous phase **(Zheng & Wang, 2021)**. When surfactant concentrations exceed critical micelle concentration values, the resulting electric double layer around droplets prevents their coalescence even under prolonged gravitational settling conditions. Studies have demonstrated that for wastewater from mechanical maintenance facilities, the zeta potential of oil droplets typically ranges from - 25 to - 45 mV, indicating high colloidal stability **(Li, 2020).** This electrokinetic barrier must be overcome before effective separation can be achieved.

Coagulation with iron(II) and iron(III) salts has been widely reported as a highly effective pre-treatment step for emulsified oily wastewater. The mechanism involves charge neutralization of negatively charged oil droplets by positively charged iron hydroxide species formed upon hydrolysis, followed by sweep flocculation in which amorphous $Fe(OH)_3$ precipitates entrap and remove residual colloids **(Elgarahy et al., 2025; Fourjani et al., 2025).** Optimal coagulation is generally observed at pH 7.5-8.5, where iron hydroxide precipitation is thermodynamically favored and the resulting flocs possess maximum surface area. Dosage optimization is critical: insufficient coagulant leaves emulsion droplets destabilized but not aggregated, while overdosing can cause charge reversal and restabilization. Reported optimal $FeSO_4$ dosages in comparable studies range from 20 to 80 mg/L depending on initial oil concentration and wastewater composition **(Haddaji et al., 2024).**

Post-coagulation filtration and adsorption polishing represents the second critical step in combined treatment schemes. Lignocellulosic materials, including wood shavings, sawdust, and agricultural by-products, have demonstrated significant sorption capacity for petroleum hydrocarbons owing to their high surface area and the presence of hydroxyl, carboxyl, and ether functional groups **(Bahramian et al., 2025).** Carbonaceous sorbents such as activated carbon and sulfonated carbon exhibit superior micropore structure and high specific surface area, typically in the range of 800-1200 m²/g, enabling effective removal of dissolved and emulsified hydrocarbons from pre-treated wastewater **(Bilad et al., 2026; Chu & Wang, 2022).** Combined use of natural and carbonaceous adsorbents in sequential filter beds has been shown to reduce residual petroleum hydrocarbon concentrations to below 2 mg/L, meeting the regulatory requirements for discharge to municipal sewerage systems **(Moldamuratov et al., 2023, 2024; Wang et al., 2026).**

Railway transport infrastructure generates oil-containing wastewater with characteristics that differ from those of the oil and gas industry or food processing plants. The specific pollutant profile includes diesel fuel residues, mineral lubricating oils, hydraulic fluids, and anti-corrosion compounds, which collectively produce complex polydisperse emulsions. The presence of fine metal particles and corrosion products originating from rolling stock maintenance further complicates treatment by contributing to emulsion stabilization and fouling of filter media. Despite the significance of this wastewater category in countries with developed railway infrastructure, dedicated treatment optimization studies remain scarce compared to oilfield-produced water research. The present study addresses this gap by evaluating a cost-effective, multi-stage physicochemical treatment approach using locally available reagents and filter materials **(Andrews et al., 2021; F. Yu et al., 2025).**

2 MATERIALS AND METHODS

The object of the study was real wastewater from a locomotive depot generated during maintenance and repair of rolling stock. The average daily wastewater volume was approximately 170 m^3. The petroleum hydrocarbon concentration after oil traps ranged from 40 to 150 mg/L.

Laboratory studies were conducted using a three-stage treatment scheme: gravitational sedimentation; coagulation–flocculation treatment; filtration–adsorption polishing.

During sedimentation, 1000 mL wastewater samples were settled in graduated cylinders for 24 hours. Coagulation treatment was carried out using iron(II) sulfate at dosages of 10-50 g/m^3, with pH adjustment to 8.0-8.5 using a lime solution. Clarification was evaluated visually and analytically.

Filtration–adsorption polishing was performed using wood shavings and sulfonated carbon **(Yu et al., 2026)**. Treatment efficiency was assessed based on filtration rate and residual petroleum hydrocarbon concentration determined by an extraction–gravimetric method in accordance with applicable standards.

