

Naturally Occurring Radioactive Materials (NORM) in Diesel and Petrol Fuels

Hariandra Muthu

Taylor's College, Taylor's Lakeside Campus, No. 1 Jalan Taylor's, 47500 Subang Jaya, Selangor

DOI: <https://doi.org/10.51583/IJLTEMAS.2025.1408000050>

Received: 08 Aug 2025; Accepted: 16 Aug 2025; Published: 04 September

Abstract: With an emphasis on their sources, detection, and possible effects on the environment and human health, this paper investigates the existence of Naturally Occurring Radioactive Materials (NORM) in petrol and diesel fuels. Crude oil contains NORM, mainly uranium, thorium, and their decay products, such as radium, which can concentrate during the refining process. Gamma spectroscopy and other detection techniques are essential for keeping an eye on these substances. Along with regulatory measures and safety standards to mitigate these risks and ensure safety, the review also discusses the environmental concerns, worker risks, and refining processes that concentrate NORM.

Keywords: NORM, radionuclide, gamma spectroscopy, environmental radioactivity, crude oil

I. Introduction

The term "naturally occurring radioactive materials" (NORM) refers to radioactive materials that are found naturally in the crust of the Earth. These materials include elements that belong to the natural decay series, such as potassium (K-40), radium (Ra-226), uranium (U-238), and thorium (Th-232). Alpha, beta, and gamma particles are released as a result of these radioactive elements' gradual decay into different radioactive substances. Even though these substances are normally present in natural settings in small amounts, their importance rises in sectors like the oil and gas industry where extensive extraction procedures are carried out. These radioactive materials can accumulate as a result of crude oil extraction, refinement, and processing, which raises questions about environmental safety, human health, and the efficient handling of industrial waste. (Muthu, Kasi, T subramaniam, & Baig, 2022) Because NORM can build up during the extraction and refining processes, its presence in crude oil is especially significant. The radioactive elements uranium and thorium, which are found in trace amounts in crude oil, are transported by geological processes and concentrate in specific petroleum reservoirs. Radium isotopes, especially Ra-226 and Ra-228, are produced when these elements undergo radioactive decay. During the oil refining process, these radionuclides can be transported with the crude oil and further concentrated, particularly in by-products like refinery sludge, scale, and other leftover materials. Although NORM levels in raw crude oil and refined petroleum products are typically low, refinery waste materials can have elevated NORM levels, which presents serious management and disposal challenges (Hariandra Muthu, Kasi, T subramaniam, & Baig, 2022).

Petroleum refining uses a number of chemicals and additives that can interact with radioactive materials in addition to NORM. The concentration of NORM in specific waste products may be influenced by solvents, other chemical agents, and catalysts utilised in the refining process. The distribution of NORM within the refinery and the treatment techniques needed to reduce the risks of radioactive exposure may also be impacted by the use of these chemicals. To prevent negative effects, the impact of these chemicals—both in terms of raising the NORM concentration and affecting the materials' environmental fate—must be closely watched. An essential component of risk management in the petroleum sector is comprehending how these additives interact with NORM (Ijabor et al., 2022).

Important questions about environmental and occupational safety are brought up by the presence of NORM in crude oil and its derivatives, including petrol and diesel. Workers who extract and refine oil may be exposed to high radiation levels, especially in refinery environments where waste byproducts with high NORM concentrations are produced. Workers who handle and dispose of waste sludge and other materials that might contain radium and other radioactive isotopes are also at risk. Long-term exposure to these materials without appropriate safety precautions can result in major health problems, such as an elevated risk of cancer, especially lung cancer, from breathing in radon gas from radium decay.

There are wider environmental issues in addition to the direct hazards to employees. The environment may become contaminated if NORM-containing refinery waste is not properly managed. Because radium, a crucial isotope in NORM, is highly soluble in water, it can readily enter soil and groundwater, contaminating them and possibly endangering human populations in the long run. Wildlife and the food chain may be impacted by bioaccumulation caused by NORM's movement in the environment, especially in soil and water. Therefore, strict safety procedures must be put in place to guarantee that NORM is handled and disposed of appropriately at every stage of petroleum production and refinement due to the possibility of environmental contamination (Alkhazzar, Hamza, & Al-Dulaimi, 2024).

