data

MDPI

Data Descriptor

Global Database for Naturally Occurring Radionuclides Associated with Offshore Oil and Gas Production

Ziran Wei [1], Songjie He [1], Stephanie Sharuga [2] and Kanchan Maiti [1,*]

[1] Department of Oceanography and Coastal Sciences, College of the Coast and Environment, Louisiana State University, Baton Rouge, LA 70803, USA; zwei12@lsu.edu (Z.W.); she5@lsu.edu (S.H.)
[2] Bureau of Ocean Energy Management, 1849 C Street NW, Washington, DC 20240, USA; stephanie.sharuga@boem.gov
* Correspondence: kmaiti@lsu.edu; Tel.: +225-578-4531

Abstract

This study compiles a comprehensive dataset on the occurrence, distribution, and potential impacts of Naturally Occurring Radionuclides (NORMs) near offshore oil and gas platforms. It encompasses data, including activities (Bq/l) and exposure levels (Msv), derived from various environmental matrices. A particular emphasis is placed on petroleum products and waste, such as produced water, scales, and sludges. The dataset contributes to a better understanding of the distribution of NORM wastes in marine environments, informs future radiological safety standards, contributes to the formulation of regulatory policies, and facilitates the design of mitigation strategies. The information—literature and data from five continents over the past 70 years—has been carefully compiled and organized to support intuitive analysis, making it a valuable tool for policymakers and researchers.

Dataset: https://doi.org/10.5281/zenodo.10729910 (accessed on 10 May 2025).

Keywords: TENORM; NORM wastes; Produced water; Offshore oil and gas

check for updates

Academic Editor: Richard Ross Shaker

Received: 27 May 2025
Revised: 20 June 2025
Accepted: 23 June 2025
Published: 1 July 2025

Citation: Wei, Z.; He, S.; Sharuga, S.; Maiti, K. Global Database for Naturally Occurring Radionuclides Associated with Offshore Oil and Gas Production. *Data* **2025**, *10*, 107. https://doi.org/10.3390/data10070107

1. Summary

Naturally occurring radionuclides (NORMs) associated with the ^{238}U, ^{232}Th, ^{235}U, and ^{40}K decay series (Figure 1) are ubiquitous in the natural environment. Derived from various geological media, these long-lived radionuclides and their progenies (e.g., ^{226}Ra, ^{230}Th, ^{210}Pb) undergo specific geological or geochemical processes, and their relative abundance has been studied extensively to solve major scientific problems in the realms of geoscience and marine science in past centuries [1]. In certain scenarios, both natural phenomena and anthropogenic activities can amplify their concentrations and distribution, posing radiological safety challenges.

