COMPARISON OF METHODS FOR REMOVING PETROLEUM PRODUCTS FROM LOCOMOTIVE DEPOT WASTEWATER

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Abstract: Six methods of removing petroleum products from locomotive depot wastewater (gravity separation, coagulation-flocculation, flotation, adsorption, membrane filtration and biological treatment) were compared by treatment efficiency, cost, energy use, waste generation and operational complexity. Criteria weights were derived by AHP (consistency ratio CR = 0.007), and the methods were ranked by TOPSIS and the weighted sum model. The Termez locomotive depot test report was used as the baseline (petroleum products 0.7 mg/l, 70% of the limit). The ranking depends on the weights: membrane filtration leads when efficiency is prioritised, gravity separation when cost and simplicity are; adsorption ranks last in all scenarios. The method scores are expert judgements based on published data, not experimental measurements.

Keywords: wastewater, petroleum products, locomotive depot, multi-criteria decision making, AHP, TOPSIS, treatment efficiency

I. Introduction

In locomotive depots, petroleum products are among the main pollutants in the wastewater generated during washing, lubrication and repair operations. Many methods are available for treating it, but which of them suits a given situation cannot be settled by a single criterion: highly efficient methods are usually more expensive and more complex, whereas inexpensive methods do not provide deep treatment [1, 2].

Methods for treating oil-contaminated wastewater have been widely reviewed in the literature. Kundu and Mishra compared gravity separation, flotation, membrane, adsorption, biological and photocatalytic methods in terms of their advantages and disadvantages [3]. Muvel et al. grouped the methods into primary, secondary and tertiary stages and reported the treatment level achieved by each [1]. Medeiros et al. also discussed the cost and operational aspects of the methods [2]. Coagulation-flocculation has been considered in a separate review [4]. At the same time, it has been noted that the problem of selecting a method on several criteria for wastewater in general is being addressed with multi-criteria decision-making (MCDM) methods, namely AHP, TOPSIS, VIKOR and ELECTRE [5].

In Uzbekistan, there is no sufficiently systematic comparison of this kind for railway enterprises. In the test report for the wastewater of the Termez locomotive depot dated January 2025, petroleum products were 0.7 mg/l and oils and greases 0.43 mg/l, which amounted to 70% and 43%, respectively, of the limit stated in the report (1.0 mg/l) [6]. Thus, in this case the question is not "which method reaches the limit" but "which method is optimal for keeping the concentration stably within the limit under a variable load".

Aim: to propose a methodology for selecting the optimal method by comparing, on multiple criteria, the methods of removing petroleum products from locomotive depot wastewater and assessing their efficiency.

Objectives:

1. To summarise the literature data on the main methods of removing petroleum products.
2. To define the comparison criteria and determine their weights by AHP.
3. To evaluate the methods by TOPSIS and the weighted sum model and to test the sensitivity of the result to the weights.
4. To calculate the required treatment level for different load scenarios on the basis of the Termez depot data.

II. Materials and Methodology

Baseline data. The parameters of the Termez locomotive depot wastewater were taken from Test Report No. 43/1 (8 January 2025) of the laboratory of the Surkhandarya Region Department of Ecology [6]: petroleum products 0.7 mg/l, oils and greases 0.43 mg/l, limit stated in the report 1.0 mg/l. The data relate to a single sample, and the location of the sampling point relative to the treatment facility is unknown.

Compared methods. Six methods were selected: gravity separation (oil trap), coagulation-flocculation, flotation, adsorption, membrane filtration (MF/UF) and biological treatment (activated sludge). Hydrocyclones were excluded from the analysis because they are described for wastewater with an inlet concentration of 200–2000 ppm [1], and advanced oxidation processes because they are economically limited at industrial scale [1].

Criteria. Five criteria were used:

Symbol	Criterion	Basis of evaluation
C1	Treatment efficiency	Oil/fat removal rate reported in the literature and achievable residual concentration [1, 2, 3, 4]
C2	Cost	Descriptions of capital and operating costs [1, 2, 4]
C3	Energy consumption	Pumping, pressure and air-supply requirements [1, 2]
C4	Waste generation	Sludge, spent sorbent, washing waste [1, 2]
C5	Operational simplicity	Maintenance, fouling, complexity of process control [1, 2]

Scoring. Each method was scored on each criterion on a scale of 1–5. For all criteria, 5 denotes the best result (e.g., for cost, 5 is the cheapest; for waste, 5 is the least waste), so in the calculation all criteria are treated as benefit-type criteria. The scores are expert judgements assigned by the authors on the basis of the qualitative and quantitative descriptions in sources [1–4]; they are not experimental measurements. Be-

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	Efficiency	Cost	Waste	Simplicity	Energy	Weight
Efficiency	1	2	3	3	4	0.403
Cost	½	1	2	2	3	0.244
Waste	1/3	1/2	1	1	2	0.137
Simplicity	1/3	1/2	1	1	2	0.137
Energy	¼	1/3	1/2	½	1	0.079

cause source [1] does not give the oil removal percentage for adsorption, its efficiency score is the least reliable.

