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# Optimized Treatment Strategies for Naturally Occurring Radioactive Materials (NORM) in Iraqi Oil and Gas Operations

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**Abstract**

Naturally Occurring Radioactive Materials (NORM) in the oil and gas industry pose significant environmental and health challenges. During extraction and production, radionuclides such as radium-226, radium-228, uranium-238, polonium-210, and lead-210 accumulate in equipment, pipelines, and sludge, forming Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM). Exposure to these radioactive contaminants can increase health risks for workers and complicate waste management. This study evaluates the effectiveness of an integrated remediation process combining thermal, chemical, and detergent-based treatments to reduce NORM contamination. Experimental procedures involved heating contaminated samples to 800°C, applying phosphoric acid to dissolve radioactive scales, and using chlorine-based detergents to facilitate radionuclide removal. The decontamination efficiency was assessed by measuring radionuclide concentrations before and after treatment using gamma spectroscopy. Results showed that acid leaching reduced uranium-238 by 64% and radium-226 by 56%, while detergent application further decreased radium-226 by 99.4%, lowering it from 700,000 Bq/kg to 4,000 Bq/kg. The final step, liquid evaporation, achieved a 99.98% reduction, with radium-226 levels dropping to 500 Bq/kg. These findings highlight the importance of a multi-step remediation approach for effectively managing NORM waste. The proposed treatment strategy provides a practical and scalable solution for reducing radiation hazards in oil and gas operations, supporting worker safety and environmental protection while aligning with international regulatory standards.

## 1. Introduction

The global energy sector relies heavily on oil and gas production to meet the increasing demand for energy. However, this industry faces significant challenges, particularly concerning environmental and health impacts associated with Naturally Occurring Radioactive Materials (NORM). NORM, present in geological formations, can become concentrated during extraction processes, leading to Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) [1]. The accumulation of these materials in equipment and by-products poses potential radiological hazards if not properly managed. As illustrated in Figure (1), natural radioactive materials, particularly uranium decay chain elements, can be transported into petroleum liquids during the extraction process. This transport mechanism results in the accumulation of radionuclides such as radium, thorium, and lead isotopes within oilfield equipment, pipelines, and sludge. These radionuclides can form hard scales inside industrial infrastructure, leading to significant contamination challenges. Additionally, radon gas and its short-lived decay products further contribute to radioactive exposure risks for workers handling petroleum fluids and residues.

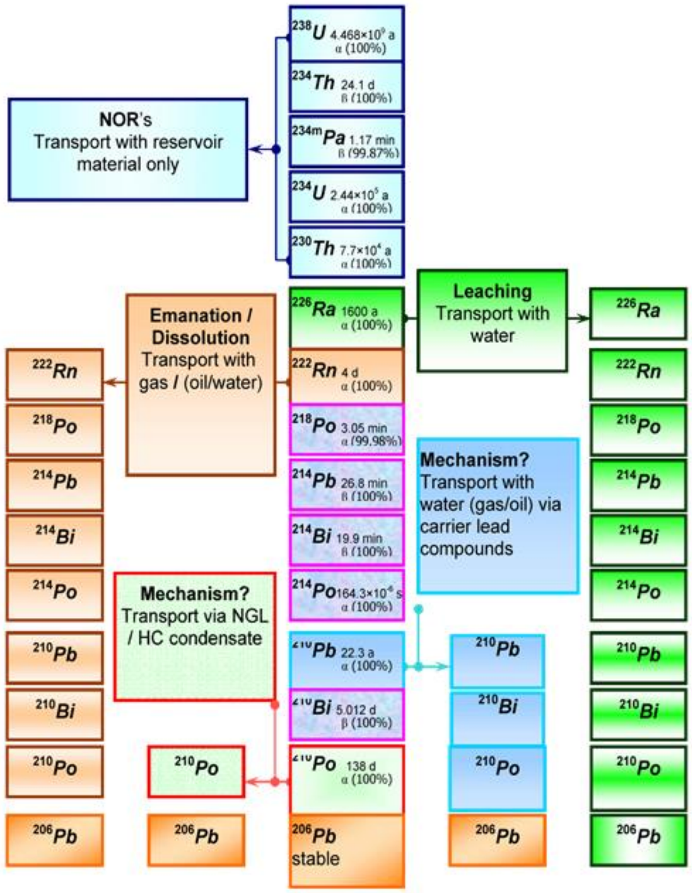


**Figure (1):** Transfer of natural radioactive materials, the uranium chain to petroleum liquids.

Figure (2) presents data on the annual radiation doses received by workers in different exposure scenarios, showing the contribution of specific radionuclides, particularly 226Ra. Occupational exposure to NORM is a key concern in oil and gas operations, as prolonged exposure to elevated radiation levels can lead to increased risks of cancer and other health issues. The figure underlines the importance of effective monitoring and mitigation strategies to minimize radiation exposure, particularly for workers handling contaminated equipment and waste.

