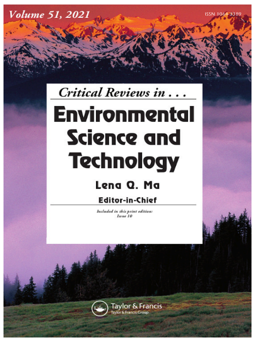

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Ecotoxicological effects of decommissioning offshore petroleum infrastructure: A systematic review

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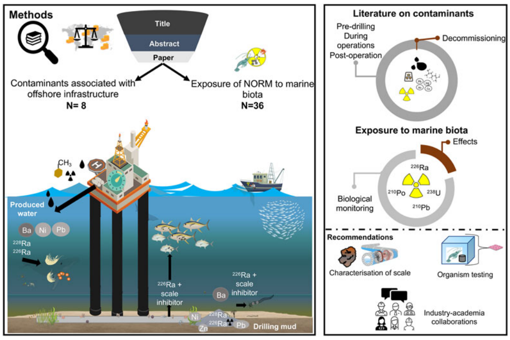
ABSTRACT



Successful decommissioning of subsea oil and gas infrastructure requires a safe and effective approach to assess and manage waste products. These products, often present as scale on internals of pipelines, include naturally occurring radioactive materials (NORM) and trace metals. Understanding the potential effects of these contaminants on marine fauna is crucial to managing global decommissioning. This review is composed of two aspects: 1) a systematic review was conducted to synthesize literature on all contaminants associated with decommissioned offshore structures and the effects of NORM contaminants on marine organisms; 2) a critical review of current environmental regulations for decommissioning and characterization of petroleum scale and NORM components. Studies defining the chemical and radiological contaminants associated with decommissioned structures were very limited. The main source of contaminants was identified from offshore platforms, with none from subsea structures. Only three studies measured variable chemical effects of radium to organisms from scale materials in subsea oil and gas infrastructure. No studies measured effects on organisms from other NORM, such as lead-210 and polonium-210. Currently, there are no international regulations on subsea pipeline closure, with NORM being underreported and not addressed in environmental impact assessments. This review highlights research gaps from environmental monitoring and characterization of NORM associated with decommissioned structures. Key recommendations for future research include characterizing NORM scale and assessing effects of scale to marine organisms through direct organism exposure experiments. This review emphasizes the need to incorporate ecotoxicology into environmental risk assessment for offshore petroleum decommissioning.

Abbreviations and acronyms: ANZG: Australian and New Zealand Guidelines; Ba: Barium; BACI: Before-After-Control-Impact; $BaSO_4$: Barium sulfate (barite); Bq: Becquerel; BTEX: Benzene, toluene, ethylbenzene, xylene; $CaSO_3$: Calcium sulfate; Cs: Cesium; DGV:

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Supplemental data for this article can be accessed at publisher's website.

Default Guideline Value; EIA: Environmental Impact Assessment; ERICA: Environmental Risk from Ionizing Contaminants: Assessment and Management; FPSO: Floating Production Storage and Offloading Unit; IAEA: International Atomic Energy Agency; ICRP: International Commission on Radiological Protection; IMO: International Maritime Organization; IR: Ionizing radiation; K: Potassium; LDC: London Dumping Convention; mSvy: millisieverts per year; Ni: Nickel; NOAA: National Oceanic and Atmospheric Administration; NORM: Naturally Occurring Radioactive Material; NOPSEMA: National Offshore Petroleum Safety and Environmental Management Authority; OSPAR: Convention for the Protection of the Marine Environment of the North-East Atlantic ; PAH: Polyaromatic hydrocarbons; Pb: Lead; Po: Polonium; Ra: Radium; ROSES: Reporting Standards for Systematic Evidence Synthesis; ROS: Reactive oxygen species; Rn: Radon; RtR: Rigs to Reef; Sr: Strontium; $SrSO_4$: Strontium sulfate; Th: Thorium; U: Uranium; Zn: Zinc

KEYWORDS NORM; radioecology; oil; gas; ecotoxicology; decommissioning

1. Introduction

1.1. Decommissioning of oil and gas infrastructure

Since the commencement of the modern offshore oil and gas industry in the Gulf of Mexico in 1947, there has been an increase in the exploitation of seafloor petroleum resources to meet the growing global demand for energy (Aagaard-Sørensen et al., 2018). Recently, it is estimated there are over 6,000 operating platforms worldwide extracting resources (Techera & Chandler, 2015). Many of these facilities will reach the end of their operational life, being no longer economically viable to continue production and will then be decommissioned (Barrymore & Ballard, 2019; Birchenough & Degraer, 2020; Bull & Love, 2019). Between 2500 and 3000 offshore petroleum projects are likely to require decommissioning worldwide in the next 17 years (IEA, 2018).

The types of structures associated with offshore petroleum production, including installation platforms; fixed to the seabed, rigs; moveable platforms; jackets; steel frame support; wells and pipelines, require decommissioning options that consider environmental, economic, human safety and engineering factors (Day et al., 2018; Fowler et al., 2019). This can range from removing all infrastructure from the seabed or leaving *in situ* (leave in place), with no intervention or with several encapsulation or burial options (Supplementary Figure 1; Bull & Love, 2019). By the end of 2020, it was estimated at least 600 structures within the major petroleum countries ceased operation, with subsequent decommissioning operations are expected to significantly increase between now and 2040 (Sommer et al., 2019). The costs of decommissioning are significant and are forecasted to increase as more assets are to undergo closure, creating large economic liabilities (Invernizzi et al., 2020). For example, in 2020, offshore oil and gas decommissioning in the United Kingdom's continental shelf was projected to cost £51 billion ($68 billion USD). Further, total removal of 55,000 km of pipeline from oil and gas operations in the Asia-Pacific was estimated to cost over US$100 billion (OGA, 2020; WoodMackenzie, 2018). Although environmental risk frameworks exist for the exploratory and operational phases of offshore petroleum, the ecological and environmental risks associated with the decommissioning stage are not fully understood.