The identification and tracking of these radioactive materials is one of the main obstacles to managing NORM in the petroleum sector. It can be challenging to detect and quantify NORM in crude oil and refined products because of their frequently low concentrations. Since gamma spectroscopy can accurately measure the gamma radiation released by radionuclides like Ra-226 and Ra-228, it is one of the most popular methods for detecting NORM in petroleum products. Both raw crude oil and refined products

like petrol and diesel can have their radioactive content precisely measured using this non-destructive method. The precise radionuclides found in petroleum products and refinery waste are also measured using other techniques like liquid scintillation counting and alpha spectroscopy. These techniques are essential for maintaining safe NORM levels in petroleum products and reducing the risks of radioactive exposure (Belamri, Bounemia, Azbouche, Boukeffoussa, & Chaouch, 2017).

Regulatory agencies have set standards and guidelines for handling NORM in the petroleum industry due to the possible health and environmental hazards it poses. By offering global guidelines for NORM management, the International Atomic Energy Agency (IAEA) makes sure that nations have the right systems in place for tracking and getting rid of these substances. Furthermore, a number of national governments, including the U.S. Regulations that particularly address the handling and disposal of NORM in the petroleum industry have been put into place by the Environmental Protection Agency (EPA). These rules are intended to shield the environment and employees from excessive radiation exposure. Monitoring NORM levels in crude oil and refined products, controlling the disposal of waste containing NORM, and making sure safety procedures are followed during the extraction and refining of oil are some of the essential components of NORM management (Abd El-mageed et al., 2011).

The purpose of safety precautions in the petroleum sector is to lower the possibility of NORM exposure for both the general public and employees. Strict safety procedures are implemented in refinery operations, and protective gear like radiation shields and personal protective equipment (PPE) are used. To avoid contaminating the environment, proper waste disposal methods are crucial, including the safe containment and treatment of waste materials containing NORM. Refinery sludge and other waste materials with high NORM concentrations are occasionally managed in specialised treatment facilities. In order to make sure that the industry continues to adhere to regulatory standards and that the public's and employees' health and safety are not jeopardised, regular monitoring and risk assessments are also conducted (Al-Saleh & Al-Harshan, 2008).

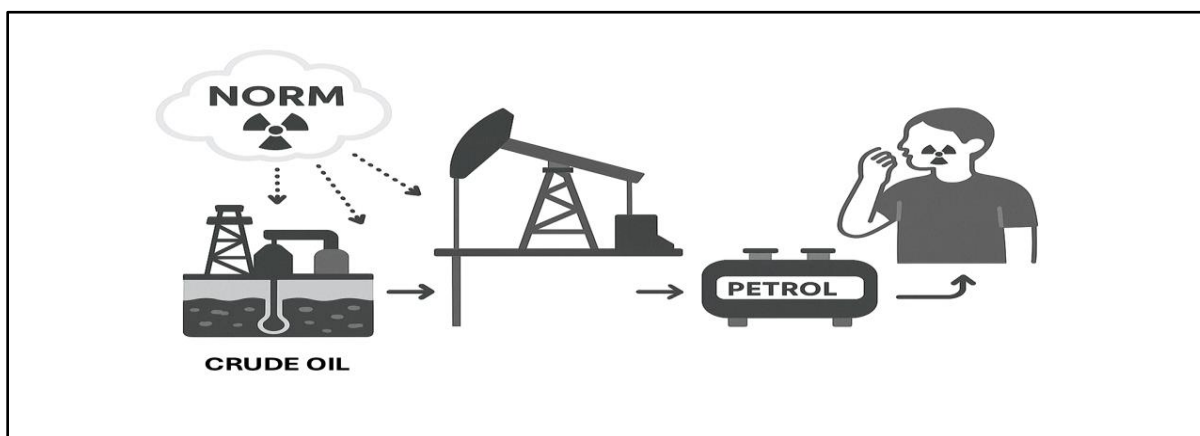


Figure. 1: Transfer of NORM to Crude Oil and to Petrol

NORM's history

The term "naturally occurring radioactive materials" (NORM) refers to radioactive materials that occur naturally in the crust of the Earth. These substances can be found in a variety of earthly raw materials, such as rocks, soils, groundwater, and petroleum deposits. The two most prevalent NORM elements are uranium (U-238) and thorium (Th-232), both of which are naturally occurring radioactive metals. Radium (Ra-226) is one of the radioactive elements that are created when uranium, for instance, undergoes radioactive decay. Radium, a major factor of concern in the context of petroleum products, is eventually produced as uranium decays through a chain of decays (H Muthu et al., 2023).