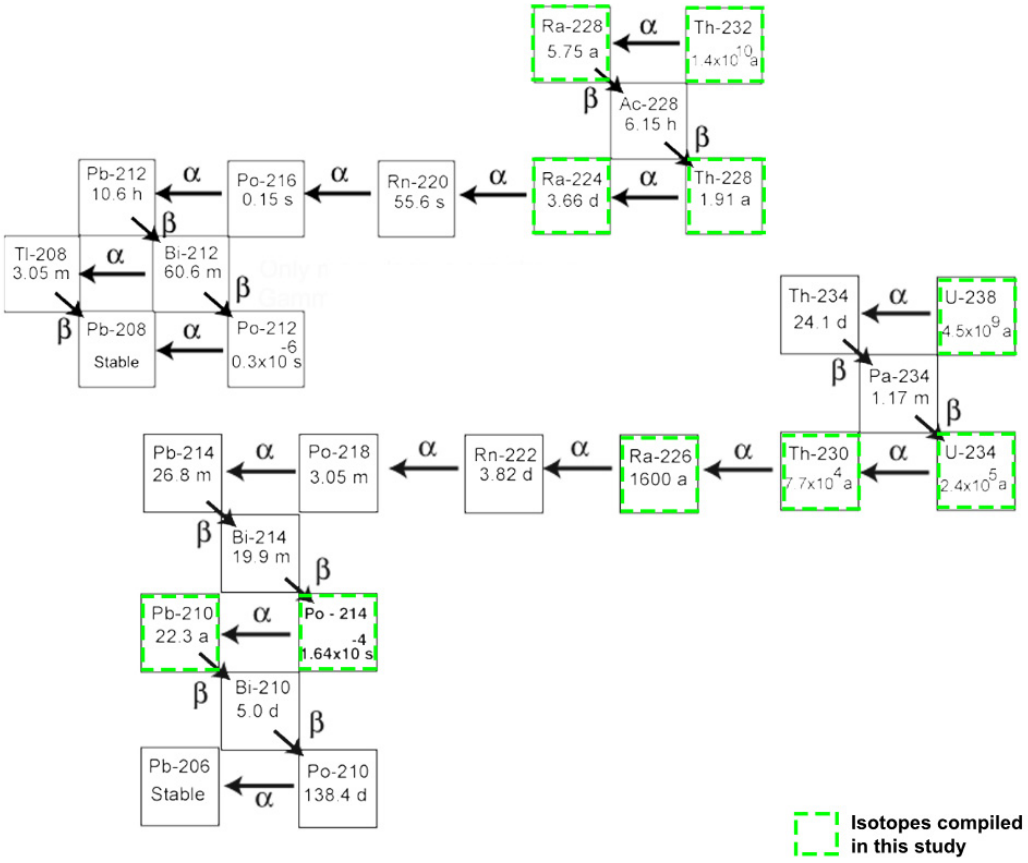

Figure 1. NORM wastes radioisotopes decay series.

Human activities—such as mining, fertilizer production, mineral processing, oil extraction, and power generation—can lead to "Technologically Enhanced NORMs" (TENORMs) [2] characterized by elevated concentrations in products or by-products [3]. This distinction is crucial because TENORMs can pose significant regulatory concerns, unlike NORMs in their native states [4]. While the term "TENORM" is widely used in existing literature, the International Atomic Energy Agency now recommends the terms "NORM residue" or "NORM waste" depending on the context in which the word is used [5,6]. "NORM waste" will be used in this manuscript based on the assumption that the NORMs transferred to the marine environment are those for which there is no further foreseen use and are intended for disposal, and to conform with the IAEA standard [5] practice for nomenclature.

Scientific exploration over the past century has revealed the presence of NORM waste in petroleum products [3,7,8]. Uranium, thorium, and radium, found abundantly in rock reservoirs housing significant hydrocarbon quantities, are the primary NORM contaminants. The concentrations vary among different reservoirs and can be partitioned among petroleum wastes (e.g., produced water, scales, and sludges) [9] based on their chemical nature and technological enhancements. Large volumes of produced water are generated in the oil and gas industry, and current projections show that these volumes are likely to increase in the future [10]. This water is often produced in high proportions relative to hydrocarbon yield, with oil-to-water ratios ranging from 1:1 to 1:100 depending on reservoir characteristics and extraction technologies. It thereby poses challenges for wastewater management, and there is a resulting need to better understand produced water generation, management, and disposal options, particularly in terms of its chemical constituents [11].

In the marine environment, NORM wastes in produced waters can pose a direct ecological threat due to elevated levels of radioactivity [12–16]. It has been suggested that

the increase in radioactivity can affect marine life, particularly for filter feeders and bottom-dwelling species, and cause potential long-term damage for the health and sustainability of oceanic food chains [17,18]. Bioaccumulation of isotopes along the marine food chain can also create potential public health concerns related to seafood consumption [18,19]. Thus, new radioecological understanding of processes, such as the interaction of waterborne radionuclides with suspended particles and sediments or the biological uptake and turnover of radionuclides [20–22], are needed to contribute to a better understanding of transfer of radionuclides along the food chain.