The effects and impacts of operational processes and petroleum spillages are well recognized, with the focus mainly on carbon emissions and oil spill events, e.g., Deepwater Horizon (c. 2010) and the Exxon Valdez oil spill (c. 1989) (Ainsworth et al., 2018; Fernando et al., 2019; Fukuyama et al., 2014; Turner & Renegar, 2017; Wise et al., 2020). These are still having protracted detrimental impacts on the ecology and hydrochemical profile of the ocean (Amezcua et al., 2014; Soto et al., 2014; Sun et al., 2015). Even though there is a thorough understanding of the hydrocarbon contaminants associated with operations and spillages, little is known about potential metal and NORM contaminants released during decommissioning.

Operators are recommended to demonstrate that decommissioning activities will have minimal impact on the surrounding marine biota (Burdon et al., 2018; NOPSEMA, 2020). The decommissioning process has the potential to affect marine organisms through physical impacts and release of scale contaminants (Burdon et al., 2018). Therefore, qualifying and quantifying such effects to marine ecosystems is a key part of the decommissioning consideration. All structures used to transport, transfer or store hydrocarbons during the life of the production facility are susceptible to contamination, including the presence of hazardous materials such as trace metals/metalloids (e.g. mercury, arsenic, hereafter referred to as metals), residual hydrocarbons and naturally occurring radioactive materials (NORM; Supplementary Figure 1). Such impacts may include reduced fishery productivity and the discharge of contaminants creating localized waters and sediments enriched in contaminants; with the latter having potential negative implications to marine biota (Almeda et al., 2014; Johannessen et al., 2007; Rouse et al., 2020). Even with the projected large-scale decommissioning of infrastructure, the long-term environmental impacts from metals and NORMs are often overlooked.

Many jurisdictions adopt marine environmental quality guidelines for threshold concentrations for metals and hydrocarbons in waters and sediments to protect marine ecosystems and biota e.g. Australian and New Zealand Guidelines for waters and sediment, National Oceanic and Atmospheric Administration (NOAA) (Burton, 2002). Guidance and recommendations for the management and application of guidelines for

NORM in industry are provided by the International Atomic Energy Agency (IAEA) exempt levels for low-level radioactive waste; concentration of a radionuclide that may result in doses to humans. These exclusion activity concentrations for NORMs are 1 Bq/g, if levels per radionuclide are below the exempt threshold, there is no regulatory concern. However, no such exemption levels for non-human biota exposure or marine ecological guidelines are available for NORM (IAEA, 2004).

1.2. Naturally occurring radioactive material (NORM) in offshore petroleum infrastructure

Uranium (^{238}U) and thorium (^{232}Th) naturally occur in petroleum reservoirs along with their radioisotope decay daughter products (e.g. radium-226, radon-222, lead-210, polonium-210; radium-228, thorium-228) (Ali et al., 2019; Nelson et al., 2015). Uranium and thorium are relatively insoluble and often remain within the reservoir, although their decay products (e.g. radium, Ra) may be soluble within the reservoir and therefore extracted with oil and formation water (Kolb & Wojcik, 1985). Once the soluble cations (e.g. barium (Ba) and radium) have saturated in solution such as the formation water stream, precipitation and/or deposition of NORM may occur at various points along production infrastructure and their co-occurring metal contaminants in the form of scale (Supplementary Figure 2). On older, uncleaned pipes, the resulting scale accumulation can reduce the internal diameter of pipelines, thereby reducing the flow rate or increasing the pressure within the pipe. This may result in significant economic costs associated with reduced production or internal cleaning via mechanical and chemical means (Todd & Yuan, 1992; Vetter & Phillips, 1970).

The degree of NORM accumulation can vary substantially from one facility to another depending on many factors including the geological formation, environmental features (e.g., depth/pressure, acidity of formation water, ambient temperature), infrastructure material and operational practices of extraction (Abdelbary et al., 2019; Ali et al., 2019; Godoy & Petinatti da Cruz, 2003; Mitchell et al., 1980). For example, in Italy and Syria, scale is often composed of carbonates in contrast to Brazil and Egypt where scale contains very few carbonates, sulfates and silicates (Abdelbary et al., 2019; Godoy & Petinatti da Cruz, 2003; Vegueria et al., 2002). However, ubiquitous components of scale present among countries and petroleum structures include barite ($BaSO_4$)and calcium carbonate ($CaCO_3$) with barite receiving the most research attention thus far (Neff, 2008; Neff et al., 1989).

1.3. Biological exposure and interactions of marine biota with NORM

Petroleum scale can make NORM and other non-hydrocarbon constituents directly available to organisms *in situ* or through release into the surrounding benthic environment. While pipeline scale is not a sediment contaminant, once the pipe corrodes the scale will deposit on and mix with the surficial layer of sediment. Benthic and pelagic communities may then be exposed to associated contaminants through dietary ingestion of particulate and dissolved particles or external adsorption through the exoskeleton (Rainbow, 1992). Interactions between marine organisms and scale-based contaminants depends on the dissolved and particulate concentrations, but also the organism's feeding behavior and physiology (Eggleton & Thomas, 2004; Simpson et al., 2005; Simpson & King, 2005). Organisms inhabiting offshore petroleum structures in close contact with scale or other petroleum sediment-associated contaminants may bioaccumulate contaminants and suffer subsequent ecotoxicological effects from the chemical and radiological properties of the scale material (Hosseini et al., 2012).