In oil and gas operations, NORM can precipitate and accumulate as scale or sludge within pipelines, separators, and other processing equipment. This buildup not only presents health risks to workers through external exposure and inhalation but also complicates waste disposal due to the radioactive nature of the residues [2]. The management of NORM is thus a critical aspect of operational safety and environmental protection in the petroleum industry.

Various remediation techniques have been explored to address NORM contamination. Thermal treatment methods, such as indirect heated vacuum distillation, have shown promise in reducing the volume and radioactivity of NORM waste by removing volatile components [4]. Chemical treatments, including the use of acids and chelating agents, can dissolve and mobilize radioactive scales, facilitating their removal from contaminated surfaces [5]. Advanced filtration systems further aid in separating radioactive particles from waste streams, enhancing the overall efficiency of decontamination processes.

In Iraq, a country with a robust oil production sector, the challenges associated with NORM are particularly pronounced. The Basrah Oil Company, for instance, has reported significant accumulations of NORM waste, primarily composed of radium-226, in their facilities [6]. The management of such waste is complicated by infrastructural limitations and the need for strategies tailored to the specific conditions of Iraqi oil fields. Collaborative efforts between industry stakeholders and regulatory bodies are essential to develop and implement effective NORM management protocols that align with international safety standards.

Internationally, companies like Saudi Aramco have developed comprehensive NORM management guidelines, focusing on monitoring, controlling contaminated equipment, waste handling, disposal, and worker protection [7]. These guidelines serve as valuable references for other oil-producing nations aiming to establish or enhance their NORM management practices.

This manuscript aims to evaluate the efficacy of combined treatment methods, specifically, the integration of thermal and chemical processes in reducing NORM contamination in oil and gas waste. By analyzing treatment outcomes and assessing potential environmental impacts, the study seeks to contribute to the development of optimized decontamination protocols suitable for application in Iraq and similar countries.

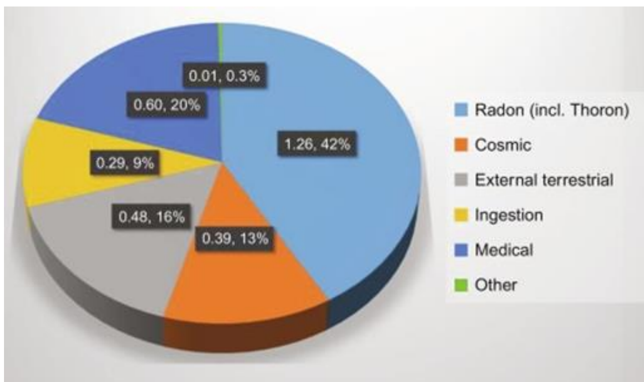


**Figure (2):** The annual doses received by workers and the specific activity of $^{226}$Ra.

## 2. Materials and Methods

### 2.1. Experimental Setup

The experimental system was designed to evaluate the effectiveness of various treatment methods for reducing NORM contamination in oil and gas waste. The system consisted of a stainless-steel treatment chamber (50 × 50 × 50 cm) equipped with a heating unit capable of reaching 800°C, a liquid processing section, and a filtration module. The setup also included a thermometer, X-ray radiation source, and a controlled dispensing system for chemical reagents.

### 2.2. Sample Preparation

To simulate real-world contamination scenarios, samples of NORM-contaminated soil and sludge were prepared with known concentrations of radionuclides, primarily U-238, Ra-226, Ra-228, Po-210, and Pb-210. The preparation process included the following steps:

1. Base Addition: Gasoline, a volatile hydrocarbon mixture obtained from crude oil distillation (boiling range: 35–175°C), was added to the contaminated matrix to facilitate the breakdown of organic compounds.
2. Acid Treatment: Phosphoric acid ($H_3PO_4$) was introduced to dissolve radioactive scale deposits. This acid, with a density of 1.874 g/cm³ and a melting point of 42.35°C, effectively promotes the solubility of radionuclides by forming soluble phosphate complexes.