In the United States, produced water constitutes approximately 90% of petroleum-associated waste and is typically enriched with radium isotopes exhibiting gross radioactivity ranging between 1–10 Bq/kg [23]. Scales found within pipes and tubes can also show high radioactivity. Sludges may contain lower activities, but have been associated with a myriad of other isotopes in addition to radium [24]. Substantial amounts of produced water, mixed with scales and sludges, are discharged into marine environments during oil and gas extraction and production activities. Elevated levels of ^{226}Ra, ^{228}Ra, and ^{210}Pb have been reported in produced water discharged from the Norwegian sea [12]. A similar trend is observed in the Gulf of Mexico [25]. Yet, systematic studies assessing NORM waste occurrences in the United States and global oceans are sporadic and lack organization. Past compilation attempts often lack comprehensive regional and global coverage. Furthermore, few studies have directly assessed oil- and gas-activity-related radionuclide discharges' impacts on marine biota, although conceptual models suggest such impacts exist [16].

This data compilation fills a current gap by providing a comprehensive dataset on the occurrence, distribution, and potential impacts of NORM wastes in various marine environmental matrices near offshore oil and gas platforms [26]. The data will support decision-making related to future radiological safety measures, regulatory policies, and mitigation strategies. The completed data product offers an easy and user-friendly way for policymakers and researchers to access the data. It includes research from the past 70 years covering five continents. Radio-ecological models, such as D-DAT [27], ERICA [28], and MARIS [29], are available in the public domain for modelling biological transfer of radioisotopes. These models can also calculate (with certain assumptions) activity concentrations of radioisotopes in fish, crustaceans, mollusks, and macro-algae starting from measured activity concentrations in seawater that are being reported in this dataset.

2. Data Description

The NORM waste dataset is publicly available at the following data repository link https://doi.org/10.5281/zenodo.10729910 (accessed on 10 May 2025) and consists of HTML and Excel files. The HTML file is gridded into a world map (Figure 2) and can easily be zoomed into an area of specific interest, such as the Gulf of Mexico (Figure 3). Due to size limitations, the interactive HTML map may not preview properly online; therefore, users are advised to download the HTML file locally for full functionality. The type of radioisotope, the date of collection, type of sample, and name of the literature cited can be retrieved for every data point plotted. There are a total of 12 radioisotopes—^{228}Ra, ^{210}Pb, ^{228}Th, ^{40}K, ^{224}Ra, ^{234}U, ^{235}U, ^{238}U, ^{210}Po, ^{230}Th, ^{232}Th, and ^{214}Bi—included in the dataset, with ^{228}Ra being the most robust subset of the data. The specific activity in Bq/L is shown as an overlay on top of the data point when hovering over it. Specific isotope layers can be toggled on and off for mapping. The Excel file contains more detailed information about the data, including specific latitude and longitude information. It also includes country information for where the samples were taken from.