Prior to the treatment experiments, wastewater samples were characterized for key physicochemical parameters. pH was measured using a calibrated digital pH meter (accuracy ±0.01 pH units). Turbidity was determined by nephelometry using a bench-top turbidimeter. Total suspended solids (TSS) were determined by gravimetric analysis following filtration through a glass fiber filter (GF/C, 1.2 µm pore size) and drying at 105 °C to constant mass. The petroleum hydrocarbon concentration was determined by the extraction–gravimetric method in accordance with **GOST 31957-2012**, using hexane as the extraction solvent. The average physicochemical characteristics of the wastewater used in the experiments are summarized in **Table 1.**

Table 1.
Physicochemical characteristics of the initial locomotive depot wastewater (author's material)

Parameter	Value / Range	Regulatory limit (RK)
pH	6.5-7.2	6.0–9.0
Turbidity, NTU	120-580	≤1.5
Total suspended solids (TSS), mg/L	85-340	≤300
Petroleum hydrocarbons (PHC), mg/L	40-150 (mean 87.5)	≤5
Chemical oxygen demand (COD), mg O_2/L	350-1200	≤500
Wastewater temperature, °C	14-22	-

Iron(II) sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$, reagent grade, purity ≥ 98.5%) was used as the coagulant. Stock solutions of 50 g/L were prepared in distilled water and used within 24 hours of preparation to prevent oxidation. pH adjustment was performed using freshly prepared lime suspension ($Ca(OH)_2$, 10 g/L) or dilute hydrochloric acid solution (0.1 M HCl) as required. Lime was preferred over sodium hydroxide for pH correction due to its lower cost and wider availability at industrial facilities in Kazakhstan, as well as its contribution to floc formation through calcium ion bridging.

The filter bed for the adsorption-filtration stage consisted of a lower layer of sulfonated carbon (particle size 2-5 mm, specific surface area 950 m²/g) and an upper layer of wood shavings (softwood, particle size 5-20 mm, bulk density 120 kg/m³). Both materials were pre-washed with distilled water and dried prior to use. The total filter bed height was 400 mm, comprising 200 mm of wood shavings and 200 mm of sulfonated carbon. Laboratory filter columns of internal diameter 50 mm were used. The hydraulic loading rate was varied between 2 and 8 m/h to evaluate filtration performance under different flow conditions.

Coagulation experiments were performed using a standard jar test procedure. A measured volume of $FeSO_4$ solution was added to 1000 mL wastewater samples in graduated cylinders under mechanical stirring at 100 rpm for 2 minutes (rapid mixing), followed by slow stirring at 40 rpm for 15 minutes (flocculation), and then settling for the designated time period. pH was monitored continuously and adjusted to the target value of 8.0-8.5 immediately before coagulant addition using lime suspension. The coagulant dosage was varied from 10 to 50 g/m³ to identify the optimal dose corresponding to maximum clarification efficiency. Samples for petroleum hydrocarbon analysis were collected from the upper 200 mm of the clarified water layer at each time interval using a pipette, avoiding disturbance of the settled sludge layer.

3 RESULTS AND DISCUSSION

The results showed that after 24 hours of settling, only a small amount of free oil was separated from the wastewater, while the concentration of emulsified hydrocarbons remained at approximately 40 mg/L. This confirms the low efficiency of mechanical treatment in the presence of stable oil emulsions.

The clarification kinetics of the wastewater after coagulation were evaluated by measuring the height of the clarified layer over time. The experimental results are summarized in **Table 2**, demonstrating rapid clarification during the first hour of treatment followed by stabilization of the clarified layer height.

Table 2.
Clarification dynamics of wastewater after coagulation

Time, h	0.1	0.2	0.5	1.0	2.0	3.0	5.0	10.0
Height of clarified layer, mm	50	200	400	450	470	475	476	476

The effect of flocculant dosage on the sedimentation rate is illustrated in **Figure 1**, demonstrating the presence of an optimal dosage corresponding to the maximum clarification efficiency.