Criteria weights (AHP). The weights were determined by Saaty's pairwise comparison method [7]. The pairwise comparison matrix is based on the authors' order of priority (efficiency > cost > waste = simplicity > energy):

The eigenvalue of the matrix is $\lambda max = 5.033$, the consistency index is $CI = (\lambda max - n)/(n - 1) = 0.008$, the random index is $RI = 1.12$ ($n = 5$), and the consistency ratio is $CR = CI/RI = 0.007$. This value is below the 0.10 threshold, i.e., the judgements are mutually consistent.

Ranking of methods. The ranking was calculated by two methods. In TOPSIS [8], the distances from the ideal and anti-ideal solutions are found from the normalised and weighted matrix; the larger the relative closeness coefficient Ci, the better the method:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}, \tag{1}$$

$$D_i^+ = \sqrt{\sum_j \left(v_{ij} - v_j^+\right)^2}, \quad D_i^- = \sqrt{\sum_j \left(v_{ij} - v_j^-\right)^2}, \tag{2}$$

$$v_{ij} = w_j \cdot \frac{x_{ij}}{\sqrt{\sum_i x_{ij}^2}}. \tag{3}$$

Here x_{ij} is the score of method i on criterion j; w_j is the weight of criterion j; v_j^+ and v_j^- are the values in the ideal and anti-ideal solutions; j = 1…5 (criteria), i = 1…6 (methods).

In the weighted sum model (SAW), each criterion is normalised to the highest score and multiplied by the weights:

$$S_i = \sum_j w_j \cdot \frac{x_{ij}}{\max x_{ij}}, \tag{4}$$

where $\max x_{ij}$ is the highest score on criterion j.

Treatment efficiency. The required treatment level was calculated by the following formula (C0 is the inlet and C the outlet concentration):

$$E = \frac{C_0 - C}{C_0} \cdot 100\,\%. \tag{5}$$

Sensitivity analysis. To test the dependence of the result on the weights, four scenarios were considered: AHP weights, equal weights (0.20 each), efficiency priority (0.50; 0.20; 0.10; 0.10; 0.10) and cost priority (0.25; 0.40; 0.10; 0.15; 0.10; in the order C1, C2, C3, C4, C5).

III. Results

Literature data. Table 1 summarises the published indicators that served as the basis for assigning the scores. They were obtained under different experimental conditions and therefore are not directly comparable; rather, they show the capability of each method.

Scores. Table 2 gives the authors' expert judgements based on Table 1 and the qualitative descriptions in the sources (5 is the best).

Ranking (with AHP weights). Table 3 gives the TOPSIS relative closeness coefficient Ci and the weighted sum value Si for each method.

By TOPSIS, the membrane method (Ci = 0.590) ranks first; by the weighted sum model, the gravity method (Si = 0.758) ranks first. The two methods differ from each other in the first four places, whereas coagulation (5th place) and adsorption (6th place) are placed identically in both.

Sensitivity to weights. Table 4 gives the ranks by TOPSIS / SAW for each scenario.

The gravity method takes first place in both calculations with equal weights and with cost priority, but drops to 3rd–5th place when efficiency has priority. The membrane method is 1st when efficiency has priority and 4th–5th when cost has priority. Only adsorption stayed in 6th place in all eight calculations.

Required treatment level. The measured concentration of petroleum products in the depot wastewater (C0 = 0.7 mg/l) is below the limit stated in the report (1.0 mg/l), so no treatment is required to reach the limit (E = 0%). To keep the concentration at 50% of the limit (0.5 mg/l), $E = (0.7 - 0.5)/0.7 = 28.6\%$ is sufficient. For higher-load cases, the required E (to reach C = 1.0 mg/l) is calculated in Table 5 as hypothetical scenarios; these C0 values are not measurement results.

IV. Discussion

No single method is best for all conditions: of the eight calculations (4 scenarios × 2 methods), the gravity method ranked first in five and the membrane method in three; no other method ranked first. This result shows that the choice is determined not by the methods themselves but by the decision-maker's priority (efficiency or cost). For this reason, the article gives a priority-dependent recommendation rather than a single "best method".

The literature itself also divides the methods into primary (gravity, coagulation), secondary (flotation, biological) and tertiary (membrane, oxidation) stages [1]. The calculation results are consistent with this picture: the inexpensive and simple gravity method as the main stage, followed by one polishing stage depending on whether efficiency or cost has priority (membrane if efficiency has priority; coagulation or the biological method if cost has priority), appears logical. This combination was not calculated; it is only an assumption based on the ranking.