3. Detergent Treatment: A chlorine-based detergent was applied to aid in the oxidation of organic matter and facilitate the removal of bound radionuclides.

### 2.3. Treatment Process

The decontamination process was conducted in sequential steps to maximize the reduction of radioactivity. The entire process is illustrated in Figure (3), which provides a schematic representation of the thermal, chemical, and filtration stages involved in the treatment.

1. Thermal Treatment: The contaminated sample was heated to temperatures ranging from 400°C to 800°C to break down volatile organic compounds and enhance the effectiveness of subsequent chemical treatments. This step also facilitated the removal of radon gas through thermal volatilization.
2. Acid Leaching: The preheated material was treated with phosphoric acid under controlled conditions to dissolve uranium and radium-bearing compounds.
3. Detergent Washing: After acid treatment, a detergent solution was applied to further remove residual contaminants.
4. Liquid Evaporation and Filtration: The treated liquid fraction was subjected to controlled evaporation, and the remaining solid residue was filtered to assess the residual radionuclide concentrations.

### 2.4. Radiation Analysis

Radionuclide activity concentrations were measured before and after treatment using gamma spectroscopy with a high-purity germanium (HPGe) detector. The activity levels of U-238, Ra-226, Ra-228, Po-210, and Pb-210 were determined in Becquerels per kilogram (Bq/kg). Each sample was analyzed in triplicate to ensure accuracy.

### 2.5. Data Analysis

The effectiveness of each treatment step was evaluated by calculating the percentage reduction in radionuclide activity. Comparative analysis of treatment methods was performed to determine the most effective approach for reducing radioactive contamination in oil and gas waste.