Biological exposure to radioactive material, both artificial radionuclides (e.g. radiocaesium; ^{137}Cs, radiostrontium; $^{89/90}$Sr) and NORM can cause detrimental biological effects on one or more levels of biological organizations (individuals, populations, ecosystems) and through trophic interactions, including increased risk of mortality, neurological and physiological disorders, genetic mutations and reduced reproductive success (Bréchignac et al., 2016; Jackson et al., 2005; Real & Garnier-Laplace, 2020). Coincidentally, studies on radiotoxic and chemotoxic effects are common for small mammals (Beresford et al., 2008), aquatic fish (Jonsson et al., 1999), plants (Kovalchuk et al., 2004; Penrose et al., 2015) and birds (Galván et al., 2014; Hermosell et al., 2013), with limited studies on NORM in the marine environment. The dose, exposure pathways, duration of exposure to contaminants, and biological responses differ between terrestrial and marine organisms. However, few studies have been conducted in the marine environment to understand how each of these factors influences the toxicology of NORM. Therefore, potentially affected marine biota may not conform to the wider understanding of multiple stressor effects from radiation and trace metals. The presence and release of radionuclides into the marine environment sourced from decommissioned infrastructure can expose marine fauna to different forms of ionizing radiation (IR); internal doses from alpha (α), beta (β), gamma (γ) and external doses from beta (β) and gamma (γ) (Vives i Batlle, 2012). NORM contaminants may impact organisms while the pipeline is intact. Radionuclides such as radium-226 have γ radiation emissions, that may penetrate the carbon steel of a pipeline. This could result in a radiological dose to organisms outside the pipe, especially for sessile invertebrates that colonize the external surfaces of the pipe. However, knowledge is limited on the chemotoxic and radiotoxic effects from NORM, dose rates emitted from scale constituents and other petroleum-associated contaminants, the form of radiation, and the effect thresholds that signal potential benchmark toxicity.

To better inform *in-situ* decommissioning strategies, a review of current knowledge on the presence of contaminants associated with offshore petroleum infrastructure and potential interactions between contaminants and marine biota is needed. This evidence will facilitate appropriate decommissioning decisions that consider ecological concerns along with engineering and socioeconomic needs.

This review covered two aspects, composed of a systematic and critical review of available literature relating to contaminants associated with the decommissioning of offshore oil and gas petroleum structures and a traditional critical review around decommissioning regulations, environment monitoring regulations, environmental monitoring and marine radiological risk assessments. The aims of the systematic review were to: (1) synthesize current literature on the presence of contaminants associated with decommissioning of offshore infrastructure and (2) evaluate the possible radiological and ecotoxicological effects of NORM contaminants associated with infrastructure by assessing the biological responses to NORM exposure. The critical review component was to synthesize literature of i) global and regional jurisdictions for offshore decommissioning; ii) characterization of petroleum scale and NORM components and iii) the use of radiological dose assessments to estimate the impact of NORM to marine biota. This review provides recommendations for standardizing decommissioning policies across jurisdictions, and proposes a framework for the collection, processing, analysis and interpretation of environmental samples around offshore infrastructure to identify contaminants of concern.

2. Methodology

2.1. Literature search

A systematic literature review was conducted from May - September 2020 to address the following aims: 1) identify the contaminants associated with decommissioned petroleum infrastructure and 2) evaluate the ecotoxicological effects of NORM on marine biota. The protocol used for the systematic review was a tiered, two stage screening process following the Reporting Standards for Systematic Evidence Synthesis, (ROSES; Haddaway et al., 2018; Supplementary Figure 3). To address the two aims, two separate searches (search 1 and search 2) were conducted using the ISI's Web of Science (all databases) and Scopus (Supplementary Figure 3). All searches used English search terms and studies were limited to English language publications, with no restriction on publication date.

Search strings were developed by checking published reviews and consulting with industry and academic experts. No terms for taxa were included, as scoping indicated different taxonomic resolutions are used in different studies. All search terms were truncated and written with a wildcard at the end to include alternative forms, alternative spelling and hyphenation. Scoping returned articles on unrelated topics such as freshwater and terrestrial environments, human exposure, medicinal health, seafood, offshore wind farms, biofouling paints, agriculture, soil and land-based contaminants. These topics were included in the search with the Boolean NOT operator to exclude results (Supplementary Table 1).

To evaluate the accuracy and comprehension of the search strategy and search terms, a test list of articles from a recent review on decommissioned infrastructure by Bull and Love (2019) was used as a benchmark to compare with the search results. If any articles were found to be absent from our results, the search string was amended.

The sets of search criteria contained the major terms related to offshore petroleum decommissioning, combined with terminology related to associated contaminants and are included in Supplementary Table 1.

The search strings targeting studies assessing the ecotoxicological effects of different types of radionuclides from the ^{238}U and ^{228}Th decay chains were performed separately, in combination with ecotoxicological terminology (Supplementary Table 2).

The search strategies performed on the titles, keywords and abstracts used in each database are available in the Supporting Information.

The search results for the final search strings were imported into EndNote X9.3 for further screening, with duplicates removed (additional Supplementary Data available in https://doi.org/10.6084/m9.figshare.13174808.v1). To ensure the review captured all available literature, the imported articles were checked to confirm the results included all the test list articles. Search 1 resulted in 5888 papers and Search 2 resulted in 1497 papers.

2.2. Article screening and study inclusion criteria

Following the ROSES procedure (Haddaway et al., 2018) articles for both respective aims of the review were included if they were: 1) available in their full text; 2) original research; 3) directly involved a type of offshore petroleum infrastructure-associated contaminant; 4) manipulative, experimental or observations from environmental monitoring surveys and assessments; 5) supported by appropriate controls; and 6) about marine animals (additional information available in Supporting Information).

For the first and second tier respectively, titles and abstracts were screened to evaluate the relevance to this study, and those deemed outside the scope of the review (did not meet the inclusion criteria) were excluded from further evaluation (Supplementary Figure 3; Supplementary Table 3). Remaining articles were read in full to determine if the article met inclusion criteria (search 1 n = 8; search 2 n = 36). At each stage of the title and abstract screening process, a subset of 10% (n = 10) of the articles were assessed by all authors independently to check for consistency in inclusion decisions. In no cases did authors disagree on the eligibility of the papers for inclusion in the systematic review.