For the Termez depot, the measured petroleum products (0.7 mg/l) are below the limit, so complex treatment is not

Table 1. Indicators reported in the literature for each method

Method	Efficiency data	Main limitations	Source
Gravity separation (oil trap)	Residual oil up to 50 mg/l with a plate separator, up to 100 mg/l with a conventional separator	Separation of droplets down to 150 µm is insufficient for modern requirements; sludge must be removed periodically	[1]
Coagulation-flocculation	84.4% oil removal with ferrous sulfate and polyacrylamide	Limited removal of organic matter; inorganic coagulants produce metal-containing sludge	[1, 2]
Flotation	From 1000 ppm to 10 ppm; over 90% of the oil; up to 80% in another source	Considerable energy for pressurisation; sludge is generated	[1, 2]
Adsorption	Oil removal percentage is not given in [1]	Suspended particles clog the medium; regeneration is required; spent sorbent is hazardous waste	[1]
Membrane (MF/UF)	MF: from 200 mg/l to 8.7 mg/l; UF: over 96% of free oil; pressure 1–2 bar	Membrane fouling, cleaning waste, high initial cost	[1, 2]
Biological (activated sludge)	Up to 99% removal of fats and oils; energy 0.30–0.65 kWh/m³	Ineffective for toxic and recalcitrant substances; large amount of sludge	[1]

Table 2. Scores of the methods on the criteria (1–5)

Method	C1 Efficiency	C2 Cost	C3 Energy	C4 Waste	C5 Simplicity
Gravity separation	2	5	5	4	5
Coagulation-flocculation	3	4	4	2	4
Flotation	4	3	2	3	3
Adsorption	3	3	2	2	3
Membrane (MF/UF)	5	2	3	4	2
Biological (activated sludge)	4	4	3	2	2

Table 3. Ranking of the methods (AHP weights: 0.403; 0.244; 0.079; 0.137; 0.137)

Method	TOPSIS, Ci	Rank	SAW, Si	Rank
Membrane (MF/UF)	0.590	1	0.740	2
Biological (activated sludge)	0.558	2	0.688	3
Flotation	0.533	3	0.685	4
Gravity separation	0.442	4	0.758	1
Coagulation-flocculation	0.439	5	0.678	5
Adsorption	0.315	6	0.571	6

Table 4. Ranks of the methods depending on the weight scenario (TOPSIS / SAW)

Method	AHP	Equal weights	Efficiency priority	Cost priority
Gravity separation	4 / 1	1 / 1	5 / 3	1 / 1
Coagulation-flocculation	5 / 5	2 / 2	4 / 5	3 / 2
Flotation	3 / 4	5 / 4	3 / 4	4 / 5
Adsorption	6 / 6	6 / 6	6 / 6	6 / 6
Membrane (MF/UF)	1 / 2	3 / 3	1 / 1	5 / 4
Biological (activated sludge)	2 / 3	4 / 5	2 / 2	2 / 3

Table 5. Treatment level required to reach the limit (1.0 mg/l)

Inlet C0, mg/l	Required E, %	Izoh
0.7	0	Termez depot, measured value [6]
3	66.7	Hypothetical scenario
10	90.0	Hypothetical scenario
50	98.0	Hypothetical scenario

required for the current single sample. However, because the value reached 70% of the limit and the sample is a single one, it is advisable to retain the gravity stage and carry out repeated measurements in order to stay within the limit when the load increases.

Adsorption ranked last in all scenarios, but its efficiency score is the least reliable (the oil removal percentage is not given in [1]). Experiments with local sorbents may change this score and could become a direction for further research.

Limitations of the Study

- The scores are expert judgements based on literature descriptions, not experimental measurements; they should be confirmed by a survey of specialists.
- The AHP matrix reflects the authors' priorities; a sensitivity analysis was therefore carried out, but determining the weights with independent experts would strengthen the result.
- Cost was not calculated in monetary terms; only a qualitative score was given.
- The efficiency indicators in Table 1 were obtained under different experimental conditions and therefore cannot be compared directly with one another.

- The Termez depot data relate to a single sample; the wastewater volume, the treatment facility and the source of the limit are unknown.

V. Conclusion

1. Six methods of removing petroleum products were compared on five criteria (efficiency, cost, energy, waste, simplicity) by AHP, TOPSIS and the weighted sum model; the consistency ratio of the AHP matrix is CR = 0.007.
2. The ranking depends on the weights: the membrane method is preferable when efficiency has priority (1st place by both TOPSIS and SAW), and the gravity method (1st place) when cost and simplicity have priority.
3. Adsorption ranked last in all eight calculations, but its score is the least reliable because of the lack of literature data.
4. In the Termez depot wastewater, petroleum products were 0.7 mg/l (70% of the limit), and no treatment is required to reach the limit (E = 0%); if the load rises to 3, 10 and 50 mg/l, the required treatment level will be 66.7%, 90% and 98%, respectively (hypothetical scenarios).
5. The results are based on expert judgements founded on the literature; the next steps are to confirm them through a survey of specialists, repeated analysis of the depot wastewater and experiments with local sorbents.

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