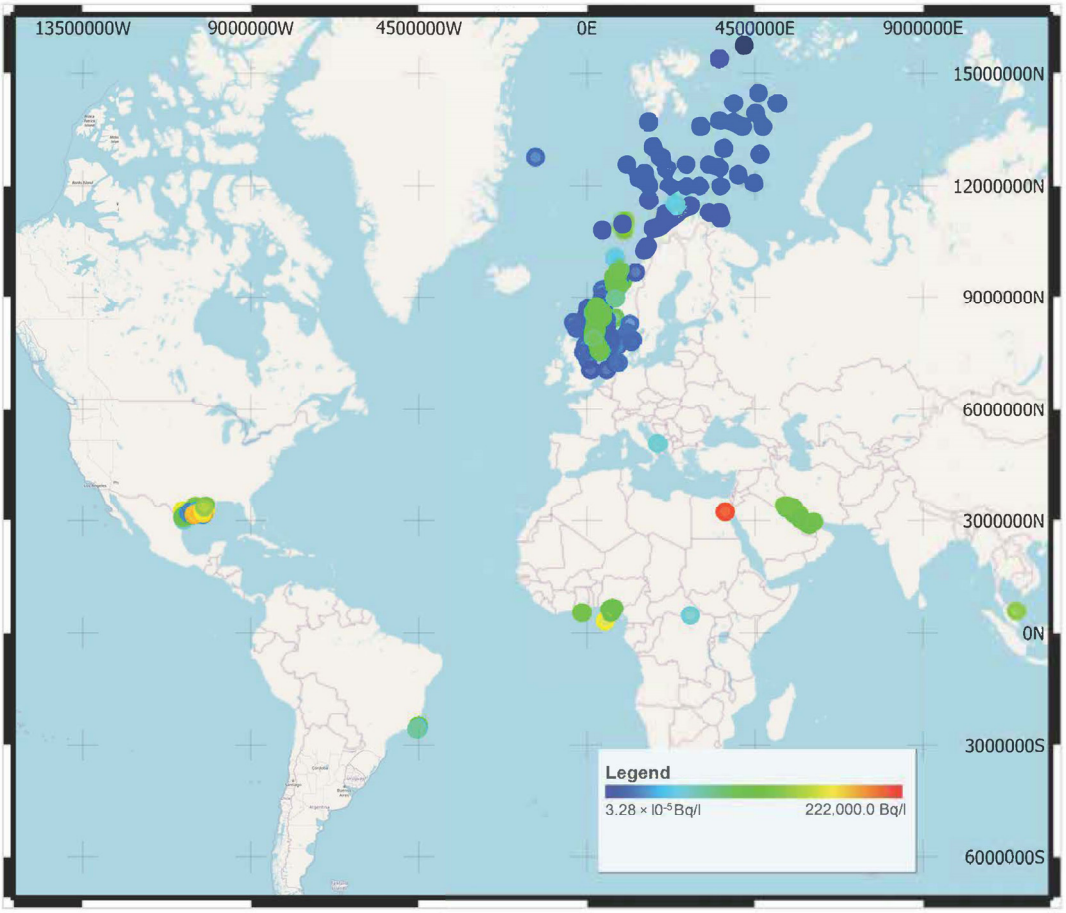

Figure 2. Map showing dissolved activity of ^{228}Ra associated with offshore oil and gas activities.

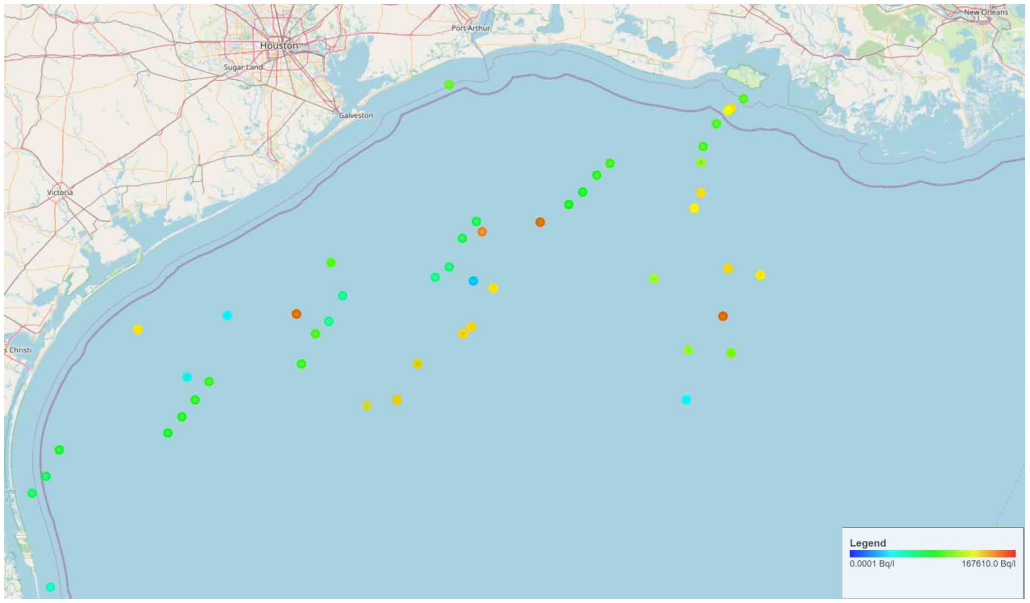

Figure 3. Map showing dissolved activity of ^{228}Ra associated with offshore oil and gas activities in the Gulf of Mexico.