Because it can build up during the extraction and refining processes, radium—in particular, Ra-226—is extremely important to the petroleum industry. Traces of uranium and thorium can be found in crude oil, a naturally occurring liquid that is found in geological reservoirs beneath the surface of the Earth. Figure. 1 shows the geological processes that create petroleum deposits, these radioactive elements, which were initially found in the nearby rock formations, may find their way into the crude oil. The geological setting in which crude oil is extracted affects the concentration of these substances in the oil. The radioactive elements are present at levels that are generally regarded as not immediately concerning for the environment or human health, but the concentrations are usually low (Bünger et al., 2000).

These radionuclides can be concentrated during the refining processes that transform crude oil into usable petroleum products like petrol, diesel and jet fuel, transforming them from low-concentration materials into higher-concentration byproducts. For instance, waste products produced during the refinement of crude oil can contain radium isotopes like Ra-226, which are especially persistent. Sludges, scales, and sediments that develop inside the refinery's pipes and tanks are examples of these waste products. These materials frequently have high NORM concentrations, which can pose major health and environmental hazards if left unchecked (Rowan, Engle, Kirby, & Kraemer, n.d.).

Because workers in oil fields and refineries may be exposed to radiation during the extraction and refining processes, the buildup of NORM during these processes is especially concerning. Workers may come into contact with materials that contain higher levels

of radium and other radioactive elements while conducting operations. Since radium and its decay products, like radon gas, pose serious health risks, it is imperative that NORM be managed at these stages to avoid needless exposure. For example, radon is a radioactive gas that can build up in areas with inadequate ventilation and raise the risk of lung cancer in those who are exposed to it for extended periods of time (Badruzzaman, Barnes, Bair, & Grice, 2009).

From an environmental point of view, soil, groundwater, and surface water contamination can result from the inappropriate disposal of NORM-contaminated waste from oil refining. If radium and other radioactive elements are not disposed of properly, they can leak into the environment and possibly harm ecosystems in the area. This is especially problematic in places that refine petroleum and generate large amounts of waste and sludge. The environmental effects of improperly contained and treated materials can be long-lasting, contaminating nearby water sources and agricultural land and increasing the health risks to the local populace (McMahon et al., 2019).

Concerns regarding NORM's worldwide effects are more widespread than just environmental hazards. Larger geographic areas may be impacted by the transportation or disposal of the waste products from oil extraction and refinement. Human and wildlife exposure to NORM may be further increased by the transportation of petroleum products and refinery byproducts with elevated NORM levels, which may cause radioactive contamination to spread to regions not directly involved in petroleum production (Ali, Zhao, Li, & Maglas, 2019).

Therefore, the need for close oversight and regulation in the petroleum sector is highlighted by the presence of NORM in crude oil and the subsequent concentration of these materials during refining processes. NORM levels in crude oil, refined products, and waste materials must be measured and tracked using appropriate detection techniques, such as gamma spectroscopy. Waste disposal procedures must stop radioactive contamination from spreading into the environment, and regulatory frameworks and safety procedures must guarantee that the concentrations of these radioactive materials stay within acceptable bounds (Ayeñi & Adebiyi, 2022).

In conclusion, crude oil and the rock formations that are associated with it naturally contain uranium, thorium, and their decay products, such as radium. NORM is created when these elements decay radioactively and can build up during the extraction and refinement of crude oil. These radionuclides can be concentrated in refinery waste during the oil refining process, which can be hazardous to the environment and human health if improperly handled. Effective monitoring and regulatory measures must be put in place in response to the NORM concerns in petroleum products in order to guarantee safe working conditions for employees of the petroleum industry and to shield the environment from radioactive contamination.