The most significant reduction in petroleum hydrocarbon concentration was achieved during coagulation with iron(II) sulfate at pH 8.0-8.5. The formation of iron hydroxide flocs ensured rapid clarification within the first 30-60 minutes. The treatment efficiency reached up to 98%, indicating effective destabilization of oil emulsions.

The final filtration stage using wood shavings and sulfonated carbon provided additional removal of residual petroleum hydrocarbons **(Chu & Liu, 2025)**. The filtration efficiency ranged from 95 to 97%, and the residual hydrocarbon concentration in treated water was reduced to approximately 2 mg/L **(Haddaji et al., 2024)**, meeting regulatory discharge requirements.

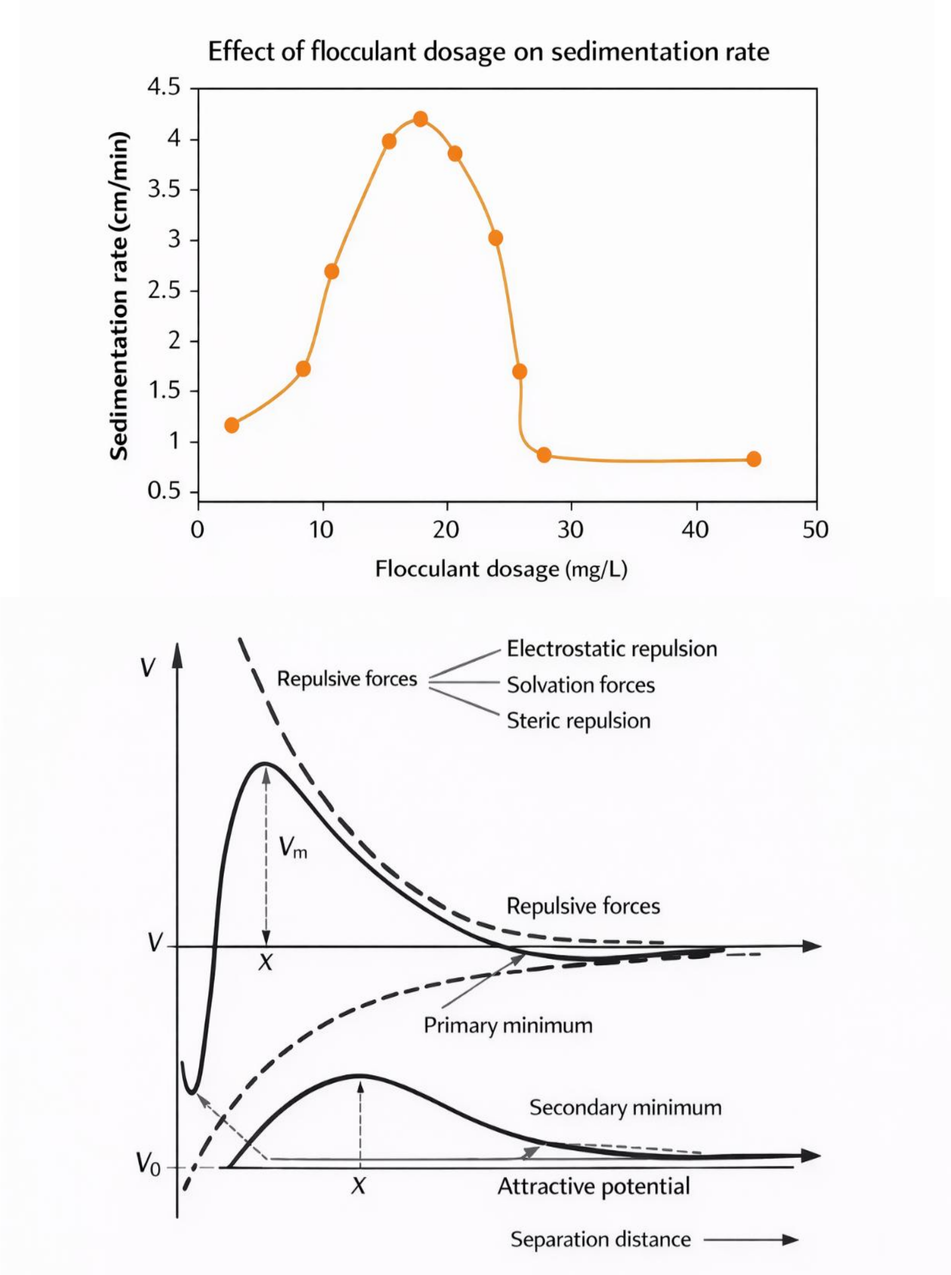

Figure 1 - Comparison of treatment schemes: (a) Scheme without coagulation; (b) Scheme with coagulation–flocculation (author's material)