The global distribution of available data is uneven. There is a dearth of data in the Asian Pacific region due to the lack of literature and research in that region. The North Sea dataset is inequitably robust because of extensive oil and gas exploration missions and meticulous data-keeping habits by DSA. Some of the data in the North Sea region

are new data that have never been previously published. In contrast to the North Sea, the Gulf of Mexico does not have sufficient coverage in terms of information on NORM wastes despite being an area of major offshore oil and gas activities. Recent comprehensive reviews (e.g., [30]) further contextualize Ra-226/228 distributions across global petroleum provinces and align with the spatial variability observed in this dataset.

3. Methods

The global marine offshore oil and gas NORM wastes database was compiled in 2022–2023 following the PRISMA ("Preferred Reporting Items for Systematic reviews and Meta-Analyses") guidelines for systematic reviews and meta-analyses (Figure 4 of [31]).

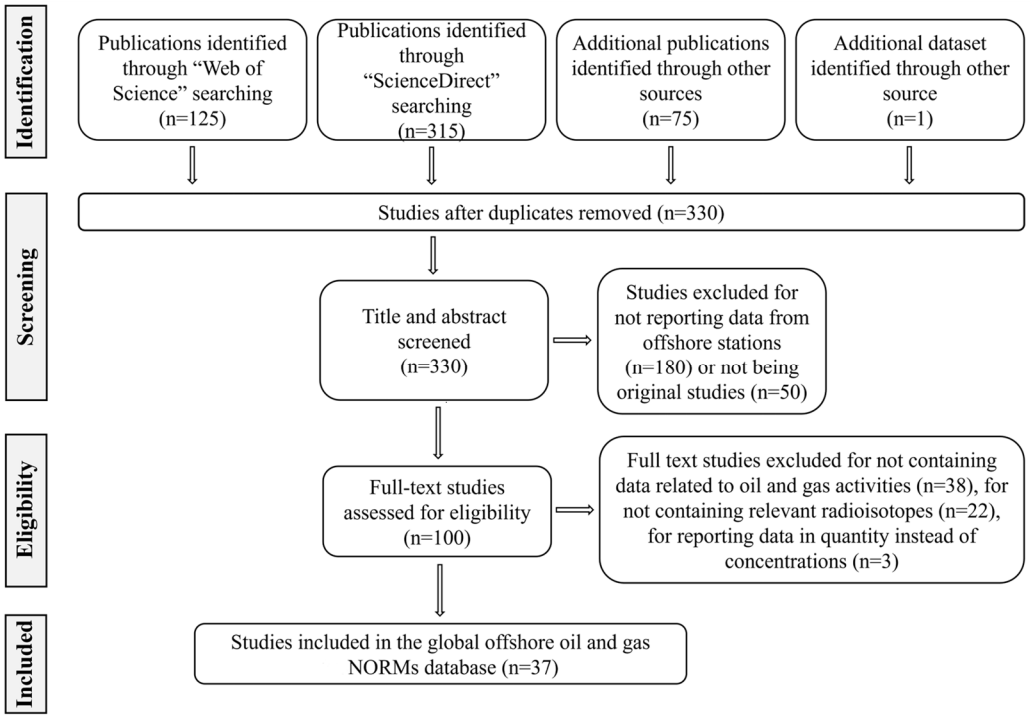

Figure 4. Prisma flowchart detailing literature selection and database compilation procedure.