Radioactivity Sources in Diesel and Petrol

In addition to being a complex mixture of hydrocarbons, crude oil also contains trace amounts of NORM. Naturally occurring in the Earth's crust, uranium and thorium can be concentrated in petroleum reservoirs and are transported by geological processes. These substances are present in many geological formations that are frequently linked to crude oil deposits, including sandstone, limestone, and shale. Radium (Ra-226 and Ra-228) and radon are among the byproducts of uranium and thorium's radioactive decay over time. During the refining process, these radioactive materials may migrate with the oil and build up in the finished product. The radium isotopes found in crude oil may concentrate in refinery byproducts such as sludge, scale, and sediments after the oil is extracted. If handled incorrectly, these by-products—which frequently contain high concentrations of radium—may endanger the health of those engaged in the refining process as well as the environment (Bünger et al., 2000).

The Impact of the Refining Process on NORM

Crude oil refining is a multi-step process that separates crude oil into different fractions, such as kerosene, diesel, and petrol. Numerous chemical treatments are applied during this process, which may unintentionally concentrate NORM in specific byproducts. Distillation, catalytic cracking, and hydro processing are common steps in the refining process that separate the hydrocarbons according to their chemical structures and boiling points. However, these procedures may concentrate NORM in the waste products produced during refining in addition to separating hydrocarbons. For example, radium and other radioactive materials may build up in refinery sludge and scale, which can deposit on pipes, tanks, and other equipment, when crude oil is heated to high temperatures during distillation and other refining procedures. The buildup of these radioactive elements in waste products highlights the necessity of appropriate waste management and disposal while also raising the possible risks related to refinery operations (Badruzzaman et al., 2009).

Techniques for Identifying NORM in Fuels

For the purpose of controlling and reducing related risks, it is essential to detect Naturally Occurring Radioactive Materials (NORM) in crude oil and its refined products. To determine whether petroleum products contain radioactive elements like uranium, thorium, and radium, a number of advanced detection techniques are used. Gamma spectroscopy, which identifies the gamma radiation released by radioactive isotopes, is one of the most widely used methods for detecting NORM. A precise technique for measuring radionuclides in a range of materials, including crude oil and refinery byproducts, is gamma spectroscopy. Alpha spectroscopy, which is especially helpful for measuring radium isotopes, and liquid scintillation counting, which is sensitive to alpha and beta radiation, are additional detection methods. These techniques are essential for tracking NORM levels at different phases of the oil

production and refining process. Refinery waste products like sludge and scale should also be examined because they can build up high NORM levels. Detection techniques enable timely intervention to reduce possible risks and help guarantee that NORM levels remain within safe bounds(Alshahrani, Korna, Fares, Ali, & Salman, n.d.).

NORM in crude oil and its refined products can be found and measured using gamma spectroscopy. Using this method, the energy and intensity of gamma rays released by radioactive isotopes in the sample are measured. It is feasible to identify particular radionuclides and determine their concentrations by analysing the gamma spectrum. For the detection of gamma-emitting isotopes, like Ra-226 and Ra-228, which are frequently present in petroleum products, gamma spectroscopy is especially useful. Even at low concentrations, these radionuclides can be accurately identified and quantified thanks to gamma spectrometers' high resolution. Research has demonstrated that gamma spectroscopy is a useful tool for tracking NORM levels in a variety of materials, such as crude oil and waste products from refineries(Gongora, Martínez, Peñalver, Aguilar, & Borrull, 2025).

Another useful method for identifying NORM is liquid scintillation counting (LSC), especially for radionuclides that emit beta and alpha particles. In LSC, a sample is combined with a scintillation cocktail, and photomultiplier tubes measure the light that is released as a result of radioactive decay. This technique is appropriate for detecting radionuclides like Ra-226 and Pb-210, which are problematic in the petroleum industry, because it is sensitive to low-energy beta and alpha particles. High counting efficiency and the capacity to measure low-energy emissions with little interference are just two benefits of LSC. Studies have demonstrated how LSC can be used to measure NORM in the oil and gas sector and how well it can identify low-energy beta and alpha emitters.