The performance of the filtration stage was evaluated by comparing settled and unsettled wastewater after coagulation. The results, including filtration rate and removal efficiency, are summarized in **Table 3**. The data indicate that preliminary settling improves hydraulic performance; however, high treatment efficiency is maintained even without the settling stage.

To evaluate the reproducibility of the experimental results, triplicate measurements were conducted for each treatment stage under identical conditions. Statistical analysis was performed on the obtained datasets. The mean petroleum hydrocarbon removal efficiency during the coagulation stage was 97.4%, with a standard deviation (SD) of ±0.8% (n = 3). The coefficient of variation (CV) was 0.82%, confirming high reproducibility of the coagulation process. For the filtration-adsorption stage, the mean removal efficiency was 96.1% (SD = ±0.7%, CV = 0.73%). The combined three-stage treatment process achieved a mean overall removal efficiency of 98.6% (SD = ±0.5%), reducing the initial petroleum hydrocarbon concentration from a mean value of 87.5 mg/L (range: 40-150 mg/L) to a final residual concentration of 1.8-2.3 mg/L, which is well below the maximum allowable concentration of 5 mg/L established by Kazakhstani regulations.

Table 3.
Filtration performance of wastewater after coagulation treatment (author's material)

No.	Time, min	Settled water		Water without settling	
		Filtration rate, ml/s	Efficiency, %	Filtration rate, ml/s	Efficiency, %
1.	5	40	95.4	30	92.5
2.	10	26	95.7	24	94.0
3.	20	22	96.0	18	95.0
4.	30	20	97.0	15	95.0
5.	40	20	97.0	15	95.0
6.	50	20	97.0	15	95.0

A comparative analysis of filtration efficiency under two operational modes (with and without settling) is presented in **Figure 2**, confirming the trends observed in **Table 3.**