In the identification phase of the review, 125 publications were identified in Web of Science, and 315 were identified in ScienceDirect using keywords such as "TENORMs", "NORM wastes", and "Marine Radioactivity". An additional 75 publications were identified through expert knowledge and examining literature cited in review papers. One dataset was identified through personal communications with a representative from the Direktoratet for strålevern og atomsikkerhet (DSA, Norwegian Radiation and Nuclear Safety Authority, Østerås Norway).

In the screening phase, the titles and abstracts of 330 studies were screened after removing duplicates. Of this, 180 studies were excluded because they did not report data from offshore stations, and 50 studies were excluded because they did not report primary research (i.e., original measurements).

During the eligibility phase, 100 studies were examined. Of these, 38 were excluded because they did not contain data related to oil and gas activities, 22 were excluded because they did not report relevant radioisotopes, and three were excluded because they reported data in quantity instead of concentrations (making comparison between studies impossible). The final offshore NORM wastes dataset related to offshore oil and gas activities included 37 studies from which a total of 3100 georeferenced NORM waste entries were extracted.

Averages of the minimum and maximum were included in the dataset when data were only reported in a range. In cases where data were presented as a mean or median ± error term,

only the mean and median were included. For situations where NORM waste concentrations were reported in figures instead of tables, the concentrations were extracted from the figure using Plot Digitizer (https://plotdigitizer.com/). When studies did not indicate the exact sampling or measurement location in geographical coordinates (i.e., latitude, longitude) but instead only revealed the general sampling area or presented it in maps, the coordinates of the specific location were approximated using Google Earth Pro.

This dataset is compatible with widely used radio-ecological risk models like ERICA and D-DAT. These tools can simulate the bioaccumulation and trophic transfer of radionuclides in marine organisms (e.g., fish, crustaceans, algae) using initial seawater activity concentrations such as those included in this dataset. By providing concentration data in a standardized and georeferenced format, this dataset facilitates direct input into these tools.

Author Contributions: Conceptualization, Z.W. and K.M.; methodology, Z.W.; software, Z.W.; validation, Z.W., S.H. and S.S.; formal analysis, Z.W.; investigation, Z.W.; resources, K.M.; data curation, Z.W.; writing—original draft preparation, Z.W.; writing—review and editing, Z.W., S.H., S.S. and K.M.; visualization, Z.W.; supervision, K.M.; project administration, K.M.; funding acquisition, K.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Bureau of Ocean Energy Management (BOEM), grant number 140M0122P0009.

Data Availability Statement: The dataset supporting the findings of this study is openly available in Zenodo at https://doi.org/10.5281/zenodo.10729910 (accessed on 10 May 2025). The dataset includes downloadable HTML and Excel files containing metadata, isotope activity levels, and georeferenced sample locations.