Since radium isotopes release alpha particles during their decay, alpha spectroscopy is especially helpful for measuring these isotopes. This method identifies particular radionuclides by gathering alpha particles released from a sample and examining their energy spectra. Refinery waste products frequently contain alpha-emitting radionuclides like Ra-226 and Ra-228, which can be detected with high resolution and sensitivity using alpha spectroscopy. Assessing possible health risks related to NORM exposure in the petroleum industry requires the ability to measure these isotopes precisely. Alpha spectroscopy has been shown to be useful in the oil industry for characterising NORM-type scales and other materials(Othman, Saleh, Ghatass, & Metwally, 2018).

Sludge and scale, two waste products from refineries, must be monitored in order to determine NORM levels and guarantee adherence to safety regulations. During the refining process, these materials have the potential to accumulate high concentrations of NORM, which could endanger both the environment and workers. Radionuclide identification and quantification are made possible by routine analysis of these waste products using gamma, LSC, and alpha spectroscopy. This enables prompt intervention and mitigation measures. To reduce exposure and safeguard the public's health, NORM in refinery waste must be effectively monitored and managed. The significance of NORM monitoring in oil and gas operations has been underlined by research, underscoring the necessity of thorough evaluation and management plans(Ayeni & Adebiyi, 2022).

NORM's Effects on the Environment and Human Health in Petrol and Diesel

Despite generally low levels of Naturally Occurring Radioactive Materials (NORM) found in petrol and diesel products, there is growing concern about their potential long-term effects on human health and the environment. NORM, particularly radium (^{226}Ra and ^{228}Ra) and its decay product radon, becomes concentrated during various petroleum industry processes, including oil production, refining, and natural gas processing. Radium tends to accumulate in oil-field scales and sludges, often precipitating with barium and strontium sulfates due to changes in temperature and pressure. Similarly, radon—a radioactive gas resulting from radium decay—can accumulate in enclosed spaces such as refineries, pipelines, and storage facilities. Over time, this buildup presents a serious health hazard, especially when radon is inhaled by workers over prolonged periods(Chen, 2022).

Health risks associated with NORM exposure are well-documented. Chronic exposure to radium can lead to bone cancer and other malignancies due to its chemical similarity to calcium, allowing it to deposit in bones(Hariandra Muthu et al., 2022). More notably, radon inhalation is a leading cause of lung cancer, particularly in occupational settings like petroleum facilities, where radon and its progeny can become airborne during maintenance or sludge handling. Studies have shown that radioactive particles can form thin films on equipment interiors, which may be disturbed and inhaled during routine work, raising internal alpha radiation doses significantly. Even though fuel station workers and consumers are generally exposed to very low radiation levels, those working directly with crude oil or refinery waste may face higher risks(IAEA, 2004).

Environmental consequences of NORM contamination are equally concerning. If refinery waste or “produced water” containing high levels of radium is not properly managed, the potential for soil and groundwater contamination increases. Radium can dissolve in water and migrate through groundwater systems, particularly in regions with permeable soils or minimal containment infrastructure. Case studies, including one from Albania and others in Nigeria and the United States, show that even moderate concentrations of radium in oil-field sludge can lead to measurable environmental contamination. In some cases, levels have exceeded global safety thresholds, prompting calls for stricter waste disposal standards and better environmental monitoring (Ahmad et al., 2021b)

Recent research underscores the importance of continued surveillance and risk mitigation. El Afifi et al. (2023) investigated the radiochemical signatures of radium isotopes in produced water, scale, and sludge waste. They found that radium-226 concentrations ranged from 0.04 to 1,480 Bq/L in produced water, from 1.1 to 2,015,000 Bq/kg in scale, and from 1 to 120,800 Bq/kg in sludge. These findings underscore the importance of monitoring and managing NORMs in petroleum industry waste(El Afifi, Mansy, &

Hilal, 2023). Nasr et al. (2024) characterized oil ash from electrical power plants, reporting average activity concentrations for radium-226, thorium-232, and potassium-40 as $1,718 \pm 85.9$ Bq/kg, 278.1 ± 13.9 Bq/kg, and 136 ± 6.7 Bq/kg, respectively. These values are higher than the worldwide average and indicate potential radiological concerns. (Nasr, Duraia, Shafaa, Ayoub, & Essa, 2024) Regulatory agencies such as the U.S. Environmental Protection Agency (EPA), International Atomic Energy Agency (IAEA), and various national bodies have issued guidance for handling and disposing of NORM waste. However, enforcement remains uneven, and gaps persist in many countries, particularly where oil extraction is less stringently regulated. Some jurisdictions, like Sweden and parts of the U.S., have adopted more comprehensive controls, requiring reporting, specialized disposal methods, and radiation monitoring (IAEA, 2009).