All articles excluded at the full text stage (n = 26) were included in a separate list with each article's reason for exclusion (Supplementary Tables 4 and 5).

2.3. Quantitative and qualitative analysis

For the remaining studies (n = 8 for search 1, n = 36 for search 2) we recorded bibliographic information (year of publication, year of study, title), geographical information (continent, country, study location) and quantitative and qualitative information which are provided in the Supporting Information.

For the respective research question, quantitative data were recorded and coded in a Microsoft Excel spreadsheet. Data from search 2 were originally extracted for use in a meta-analysis, but insufficient data were available. Information was therefore summarized in graphs, tables and trends interpreted qualitatively.

An additional database was created of current offshore decommissioning jurisdictions and their associated decommissioning regulations from across the world. The methodology is available in the Supporting Information.

3. Results and discussion

3.1. Offshore-associated petroleum contaminants: Geographic focus, study period and methodologies

Of the initial 162 papers considered, only 8 publicly accessible studies assessed the presence of contaminants directly associated with offshore petroleum infrastructure. However, no studies investigated decommissioned infrastructure, instead all were focused on predrilling, drilling and postdrilling operations. Most studies were conducted in Europe (n = 4) and North America (n = 2), with single studies in Africa and South America

(Supplementary Figure 4a). No studies were identified from Asia or Oceania. The majority of research was done 10-20 years ago with each assessment focused on a particular geographical location and conducted in consecutive years (Supplementary Figure 4b).

Studies predominantly consisted of field-based surveys in the form of BACI designs ($n = 3$), following standard environmental impact assessments techniques such as a) radial designs by allocating samples according to distances from infrastructure and b) transect designs using distance interval radial transects around infrastructure. Laboratory experiments or robust comparative in-situ surveys with control sites and quality assurance measures were rare ($n = 2$). Only two studies had a control or reference site for comparisons with environmental background levels (Okogbue et al., 2016; Yeung et al., 2011), whilst three studies inferred background levels from other papers (Dowdall & Lepland, 2012; Gomiero, da Ros et al., 2011; Steinhauer et al., 1994). Two studies examined the effect of season variability (i.e. summer and winter) (Durell et al., 2006; Okogbue et al., 2016).

3.2. Contaminant classes, sources and associated infrastructure

Several studies ($n = 5$) assessed more than one contaminant, with a combination of predominantly hydrocarbons (e.g. total polynuclear aromatic hydrocarbons, BTEX, phenols) and trace metals. The common alkali-earth metals and metals analyzed were barium, zinc, arsenic, cadmium, chromium, copper and lead (Supplementary Figure 5). Only two studies investigated NORM and quantified the presence of various radionuclides (^{226}Ra, ^{228}Ra), and none assessed the daughter radionuclides (e.g. ^{210}Pb, ^{210}Po).

Elevated concentrations of metals (Pb and Zn) and Ba (often in the form of barite; $BaSO_4$) relative to background levels and applied sediment quality guidelines were reported in most studies (Table 1). Gomiero, De Biasi et al. (2011) found elevated concentrations of Ba and Zn from one month to three years after drilling operations. Altin et al. (2008) analyzed an unknown number of drilling mud samples taken from a database of metal concentration recordings from the vicinity of petroleum installations in Norway. No numerical means were provided, instead the range of various metal concentrations (Ba, Ni, Pb, Zn) were above the environmental Default Guideline Values for Australia and New Zealand (Table 1).

Ba and Zn are regularly found in produced water at higher concentrations than seawater, with the corrosion of offshore structures also identified as a source of Pb and Zn (Al-Ghouti et al., 2019; Neff, 2008; Okogbue et al., 2016). The accumulation of drill cuttings on the sea floor can also increase the concentrations of Ba and other metals in the sediments near the discharge point (Neff, 2002; 2008; Neff et al., 1989). Concentrations of

Table 1. Studies included in this review with elevated concentrations of offshore petroleum-associated contaminants above the Australian and New Zealand sediment quality guidelines; indicated in bold (ANZG, 2018).

Author	Year of study	Contaminant analyzed	Source or process of origins of contaminant	Pre-drilling mean concentration (mg/kg dw) (sampling year)	During operations mean concentration (mg/kg dw) c(sampling year)	Post-drilling mean concentration (mg/kg dw) (sample year)	ANZG sediment DGV (mg/kg dw)
Steinhauer et al.	1994	PAH	Discharges from platform to seabed (sediment)	**55** (1986)	–	**48** (1990)	10
		Ba	Discharges from platform to seabed (sediment)	752 (1986)	–	862 (1990)	NA
		Ba	Drilling mud[a]	–	107782	–	NA
		Ba	Drilling cuttings[a]	–	5200	–	NA
		Pb	Drilling cuttings[a]	–	**1926**	–	50
		Ni	Drilling mud[a]	–	**41**	–	21
		Ni	Drilling cuttings[a]	–	**67**	–	21
		Zn	Drilling mud[a]	–	**290**	–	200
		Zn	Drilling cuttings[a]	–	**1346**	–	200
Altin et al.	2008	Ba	Drilling cutting near platform	–	(720-449000)*	–	NA
		Ni	Drilling cutting near platform	–	(3.8-19.9)*	–	21
		Pb	Drilling cutting near platform	–	(0.4-**4225**)*	–	50
		Zn	Drilling cutting near platform	–	(0.06-**12300**)*	–	200
Gomiero et al.	2011	Ba[b]	Sediment near platform	–	224 ± 9.4 (2003)		NA
		Ba[c]	Sediment near platform	–	323 ± 30.8 (2005)		NA

[a] Sampled at five weeks of operations from the platform.

[b] Sediment samples were taken one month after drilling.

[c] Sediment samples were taken three years after drilling.

* Only the range concentrations were reported. No means or standard errors were provided in the study.