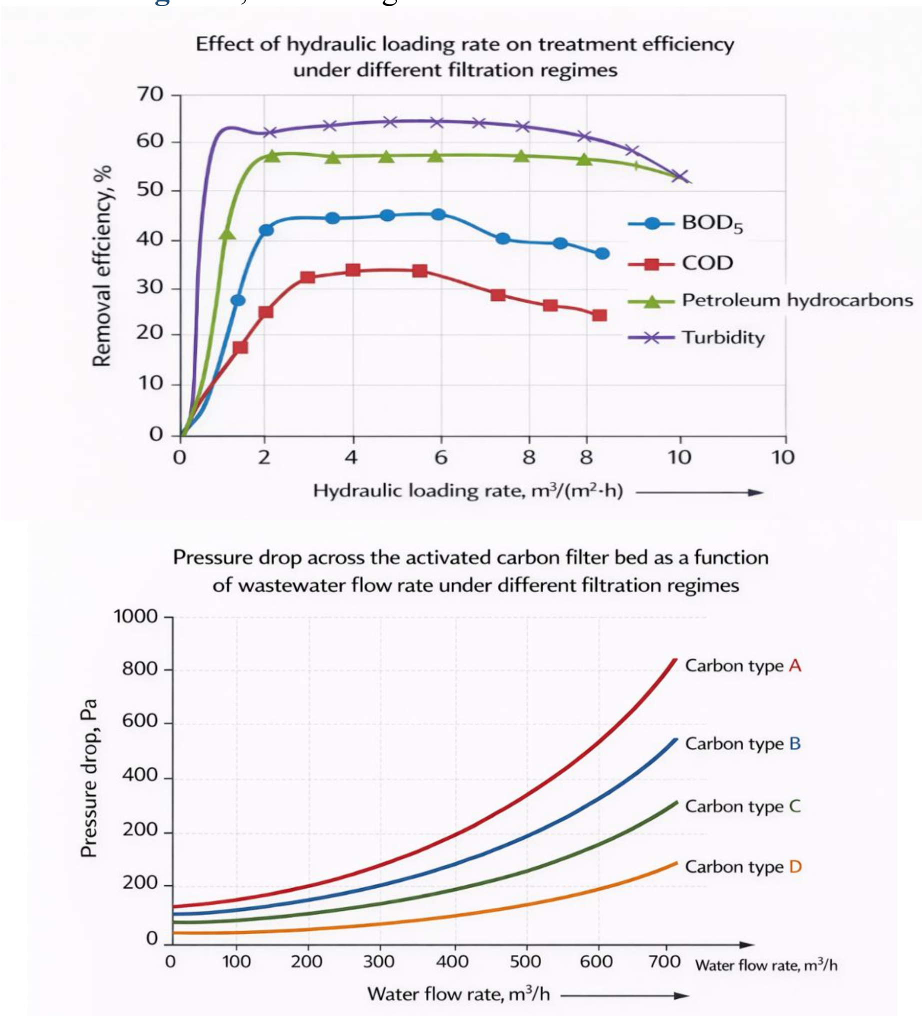

Figure 2 - Performance of filtration under different operational conditions in the treatment of oil-containing wastewater: (a) Effect of hydraulic loading rate on removal efficiency under different filtration regimes; (b) Pressure drop across the activated carbon filter bed as a function of wastewater flow rate for different carbon types **(Haddaji et al., 2024)**

The clarification kinetics data from Table 1 were subjected to regression analysis. The relationship between clarification time and clarified layer height followed a first-order exponential saturation model of the form $H(t) = H\infty \cdot (1 - e^{-kt})$, where $H\infty = 476$ mm is the asymptotic clarified layer height and $k = 1.87\ h^{-1}$ is the rate constant ($R^2 = 0.998$). This high coefficient of determination confirms that the proposed model adequately describes the clarification process. The half-time of clarification (time to reach 50% of $H\infty$) was calculated as $t_{12} = 0.37$ h (approximately 22 minutes), indicating rapid floc formation and settling after coagulant addition.

A comparative analysis of the results obtained in the present study with those reported by other researchers for similar treatment systems is presented in Table 4. The coagulation efficiency of 97–98% achieved using iron(II) sulfate at pH 8.0-8.5 in the present study is consistent with values reported by Haddaji et al. (2024), who obtained 94-97% removal using aluminum sulfate-based coagulation for vegetable oil refinery wastewater at pH 7.5-8.0. Chu and Liu (2025) reported 91–96% removal efficiency for oilfield produced wastewater using irradiation-assisted coagulation, noting that conventional coagulation alone achieved only 83-88% under optimal conditions. This comparison highlights the importance of pH optimization specific to the iron-based coagulation system employed in the present work, as the alkaline conditions promoted not only charge neutralization but also enhanced sweep flocculation through $Fe(OH)_3$ precipitation.

Table 4 summarizes the comparative performance data.

Table 4.
Comparison of coagulation-filtration treatment performance for oily wastewater across different studies (author's material)

Source	Wastewater type	Coagulant	Coagulation efficiency, %	Residual oil, mg/L
Present study	Locomotive depot (railway)	$FeSO_4$ + lime	97-98	1.8-2.3
Haddaji et al. (2024)	Vegetable oil refinery	$Al_2(SO_4)_3$ + polymer	94-97	3.5-5.0
Chu & Liu (2025)	Oilfield produced water	Irradiation + coagulation	91-96	4.0-8.0
Bahramian et al. (2025)	Synthetic oil-water emulsion	Porous polymer adsorption	≥98	<1.0

The comparative data in **Table 4** indicate that the combined $FeSO_4$-based coagulation with lime pH correction, followed by wood shavings and sulfonated carbon filtration, achieves performance levels competitive with more complex treatment systems. Notably, the proposed scheme employs relatively inexpensive and widely available reagents, which is an important consideration for practical implementation in medium-scale railway facilities in Kazakhstan and other Central Asian countries.