To address these issues, further research is needed in several key areas. Long-term occupational exposure studies should be conducted to better understand the cumulative effects of NORM on refinery workers and maintenance personnel. Environmental monitoring of soil and groundwater near refinery and drilling waste disposal sites is essential to track potential contamination. Additionally, there is a need for improved radon gas measurement in enclosed petroleum facilities, as well as studies evaluating the effectiveness of various remediation methods such as chemical leaching, land-farming, and engineered barriers. Finally, biological studies using biomarkers or genotoxicity testing can help identify early signs of NORM-related health impacts in at-risk populations (Othman et al., 2018).

Additional studies have investigated the accumulation and mobility of NORM elements within petroleum production environments. For example, research conducted in oil fields in the Middle East showed that radium isotopes bind strongly to barite scale deposits inside pipes and equipment, but changes in chemical conditions during maintenance or production interruptions can cause radium remobilization into produced water and sludge. This cyclical release raises concerns about repeated exposure risks to workers and environmental receptors near disposal sites (Rowan et al., n.d.). The study also emphasized the need for routine monitoring of NORM concentrations at various process stages, as these concentrations can fluctuate significantly depending on operational factors.

Further, investigations into the human health impact of NORM exposure have extended to biomonitoring studies in refinery workers. A 2025 epidemiological study assessed biomarkers of DNA damage and oxidative stress in workers exposed to radon and radium in oil and gas facilities. The results indicated elevated genotoxic markers correlating with cumulative occupational exposure, suggesting early biological effects before clinical symptoms emerge. These findings highlight the importance of integrating molecular-level assessments with traditional radiological dose measurements to better understand subclinical health impacts and inform preventive strategies. (Kashkinbayev et al., 2025)

On the environmental front, recent assessments have focused on the fate of radium and its decay products in groundwater near former oil production sites. A 2024 study from the United States evaluated radionuclide migration through aquifers beneath abandoned oil fields, demonstrating that radium can persist in sediments and slowly leach into groundwater over decades. (Gannon et al., 2025). This long-term leaching poses risks to drinking water supplies in surrounding communities and underscores the need for extended environmental monitoring and remediation efforts, especially where legacy waste disposal practices were less regulated. The study recommended adopting advanced geochemical barrier technologies and stricter regulations on produced water management to mitigate these risks (Zhang et al., 2025).

Regulations and Safety Requirements

Numerous national and international regulatory frameworks have been created in an effort to reduce the risks related to NORM in the petroleum sector. Guidelines for the control and observation of NORM in oil and gas operations are provided by the International Atomic Energy Agency (IAEA). These recommendations guarantee that appropriate waste disposal techniques are used and that NORM levels are maintained within reasonable bounds. The Environmental Protection Agency (EPA) is in charge of regulating NORM in oil and gas operations in the US. The EPA keeps an eye on the radiation levels in goods like petrol and diesel and establishes guidelines for the safe disposal of refinery waste. Although national laws differ from one nation to the next, the overall objective is to guarantee that NORM levels do not surpass environmentally, consumer, or worker-safe thresholds. Adherence to these rules is essential for preserving environmental preservation and public safety (Azhdarpoor, Hoseini, Shahsavani, Shamsedini, & Gharehchahi, 2021).