From each study, concentrations were retrieved from predrilling, during operations and postdrilling sampling events. PAH- polyaromatic hydrocarbons; Ba- Barium; Pb- Lead; Ni- Nickel; Zn- Zinc. DGV- Default Guideline Value for sediment. NA- Quality guidelines are unavailable. The sediment DGVs are intended to indicate the concentrations below which there is a low risk of adverse effects occurring to benthic organisms.

Ba in drilling mud have been found to exceed 1000 mg/g near offshore drilling discharges (Altin et al., 2008; Steinhauer et al., 1994).

Steinhauer et al. (1994) sampled discharged sediment from a platform and found elevated Ba between predrilling (1989; treated as background levels) and postdrilling (1990) operations. When compared to current environmental quality guidelines, only the postdrilling concentrations of PAHs (48 mg/kg dw; n = 31) were above the sediment quality value (SQV) of 10 mg/kg dw. The drilling mud and drill cuttings contained elevated levels of Ni (41 mg/g dw; 67 mg/g dw) and Zn (290 mg/g dw; 1346 mg/g dw) above the SQV. Okogbue et al. (2016) and Yeung et al. (2011) quantified contaminant concentrations from produced water and sediment, and all were below environmentally relevant guidelines (additional Supplementary Data available from: https://doi.org/10.6084/m9.figshare.13174808.v1). Other metals quantified from all eight studies did not exceed the Australian and New Zealand sediment or marine water quality guidelines (Supplementary Data: https://doi.org/10.6084/m9.figshare.13174808.v1).

Dowdall and Lepland (2012) and Jerez Vegueria et al. (2002) investigated the presence of radionuclides in archived sediments and produced water, respectively. Dowdall and Lepland (2012) found high levels of ^{226}Ra (19.9 ± 0.7 – 730 ± 56.7 Bq kg/dw) and ^{40}K (641 ± 116.9 – 730.7 ± 56.7 Bq kg/dw) from sediment cores surrounding eight offshore platforms. Jerez Vegueria et al. (2002) analyzed produced water from two platforms across two years of offshore operation and found concentrations of ^{226}Ra and ^{228}Ra ranging from <0.01 to 6 Bq/L with a mean of 1.9 ± 0.17 Bq/L and <0.05 to 12 Bq/L with a mean of 2.9 ± 0.39 Bq/L, respectively. These studies illustrate the possibility that sediments and waters surrounding offshore infrastructure may contain petroleum-associated NORMs.

NORMs and Ba do not have associated environmental quality guidelines; therefore, no comparisons could be made to the studies reviewed here to deem if the operational and postdrilling concentrations were environmentally safe and posed low risks to biological organisms. Often offshore oil and gas companies and operators are unaware of the presence of radioactive material in environmental media such as sediment and water (Carvalho, 2017). As Ba and Ra have similar geochemical behaviors and mobility in the marine environment, the fate of Ba in drill cuttings or mud during operational activities could provide key information of the expected long-term fate and behavior of Ra and the daughter radioisotopes during decommissioning (Carroll et al., 1993; Legeleux & Reyss, 1996).

The main sources of contaminants identified from offshore petroleum activities were produced water (by-product during the extraction process of oil and gas), accidental discharges from vessels, drilling mud and surface sediment/drill cuttings (cuttings discharged at seabed and drilling piles;

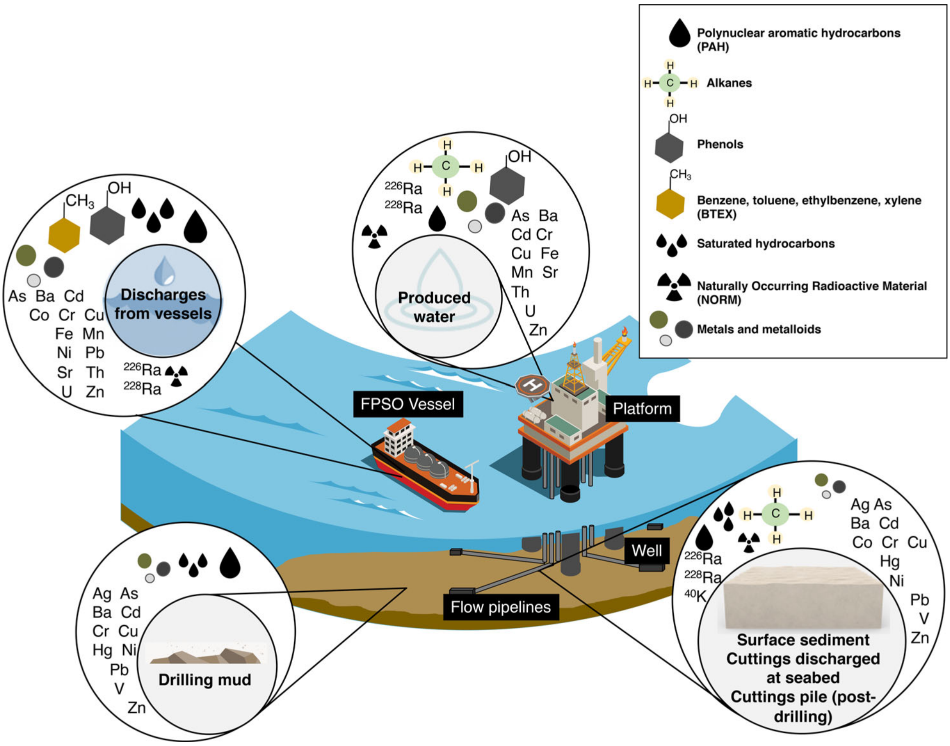


Figure 1. Key sources and activities related to the release and/or accumulation of offshore petroleum infrastructure-associated contaminants as reported from the literature (n = 8). Original illustration was created by the primary author MacIntosh.