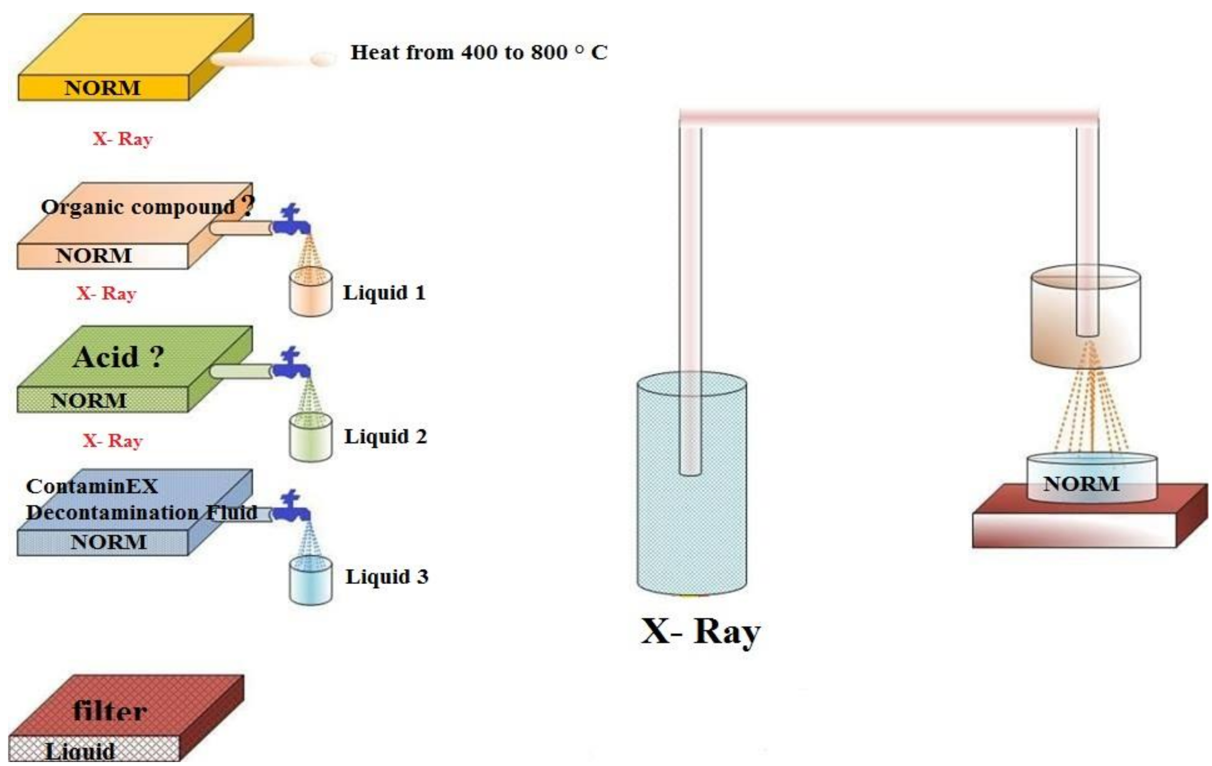


**Figure (3):** The process layout plan.

### 3. Results and Discussion

Tables (1 & 2) present the activity concentrations of radionuclides (U-238, Ra-226, Po-210, Pb-210, and Ra-228) in oil and gas waste before and after different treatments, specifically organic matter combined with X-ray radiation (Table 1) and acid treatment with X-ray radiation (Table 2). The data provide present the efficiency of these methods in reducing radioactive contamination and their implications for environmental and occupational safety.

In Table (1), the application of organic matter and X-ray radiation resulted in moderate reductions in radionuclide concentrations. Ra-226 and Ra-228, the primary contributors to external gamma exposure, decreased by 20% and 32%, respectively, while U-238 showed a 31% reduction. Po-210 and Pb-210 exhibited decreases of 20% and 28%, respectively. These reductions can be attributed to adsorption and complexation mechanisms, where organic compounds interact with radionuclides, altering their solubility and mobility [8]. In addition, X-ray radiation may induce radiolysis, leading to further chemical reactions that aid in reducing radioactive contaminants. However, the overall efficiency of organic matter treatment alone remains limited, as significant amounts of radioactivity persist in the treated material. This suggests that additional chemical interventions are necessary to break the radiological binding mechanisms within the contaminated matrix [9].

**Table (1):** The activity concentration [Bq/kg] for the organic matter and x-rays radiation.

| Radionuclide | Hard scale + Sludge Bq/kg | Adding base mL/kg |
|---|---|---|
| U-238 | 450 | 310 |
| Ra-226 | 2 million | 1.6 million |
| Po-210 | 1000 | 800 |
| Pb-210 | 70000 | 50000 |
| Ra-228 | 2.5 million | 1.7 million |

Table (2) demonstrates that acid treatment significantly enhances radionuclide removal compared to organic matter alone. U-238 activity concentration dropped by 64%, from 310 to 110 Bq/kg, while Ra-226 decreased by 56%, from 1.6 million to 700,000 Bq/kg. Po-210 and Pb-210 showed reductions of 58% and 60%, respectively, indicating increased solubility under acidic conditions [1]. Ra-228 also exhibited a higher removal efficiency, with a 41% decrease, compared to 32% in Table (1). The improved decontamination performance can be attributed to the acidic medium promoting radionuclide leaching, increasing solubility, and breaking the chemical bonds that bind radioactive particles to the solid matrix [5]. Acid treatment likely enhances complex formation, making radionuclides more extractable, while also facilitating the release of bound contaminants into the liquid phase.

**Table (2):** The activity concentration [Bq/kg] for the sample after acid addition and x-rays radiation.

| Radionuclide | Hard scale + Sludge Bq/kg | Adding acid mL/kg |
|---|---|---|
| U-238 | 310 | 110 |
| Ra-226 | 1.6 million | 700000 |
| Po-210 | 800 | 340 |
| Pb-210 | 50000 | 20000 |
| Ra-228 | 1.7 million | 1 million |

The comparative analysis of Tables (1 & 2) shows the superiority of acid treatment over organic matter in reducing radionuclide activity concentrations. However, neither method alone is sufficient to bring activity levels below regulatory limits, particularly for Ra-226 and Ra-228, which remain in the range of hundreds of thousands of Bq/kg even after treatment [5]. This suggests that a multi-step decontamination strategy is necessary, incorporating additional treatments such as chelating agents, high-temperature thermal processing, or advanced filtration techniques to further reduce contamination levels [10].

Tables (3 & 4) present the results of NORM (Naturally Occurring Radioactive Materials) decontamination using a sequential treatment approach involving detergent application, X-ray radiation, acid treatment, and evaporation. The data reflect a significant reduction in radionuclide activity, demonstrating the effectiveness of multi-step remediation.