Conclusion

In conclusion, even though there is typically little NORM in petrol and diesel fuels, it is still vital to take into account the possible hazards connected to these substances, especially when it comes to refinery waste. NORM is concentrated in by-products such as sludge and scale during the refining process, which, if not properly managed, can present environmental and occupational hazards. Monitoring the presence of NORM in crude oil and refined products requires the use of detection techniques like gamma and alpha spectroscopy. The EPA and IAEA regulations, among others, are crucial in reducing the dangers that NORM poses. Effective regulation, monitoring, and waste management procedures help to reduce the risks associated with NORM in the petroleum industry, notwithstanding the possibility of negative effects on human health and the environment. The petroleum industry must remain vigilant in managing NORM as technology and regulatory standards continue to advance in order to protect the environment, the public, and employees.

References:

1. Abd El-mageed, A. I., El-Kamel, A. H., Abbady, A., Harb, S., Youssef, A. M. M., & Saleh, I. I. (2011). Assessment of natural and anthropogenic radioactivity levels in rocks and soils in the environments of Juban town in Yemen. *Radiation Physics and Chemistry*, 80(6), 710–715. <https://doi.org/10.1016/j.radphyschem.2011.02.025>
2. Al-Saleh, F. S., & Al-Harshan, G. A. (2008). Measurements of radiation level in petroleum products and wastes in Riyadh City Refinery. *Journal of Environmental Radioactivity*, 99(7), 1026–1031.
3. Ali, M. M. M., Zhao, H., Li, Z., & Maglas, N. N. M. (2019). Concentrations of TENORMs in the petroleum industry and their environmental and health effects. *RSC Advances*. Royal Society of Chemistry. <https://doi.org/10.1039/c9ra06086c>
4. Alkhazzar, A., Hamza, H., & Al-Dulaimi, R. (2024). Natural Radioactivity Concentrations in Air Samples in Baghdad City. *Turkish Journal of Nuclear Sciences*, 37(1), 1–6.
5. Alshahrani, B., Korna, A. H., Fares, S. S., Ali, A. H., & Salman, M. (n.d.). Assessing radiological hazards from NORM in oil and gas production residues: a comprehensive study. *Radiation Effects and Defects in Solids*, 1–24. <https://doi.org/10.1080/10420150.2025.2465295>
6. Ayeni, D. A., & Adebisi, F. M. (2022). Evaluation of Natural Radioactivity and Radiation Hazards of Soils around Petroleum Products Marketing Company using Gamma Ray Spectrometry. *Tanzania Journal of Science*, 48(2), 304–312. <https://doi.org/10.4314/tjs.v48i2.7>
7. Azhdarpoor, A., Hoseini, M., Shahsavani, S., Shamsedini, N., & Gharehchahi, E. (2021). Assessment of excess lifetime cancer risk and risk of lung cancer due to exposure to radon in a middle eastern city in Iran. *Radiation Medicine and Protection*, 2(3), 112–116. <https://doi.org/10.1016/J.RADMP.2021.07.002>
8. Badruzzaman, A., Barnes, S., Bair, F., & Grice, K. (2009). Radioactive Sources in Petroleum Industry: Applications, Concerns and Alternatives (Vol. Asia Pacif, p. SPE-123593-MS). <https://doi.org/10.2118/123593-MS>
9. Belamri, M., Bounemia, L., Azbouche, A., Boukeffoussa, K., & Chaouch, C. L. (2017). Assessment of air pollution by heavy metals in the urban center of Algiers. *Australian Journal of Basic and Applied Sciences*, 11(5), 35–44.
10. Bünger, J., Krah, J., Baum, K., Schröder, O., Müller, M., Westphal, G., ... Hallier, E. (2000). Cytotoxic and mutagenic effects, particle size and concentration analysis of diesel engine emissions using biodiesel and petrol diesel as fuel. *Archives of Toxicology*, 74(8), 490–498. <https://doi.org/10.1007/s002040000155>
11. Chen, J. (2022). A review of current inventory for major industries involving naturally occurring radioactive materials in Canada. *Journal of Radiological Protection*, 42(3), 31520.