Figure 1). Seven studies were associated with offshore platforms, whilst one focused on discharges from a FPSO (floating production storage and offloading) vessel (Okogbue et al., 2016). No studies assessed the presence of contaminants associated with other major structures, for example subsea pipelines, wells, jackets or rigs.

3.2.1. Data limitations from available literature

Contaminant concentrations varied between studies due to differing sample collection and analytical methods and therefore direct data comparisons could not be performed. The variability of natural background concentrations and methodologies from industry-impacted studies (closed access to datasets) limited the ability of this review to assess if non-hydrocarbon associated contaminants were elevated due to offshore petroleum infrastructure. The scope of this review may have also been limited by the lack of open access data on the topic. Given our knowledge of the extensive environmental monitoring in the oil and gas industry during operations, the small number of papers retrieved from the systematic search was likely influenced by the search terms, which limited results to studies specifically about decommissioning, rather than operations. This would have restricted the search outputs along with the inclusion and exclusion criteria of the systematic process. There are few long-term studies that investigate the potential long-term effects of offshore contaminants (Henry et al., 2017). As only peer-reviewed literature was systematically reviewed, the gray literature may have contained data appropriate for this review that was inaccessible. Commercial-in-confidence industry reports, consultancy reports and environmental plans tend not be released to the public, therefore limiting the extent of accessible data from gray literature. This creates challenges for industry, external research institutions and academic stakeholders. Here we have incorporated all available literature to assess the likely presence of contaminants during decommissioning and highlight that data transparency and consistent methodologies would further improve this assessment.

3.3. Ecotoxicological effects of petroleum associated NORM on marine biota

Numerous studies have been published on the accumulation of radionuclides by a range of marine organisms ($n = 36$; Supplementary Figure 6). The studies comprised a total of 154 marine species that were mostly ray-finned fish (31%), mollusks (28%) and crustaceans (24%) (Supplementary Figure 6). Very few publications addressed the bioavailability of radionuclides associated with petroleum processes to marine biota. Most of the literature only measured direct exposure and concentrations of NORM from natural sources to marine biota (78%; Figure 2). However, studies assessing direct biological effects of NORM in marine organisms are limited. From the 36 studies examined, only three measured NORM effects on marine biota (Figure 2). All three studies measured variable effects (genetic, mortality, reproduction and biochemical functions) from experimental exposure to ^{226}Ra in solid and solution. No studies measuring the effects of ^{226}Ra at the individual level were able to infer community or population effects with validated statistical evidence.

Two of the effect studies were dietary exposure experiments designed to assess the influence of scale inhibitor, ^{226}Ra with/without barite on marine organisms (Grung et al., 2009; Olsvik et al., 2010). Olsvik et al. (2010) studied the genetic effect of adding a scale inhibitor (compound not mentioned) to dietary exposures of ^{226}Ra, barite or radium sulfate on the resulting doses for developing Atlantic cod blastula cells (*Gadus morhua*). The experimental concentration of 2 Bq/L of ^{226}Ra had limited effects on the transcription of marker genes for embryonic development suggesting that effects on fish eggs would only occur if exposed to higher doses of radiation

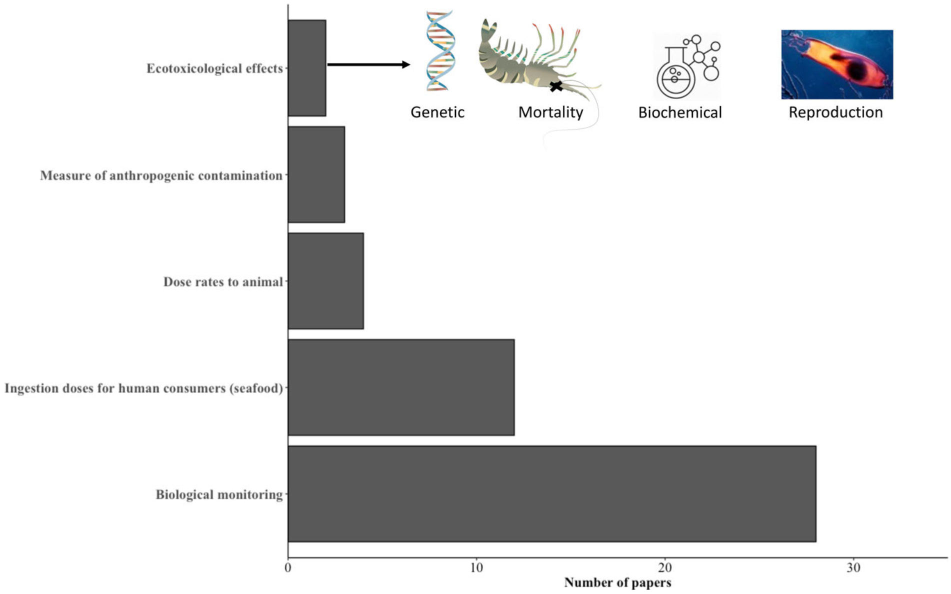


Figure 2. Main aim of the studies measuring either exposure, uptake, human consumption or effects of NORM contaminants on marine biota (n = 36). Biological monitoring includes (a) natural activity concentrations in marine biota for environmental surveys and (b) monitoring radionuclide concentrations in seafood for risk assessment to human consumers. Measure of anthropogenic contamination are studies assessing biota in contaminated areas from NORM related events (e.g. power plant discharge).