Table (3) shows the impact of detergent addition after acid treatment. The detergent effectively reduced radionuclide activity, particularly for Ra-226, which showed a dramatic decrease from 700,000 Bq/kg to 4,000 Bq/kg. U-238 and Ra-228 also exhibited notable reductions, reaching 50 Bq/kg and 210,000 Bq/kg, respectively. This suggests that detergent enhances the desorption of radionuclides by disrupting surface tension, increasing solubility, and facilitating the removal of radioactive particles from solid matrices [3]. The observed efficiency can be attributed to the interaction of detergent molecules with radium and lead compounds, which likely alters their surface properties, making them more amenable to extraction [9].

The results further indicate that Po-210 and Pb-210 were reduced to 150 Bq/kg and 5,000 Bq/kg, respectively. These reductions align with studies on surfactant-assisted radionuclide removal, where chelating agents in detergents help detach and mobilize contaminants from solid particles [8]. The substantial decrease in Ra-226 suggests that detergent application is crucial for breaking residual binding interactions left unaddressed by acid treatment alone.

**Table (3):** The sample's activity concentration [Bq/kg], with the addition of detergent and x-ray radiation.

| Radionuclide | Hard scale + Sludge Bq/kg | Adding detergent mL/kg |
|---|---|---|
| U-238 | 110 | 50 |
| Ra-226 | 700000 | 4000 |
| Po-210 | 340 | 150 |
| Pb-210 | 20000 | 5000 |
| Ra-228 | 1 million | 210000 |

Table (4) presents the cumulative effect of the complete treatment process, including base addition, acid treatment, detergent washing, and liquid evaporation. The final treatment stage resulted in exceptionally low residual activity concentrations, with U-238, Ra-226, Po-210, and Pb-210 reaching 30 Bq/kg, 500 Bq/kg, 50 Bq/kg, and 500 Bq/kg, respectively. The most notable reduction was for Ra-226, which started at 2 million Bq/kg and was brought down to 500 Bq/kg, representing a 99.98% reduction.

**Table (4):** The activity concentration [Bq/kg] for the sample after the whole process.

| Radionuclide | Hard scale + Sludge Bq/kg | Adding base | Adding acid | Adding detergent | Evaporating the liquid |
|---|---|---|---|---|---|
| U-238 | 450 | 310 | 110 | 50 | 30 |
| Ra-226 | 2 million | 1.6 million | 700000 | 4000 | 500 |
| Po-210 | 1000 | 800 | 340 | 150 | 50 |
| Pb-210 | 70000 | 50000 | 20000 | 5000 | 500 |
| Ra-228 | 2.5 million | 1.7 million | 1 million | 210000 | 90000 |

These findings confirm that a stepwise treatment sequence is necessary to achieve regulatory compliance. Acid treatment provided a strong initial reduction, detergent facilitated additional solubilization, and evaporation removed residual contaminants in the liquid phase [4]. The final Ra-228 concentration of 90,000 Bq/kg indicates that while the process is highly effective, additional refinement, such as advanced filtration or ion-exchange resins might be required for complete remediation [11].

## 4. Conclusions

Effectively managing NORM in oil and gas waste is crucial for ensuring worker safety and environmental protection. This study demonstrated that a multi-step remediation approach combining thermal treatment, acid leaching, detergent application, and liquid evaporation significantly reduces radionuclide contamination. Acid treatment effectively dissolved radioactive scales, achieving a 64% reduction in uranium-238 and a 56% reduction in radium-226. The subsequent detergent treatment enhanced the removal of residual contaminants, reducing radium-226 by 99.4% to 4,000 Bq/kg. The final liquid evaporation step further lowered residual activity concentrations, achieving a 99.98% reduction and bringing radium-226 levels down to 500 Bq/kg. These results confirm that no single treatment method is sufficient to meet regulatory safety thresholds, highlighting the necessity of an integrated decontamination process. The proposed approach offers a scalable, practical solution for oil and gas industries dealing with NORM-contaminated waste. Future work should focus on optimizing treatment parameters, exploring advanced filtration methods, and assessing long-term environmental impacts. Collaboration between industry stakeholders and regulatory agencies is essential to ensure safe handling, disposal, and monitoring of NORM waste in compliance with international radiation safety standards. Implementing this remediation strategy can significantly mitigate radiation exposure risks, contributing to a safer and more sustainable oil and gas sector.

**Conflict of Interest:** The authors declare that there are no conflicts of interest associated with this research project. We have no financial or personal relationships that could potentially bias our work or influence the interpretation of the results.

**Safety Considerations:** Safety and radiation protection instructions must be complied with by wearing appropriate equipment for such work, as stipulated by the International Atomic Energy Agency, to preserve the safety of workers and the environment.

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