Acknowledgments: The authors thank the Norwegian Radiation and Nuclear Safety Authority (DSA) for data sharing and communication. We also acknowledge the administrative and technical support provided by Louisiana State University and the Bureau of Ocean Energy Management.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Patterson, C.C.; Tilton, G.R.; Inghram, M.G. Age of the Earth. *Science* **1955**, *121*, 69–75. [CrossRef] [PubMed]
2. National Research Council. *Evaluation of Guidelines for Exposures to Technologically Enhanced Naturally Occurring Radioactive Materials*; National Academies Press: Washington, DC, USA, 1999.
3. Heaton, B.; Lambley, J. TENORM in the oil, gas and mineral mining industry. *Appl. Radiat. Isot.* **1995**, *46*, 577–581. [CrossRef]
4. El Afifi, E.M.; Mansy, M.S.; Hilal, M.A. Radiochemical signature of radium-isotopes and some radiological hazard parameters in TENORM waste associated with petroleum production: A review study. *J. Environ. Radioact.* **2023**, *256*, 107042. [CrossRef] [PubMed]
5. International Atomic Energy Agency (IAEA). *Management of NORM Residues (TECDOC-1712)*; IAEA: Vienna, Austria, 2013.
6. International Atomic Energy Agency (IAEA). *Security Glossary: Terminology Used in Nuclear Safety, Nuclear Security, Radiation Protection and Emergency Preparedness and Response*; IAEA: Vienna, Austria, 2022; pp. 139–141.
7. Gazineu, M.H.P.; de Araujo, A.A.; Brandao, Y.B.; Hazin, C.A.; Godoy, J.M.d.O. Radioactivity concentration in liquid and solid phases of scale and sludge generated in the petroleum industry. *J. Environ. Radioact.* **2005**, *81*, 47–54. [CrossRef]
8. Landsberger, S.; Brabec, C.; Canion, B.; Hashem, J.; Lu, C.; Millsap, D.; George, G. Determination of ^{226}Ra, ^{228}Ra and ^{210}Pb in NORM products from oil and gas exploration: Problems in activity underestimation due to the presence of metals and self-absorption of photons. *J. Environ. Radioact.* **2013**, *125*, 23–26. [CrossRef]
9. Smith, A. Radioactive-scale formation. *J. Pet. Technol.* **1987**, *39*, 697–706. [CrossRef]
10. EPA Report, Summary of Input on Oil and Gas Extraction Wastewater Management Practices Under the Clean Water Act EPA-821-S19-001, 2020, pp. 1–38. Available online: https://19january2021snapshot.epa.gov/eg/summary-input-oil-and-gas-extraction-wastewater-management-practices-under-clean-water-act-final_.html (accessed on 14 January 2024).
11. Attallah, M.; Hamed, M.M.; El Afifi, E.; Aly, H. Removal of ^{226}Ra and ^{228}Ra from TENORM sludge waste using surfactants solutions. *J. Environ. Radioact.* **2015**, *139*, 78–84. [CrossRef]