(above 117 Bq/L) (Supplementary Table 6). However, the researchers also found that organic compounds scale inhibitor may increase the bioavailability of ^{226}Ra. Similarly, Grung et al. (2009) spiked sediment with Ra and a scale inhibitor (SI 4470; MI Production Chemicals, Norway) to measure oxidative stress in sediment-dwelling ragworms (*Herdise diversicolor*). Exposure significantly increased concentrations in pore water and uptake within the ragworms (Control = 11.1 Bq/kg; Treatment= 145 Bq/kg). Research has used simulations to model the adsorption of ^{226}Ra to organic particles in seawater and the interactions with Ba(Ra)SO_4 following sediment deposition (Rye et al., 2009). As ^{226}Ra is known to co-precipitate with barite (highly insoluble), barite has the potential to impact the mobility of ^{226}Ra in the marine environment. Unlike some essential metals (calcium, magnesium, iron), radionuclides provide no biological function, hence organisms do not actively incorporate them (Simkiss, 1984; Williams et al., 1981). Grung et al. (2009) illustrated that endocytosis in sediment dwelling organisms contributes to NORM exposure and acts as an active pathway for NORM uptake and potential bioaccumulation. Yet neither paper illustrated any statistically significant effects on the measured endpoints for the animals exposed to ^{226}Ra or considered the co-contaminants and the solid-phase speciation of the scale (i.e. ^{210}Po, ^{210}Pb, Hg; Supplementary Table 6).

Jensen et al. (2016) assessed the influence of produced water components on the mortality and reproductivity of copepod eggs, with molecular and individual-level endpoints. Water exposure to soluble ^{226}Ra did not produce any detectable effects on individual level performance, however exposure to artificial produced water reduced egg production in the female copepods. Studies suggest exposure and the effects from produced water on marine organisms are localized and the impact from operational discharges are fairly low (Grung et al., 2009). However, a stress response at the molecular level was evidenced by transcriptional changes to genes associated with the reactive oxygen species (ROS). In marine organisms, the primary mode of action of radiation is the ionization of water into reactive oxygen species (ROS). However, if the presence of ROS exceeds the scavenging capacity of cellular antioxidants then the cells undergo oxidative stress and can further exert damage to cellular structures and biomolecules (i.e. DNA), inducing toxic effects (Blaylock & Trabalka, 1978). Even if organisms have the innate ability to repair induced damage from naturally occurring radiation, enhanced doses from industrial activities such as the petroleum decommissioning process could interfere with the sensitivity levels of marine fauna.

^{210}Pb and ^{210}Po are present as cations in seawater and bind to surfaces, including barite and exterior skeletons of biological organisms (Cook et al., 2018). Therefore, the isotopes are likely to be bound to sediment particles on the benthos and in particulate forms on organic matter floating in the water column (Fisher et al., 1989; Stewart & Fisher, 2003). The bioavailability of radionuclides in seawater is determined by their physico-chemical forms. Once released into the marine environment, radionuclides present as particles and colloids could be more biologically available. Though this illustrates the potential for ^{226}Ra and other radionuclides associated with $BaSO_4$ to suspend in the water column and become bioavailable for pelagic and benthic organisms (plankton, fish, crustaceans), the processes that lead to these pathways and level of measurable effects are still unknown. There has been a strong link identified across studies between the distributions of ^{210}Pb and ^{210}Po and that of parent ^{226}Ra, so the occurrence of ^{226}Ra may predict the behavior of the daughters (Cook et al., 2018). As ^{210}Pb and ^{210}Po are daughter products of ^{226}Ra, it is likely the daughters are strongly integrated within the scale $BaSO_4$ matrix and therefore also exhibit low solubility potential and minimal bioavailability.

Despite the three studies on the likely effects of petroleum associated radionuclides in the marine environment, the biological and geochemical mechanisms underlying the potential bioavailability of these radionuclides to organisms remains unclear (Alam & Mohamed, 2011; Stewart et al., 2005). There are too few data to draw conclusions on ecotoxicological effects of acute and chronic irradiation on marine organisms exposed to NORM associated with the offshore petroleum industry. As there is no published accessible data on the effects of drilling waste on sediment fauna populations or communities, we need to rely on risk modeling to assess contaminant effects on these functional groups (Bakke et al., 2013). A limitation is restricted access to data on the potential effects that exposure to alpha and gamma emitters via respiration or ingestion can have on organism mortality or physiology.

The bioavailability of radionuclides from scale-based contaminants in a marine environment is largely dependent on the partitioning behavior (i.e. between the solid and liquid phases) and the binding strength of the contaminant to sediments (Vives i Batlle, 2012). This is impacted by hydrological processes and physico-chemical conditions, which affect the solubility and sedimentation of these elements. Therefore, information on radionuclide speciation specific to NORM scales and the mobility of different radionuclides species is important to estimate the bioavailability to marine organisms. Furthermore, there have been no studies that have investigated the combined effects relationship between NORM and other metals (e.g. multiple stressors) (Hingston et al., 2005; Wood et al., 2005).

3.4. Global and regional jurisdictions for offshore decommissioning

3.4.1. Regulation of subsea pipeline decommissioning

The closure of pipelines is a process regulated on an international, regional or national level. Evidence shows most offshore petroleum participating countries do not have documented guidelines and conventions for decommissioning requirements of subsea pipelines (Supplementary Table 7). Progress in developing decommissioning regulations for subsea pipelines has been hindered by the absence of international protocols or foundations. In particular, the International Maritime Organization (IMO) provided no guidance in relation to pipelines when developing the decommissioning legislation (Robert, 2013).

Current regulations at the national level support complete pipeline removal at the end of life (Supplementary Table 7), yet *in-situ* decommissioning is not prohibited. Countries have their own decision-making approach to form national or regional protocols for pipeline regulations (Robert, 2013). At the national level, the common decisions regarding decommissioning pipelines are on a case-by-case basis, usually through a cost-benefit analysis or a comparative approach (additional Supplementary Data available in: https://doi.org/10.6084/m9.figshare.13174808.v1). For example, Norway, the United Kingdom and the Netherlands have well defined conditions and protocols applicable to pipelines (Supplementary

Table 7). These countries are mature regarding decommissioning activities and are experienced in effective collaboration and exchange of knowledge and expertise in this field (Bull & Love, 2019; Coste, 1989; Fowler et al., 2014). Additionally, the OSPAR (Convention for the Protection of the Marine Environment of the North-East Atlantic; 1992) Decision 98/3 seems to uphold an ecosystem approach with consideration of ideal environmental practices for pipelines (OSPAR, 2018).