12. El Afifi, E. M., Mansy, M. S., & Hilal, M. A. (2023). Radiochemical signature of radium-isotopes and some radiological hazard parameters in TENORM waste associated with petroleum production: A review study. *Journal of Environmental Radioactivity*, 256, 107042. <https://doi.org/https://doi.org/10.1016/j.jenvrad.2022.107042>
13. Gannon, R. S., Landon, M. K., Kulongoski, J. T., Stephens, M. J., Ball, L. B., Warden, J. G., ... Cozzarelli, I. M. (2025). Relations of groundwater quality to long-term surface disposal of produced water near the Midway-Sunset and Buena Vista Oil Fields, California, USA. *Science of The Total Environment*, 987, 179637. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2025.179637>
14. Gongora, M., Martínez, J., Peñalver, A., Aguilar, C., & Borrell, F. (2025). Streamlined approach for radium isotopes quantification in water samples by α and γ -spectrometry. *Journal of Radioanalytical and Nuclear Chemistry*. <https://doi.org/10.1007/s10967-025-10170-7>
15. IAEA. (2004). Soil sampling for environmental contaminants. International Atomic Energy Agency Vienna.
16. IAEA. (2009). Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments. International Atomic Energy Agency. Retrieved from <https://books.google.com.my/books?id=hQUuQwAACAAJ>
17. Ijabor, B. O., Omojola, A. D., Omojola, F. R., Chukwueke, F. C., Azuka, P. K., Agama, P., & Okafor, F. M. (2022). Radiological assessment of petroleum products in Aniocha South Local Government Area of Delta State, South-South Nigeria. *Radiation Protection and Environment*, 45(1), 33–40.
18. Kashkinbayev, Y., Kazhiyakhmetova, B., Altaeva, N., Bakhtin, M., Tarlykov, P., Saifulina, E., ... Bolatov, A. (2025). Radon Exposure and Cancer Risk: Assessing Genetic and Protein Markers in Affected Populations. *Biology*, 14(5), 506. <https://doi.org/10.3390/biology14050506>
19. McMahon, P. B., Vengosh, A., Davis, T. A., Landon, M. K., Tyne, R. L., Wright, M. T., ... Ballentine, C. J. (2019). Occurrence and Sources of Radium in Groundwater Associated with Oil Fields in the Southern San Joaquin Valley, California. *Environmental Science and Technology*, 9398–9406. <https://doi.org/10.1021/acs.est.9b02395>
20. Muthu, H., Ramesh, K., Ph, D., Ramesh, S., Ph, D., & Bashir, S. (2023). Dose assessment of ^{137}Cs in agricultural surface soil in Selangor, Malaysia. *International Journal of Radiation Research*, 21(1), 97–103. <https://doi.org/10.52547/ijrr.21.1.13>
21. Muthu, Hariandra, Kasi, R., T subramaniam, R., & Baig, S. (2022). Radioactivity concentration and transfer factors of natural radionuclides ^{226}Ra , ^{232}Th , and ^{40}K from peat soil to vegetables in Selangor, Malaysia. *Nuclear Technology and Radiation Protection*, 37, 57–64. <https://doi.org/10.2298/NTRP2201057M>
22. Nasr, A. S., Duraia, E. S. M., Shafaa, M. W., Ayoub, H. A., & Essa, A. M. (2024). Evaluation and characterization of the

- radiological environmental impact of waste generated from the oil ash. *Journal of Radioanalytical and Nuclear Chemistry*, 333(11), 5867–5879. <https://doi.org/10.1007/s10967-024-09614-3>
23. Othman, I. M. E.-S. A., Saleh, I. H., Ghatass, Z. F., & Metwally, M. A.-A. (2018). Radiological risk assessment in a type of complex petroleum refinery in Egypt. *Arab Journal of Nuclear Sciences and Applications*, 51(4), 31–43.
 24. Rowan, E. L., Engle, M. A., Kirby, C. S., & Kraemer, T. F. (n.d.). Radium Content of Oil-and Gas-Field Produced Waters in the Northern Appalachian Basin (USA): Summary and Discussion of Data. Retrieved from <http://www.usgs.gov/pubprod>
 25. Zhang, Z., Yi, L., Ren, H., Lyu, T., Liu, C., Li, S., ... Li, R. (2025). Geochemical behavior of high-level radium contamination in representative coastal saltworks. *Journal of Hydrology*, 652, 132716. <https://doi.org/https://doi.org/10.1016/j.jhydrol.2025.132716>