12. Eriksen, D.; Sidhu, R.; Strålberg, E.; Iden, K.I.; Hylland, K.; Ruus, A.; Røyset, O.; Berntssen, M.H.G.; Rye, H. Radionuclides in produced water from Norwegian oil and gas installations—Concentrations and bioavailability. *Czechoslov. J. Phys.* **2006**, *56*, D43–D48. [CrossRef]
13. Grung, M.; Ruus, A.; Holth, T.F.; Sidhu, R.S.; Eriksen, D.Ø.; Hylland, K. Bioaccumulation and lack of oxidative stress response in the ragworm H. diversicolor following exposure to ^{226}Ra in sediment. *J. Environ. Radioact.* **2009**, *100*, 429–434. [CrossRef]
14. Jensen, L.K.; Halvorsen, E.; Song, Y.; Hallanger, I.G.; Hansen, E.L.; Brooks, S.J.; Hansen, B.H.; Tollefsen, K.E. Individual and molecular level effects of produced water contaminants on nauplii and adult females of Calanus finmarchicus. *J. Toxicol. Environ. Health Part A* **2016**, *79*, 585–601. [CrossRef]
15. Olsvik, P.A.; Berntssen, M.H.; Hylland, K.; Eriksen, D.Ø.; Holen, E. Low impact of exposure to environmentally relevant doses of ^{226}Ra in Atlantic cod (Gadus morhua) embryonic cells. *J. Environ. Radioact.* **2012**, *109*, 84–93. [CrossRef] [PubMed]
16. Valeur, J.R. Environmental impacts of NORM disposal—With emphasis on discharges to sea. *SPE Proj. Facil. Constr.* **2011**, *6*, 124–131. [CrossRef]
17. Bohne-Kjersem, A.; Bache, N.; Meier, S.; Nyhammer, G.; Roepstorff, P.; Saele, O.; Goksøyr, A.; Grøsvik, B.E. Biomarker candidate discovery in Atlantic cod (*Gadus morhua*) continuously exposed to North Sea produced water from egg to fry. *Aquat. Toxicol.* **2010**, *96*, 280–289. [CrossRef]
18. Koppel, D.J.; Kho, F.; Hastings, A.; Crouch, D.; MacIntosh, A.; Cresswell, T.; Higgins, S. Current understanding and research needs for ecological risk assessments of naturally occurring radioactive materials (NORM) in subsea oil and gas pipelines. *J. Environ. Radioact.* **2022**, *241*, 106774. [CrossRef]
19. Harrison, J.; Leggett, R.; Lloyd, D.; Phipps, A.; Scott, B. Polonium-210 as a poison. *J. Radiol. Prot. Off. J. Soc. Radiol. Prot.* **2007**, *27*, 17–40. [CrossRef]
20. Bahrou, A.S.; Ollivier, P.R.; Hanson, T.E.; Tessier, E.; Amouroux, D.; Church, T.M. Volatile dimethyl polonium produced by aerobic marine microorganisms. *Environ. Sci. Technol.* **2012**, *46*, 11402–11407. [CrossRef]
21. Hussain, N.; Ferdelman, T.G.; Church, T.M.; Luther, G.W., III. Bio-volatilization of polonium: Results from laboratory analyses. *Aquat. Geochem.* **1995**, *1*, 175–188. [CrossRef]
22. Wei, Z.; Cochran, J.K.; Horowitz, E.; Fitzgerald, P.; Heilbrun, C.; Kadko, D.; Stephens, M.; Marsay, C.M.; Buck, C.S.; Landing, W.M. ^{210}Pb and ^{7}Be as coupled flux and source tracers for aerosols in the Pacific Ocean. *Glob. Biogeochem. Cycles* **2022**, *36*, e2022GB007378. [CrossRef]
23. Ali, M.M.; Zhao, H.; Li, Z.; Maglas, N.N. Concentrations of TENORMs in the petroleum industry and their environmental and health effects. *RSC Adv.* **2019**, *9*, 39201–39229. [CrossRef]
24. Jonkers, G. Characterization of NORM in the Oil and Gas Production Industry. Proc. of NORM. 1997. Available online: https://ena-norm.eu/wp-content/uploads/2024/04/I.IV_.7.pdf (accessed on 14 January 2024).
25. Lagera, L.; Hart, A.; Graham, B. *Radionuclides, Metals, and Hydrocarbons in Oil and Gas Operational Discharges and Environmental Samples Associated with Offshore Production Facilities on the Texas/Louisiana Continental Shelf with an Environmental Assessment of Metals and Hydrocarbons*; Continental Shelf Associates, Inc.: Stuart, FL, USA, 1999.
26. MacIntosh, A.; Dafforn, K.; Penrose, B.; Chariton, A.; Cresswell, T. Ecotoxicological effects of decommissioning offshore petroleum infrastructure: A systematic review. *Crit. Rev. Environ. Sci. Technol.* **2022**, *52*, 3283–3321. [CrossRef]
27. Vives Batlle, J.; Wilson, R.C.; Watts, S.J.; Jones, S.R.; McDonald, P.; Vives-Lynch, S. Dynamic model for the assessment of radiological exposure to marine biota. *J. Environ. Radioact.* **2008**, *99*, 1711–1730. [CrossRef] [PubMed]
28. Brown, J.E.; Alfonso, B.; Avila, R.; Beresford, N.A.; Copplestone, D.; Hosseini, A. A new version of the ERICA tool to facilitate impact assessments of radioactivity on wild plants and animals. *J. Environ. Radioact.* **2016**, *153*, 141–148. [CrossRef] [PubMed]
29. Povinec, P.P.; Scotto, P.; Osvath, I.; Ramadan, H.1. *The Marine Information System (MARIS)*; IAEA Report; IAEA: Vienna, Austria, 2004.
30. Sohrabi, M. *"Low Dose" and/or "High Dose" in Radiation Protection: A Need to Setting Criteria for Dose Classification*; IAEA-CN-67/154; IAEA: Vienna, Austria, 1997; pp. 487–490.
31. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G.; Group*, P. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Ann. Intern. Med.* **2009**, *151*, 264–269. [CrossRef] [PubMed]