The filtration data in **Table 3** also merit further discussion. The gradual decrease in filtration rate from 40 mL/s (at 5 min) to a stable 20 mL/s (at 30 min and beyond) for settled wastewater reflects progressive filter medium loading. The stabilization rate observed after 30 minutes indicates equilibrium between particulate deposition and compaction of the filter bed. For the unsettled wastewater variant, a similar stabilization pattern was observed, with the steady-state rate of 15 mL/s being approximately 25% lower than for settled water, which is consistent with the higher suspended solids load reaching the filter. Despite this difference in hydraulic performance, the ultimate removal efficiency was nearly identical (97% vs. 95%), demonstrating the robustness of the adsorption-filtration stage. From a practical standpoint, this observation suggests that the pre-settling step may be omitted in cases where hydraulic load is a limiting factor, without significant loss in effluent quality, although this would require more frequent filter regeneration.

4 CONCLUSIONS

The results of the present study on the treatment of oil-containing wastewater from railway locomotive depots by combined physicochemical methods allow the following conclusions to be drawn:

1. Gravitational sedimentation alone is insufficient for the treatment of oil-containing wastewater from locomotive depots due to the high aggregative stability of oil-in-water emulsions stabilized by surfactants and corrosion products. After 24 hours of settling, residual petroleum hy-

drocarbon concentrations remained at approximately 40 mg/L, far exceeding the regulatory limit of 5 mg/L.

2. Coagulation–flocculation using iron(II) sulfate at a dosage of 10-50 g/m³ with pH adjustment to 8.0-8.5 by lime solution is the most effective treatment stage, achieving petroleum hydrocarbon removal efficiency of 97-98% (mean 97.4 ± 0.8%). Rapid clarification was achieved within the first 30-60 minutes, with half-time t_{12} = 22 minutes.

3. Filtration–adsorption polishing using a sequential bed of wood shavings and sulfonated carbon provided additional petroleum hydrocarbon removal of 95-97% (mean 96.1 ± 0.7%), reducing the residual concentration to 1.8-2.3 mg/L, well below the regulatory maximum of 5 mg/L established by Kazakhstani standards. Steady-state filtration was reached within 30 minutes of operation.

4. The scientific novelty of the present work lies in the systematic experimental evaluation and optimization of a combined three-stage physicochemical treatment scheme specifically applied to locomotive depot wastewater in the context of Central Asian regulatory requirements. For the first time, the clarification kinetics of this type of industrial effluent have been described by a first-order exponential saturation model (R^2 = 0.998), and statistical reproducibility of the treatment results has been confirmed (coefficient of variation below 1% for all stages).

5. The practical significance of the proposed treatment scheme consists in the use of widely available, low-cost reagents (iron(II) sulfate and lime) and locally sourced filter materials (wood shavings and sulfonated carbon), enabling implementation at railway maintenance facilities without specialized equipment. The scheme is adaptable to a daily wastewater volume of approximately 170 m³ typical of medium-scale locomotive depots and ensures compliance with the maximum allowable petroleum hydrocarbon concentration of 5 mg/L for discharge to municipal sewerage systems as required by Kazakhstani regulations.

6. The overall three-stage treatment process demonstrated a combined removal efficiency of 98.6 ± 0.5%, which is comparable to or exceeds the performance reported in the literature for similar combined coagulation-adsorption systems applied to other industrial oily wastewaters. The results confirm that the proposed technological scheme is both scientifically justified and practically implementable and can be recommended as a standard approach for the pre-treatment of oil-containing wastewater at railway transport facilities throughout Kazakhstan.

7. From the perspective of civil and transport engineering, the proposed physicochemical treatment technology can be recommended for integration into the design of new railway depots, industrial facilities, and transport infrastructure projects, as well as for the reconstruction and modernization of existing wastewater treatment systems. The use of inexpensive and locally available materials makes the proposed solution economically attractive for construction projects while ensuring compliance with environmental regulations. The obtained results provide an engineering basis for designing sustainable wastewater treatment facilities that improve the environmental performance, operational reliability, and long-term sustainability of transport and industrial infrastructure.

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