While the IMO Guidelines provide strict measures to reduce risks to local fisheries and maritime navigation during decommissioning, international law is ambiguous, outdated and centered around human-focused objectives and reasoning (Ounanian et al., 2020). This places pressure on national governments to formulate policies and frameworks for pipelines. To include more eco-centric motives into global regulations on offshore decommissioning, marine ecosystem restoration practices need to be incorporated (Ounanian et al., 2020).

Research demonstrates there are several key conditions with the current decommissioning policies from countries who are bound by the IMO Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in the Exclusive Economic Zone (Birchenough & Degraer, 2020; Boza & Gutierrez Rico, 2019; Bull & Love, 2019; Chandler et al., 2017; Fam et al., 2018; Fowler et al., 2014). The IMO guidelines were written with a direct focus on anthropocentric risks (e.g. economy, human health) from absolute abandonment of offshore structures. It was not until 1996 when the London Dumping Convention (LDC) became the first global convention to regulate the protection of the marine environment regarding the disposal of waste at sea (IMO, 2006). However, the LDC does not prohibit decommissioning human-made structures *in situ* (Techera & Chandler, 2015) the definition of '*dumping*' is vague as it does not include pipelines as a category of abandoned structures. The LDC does not specify oil rigs and other determinable abandoned structures can be dumped, yet the definition of an '*abandoned or disused installation or structure*' is unclear. The lack of clarification in the LDC results in ambiguity around the definition of pipelines as human-made structures or waste and therefore waste governance processes are unclear.

The uncertainty of dealing with pipelines amongst all participating countries is complicated by the absence of standardized regulations in international governance and decision-making. The United Nations Convention on the Law of the Sea (1989) has no clarity regarding the fate of subsea pipelines (ASCOPE, 2012; Fam et al., 2018; OSPAR, 2007). This raises concerns on what might constitute an environmentally responsible approach to decommissioning pipelines within international law. A lack of international clarity on decommissioning frameworks and pipelines combined with the variable environments between countries will not create a one-size-fits-all approach. The marine environment differs widely between countries and is influenced by local and regional factors (e.g. oceanography, native biota), with the decommissioning frameworks founded from the local ecosystem (e.g. tropical coral reef, cold-water deep-sea) (Fowler et al., 2014). Given that geographical discrepancies and ecological factors play a key role in defining local decommissioning regulations, standardizing an overarching global framework that can be applied to different marine environments would allow for a global perspective for directing pipeline decommissioning plans.

3.4.2. Environmental plans and management of NORM

Most countries require environmental impact assessments (EIA) or reviews to support their decommissioning plans (Supplementary Table 8). These are used to predict likely effects on the environment, ensure the practices are safe and pose low risks and are required by operators to outline the extent of decommissioning e.g. structures to be decommissioned, characteristics of the substances and an inventory of contaminants, chosen method of disposal based on a risk assessment. Whilst it is a standard international requirement, our review shows metals and NORM contaminants are often not considered in environmental impact assessments (Supplementary Table 8).There is no comprehensive international treaty dealing with the management of NORM from decommissioned structures, seemingly only the Russian Federation includes NORM in the decommissioning EIA requirements (Supplementary Table 8). In all examined countries, even though operators are required to identify contaminants likely to be dispersed and cause potential exposure of biota, only hydrocarbons and petroleum components are assessed.

The environmental risks are considered to be the spillage of oil and petroleum components, due to the large volumes contained within structures and the hazards they pose to the marine environment and human health (Alexander et al., 2017; Bender et al., 2018). Additionally, the technology for removal and effective cleaning of hydrocarbons has been extensively researched and has well defined waste disposal management protocols (Akinpelu et al., 2019; Naeem & Qazi, 2020). As a result, there appears to be little understanding of the amount of NORM expected during decommissioning, especially within subsea infrastructure (pipelines, flow lines and well equipment) (McKay et al., 2020). Environmental plans rarely mention the presence of NORM and potential non-hydrocarbon contaminants and their likely biological effects are rarely investigated (Supplementary Table 8).

A major issue is operators across the globe have insufficient data in advance of decommissioning and cleaning procedures to accurately quantify and predict the extent and/or effects of NORM and metal contaminants. Furthermore, few countries acknowledge the presence of IR or radioactive waste as a by-product of decommissioning processes. There are limited waste or depository facilities for NORM and hazardous metals, with many non-existent in developing countries (Ferronato & Torretta, 2019). It is likely the sources and types of contaminants released into the marine environment will increase, given the current and projected scope of decommissioning (Fowler et al., 2018, 2019). Hence, an assessment of the ecological and toxicological risks of these contaminants of concern is urgently required and should be considered in future EIA to ensure mitigation efforts include those contaminants.

Leaving oil and gas structures *in situ* can support establishment of an ecosystem and provide potential benefits to the local faunal community, albeit one that does not reflect the original sedimentary habitat (Claisse et al., 2019; Fowler et al., 2019; Love & York, 2006; McLean, Vaughan et al., 2020; Ounanian et al., 2020). Despite this, recognizing the ecological value of decommissioned infrastructure often excludes the consideration of associated contaminants. This is highlighted in an expert opinion article, where more than 60% of representatives from the benthic ecology field did not consider contaminants as a major negative impact from decommissioning (Fowler et al., 2018). This emphasizes that effective global decommissioning practices for offshore structures are often hindered by a lack of information on relevant contaminant stressors. Due to the paucity of data, ecologists and policy makers cannot make informed decisions because the extent of contaminants after leaving a structure *in situ* or partial disposal in the deep-sea and the ecotoxicological effects on biological organisms, are still largely unknown. As to whether *in situ* decommissioning will benefit or harm the marine environment, research and worldwide policies need to incorporate comprehensive environmental assessments of decommissioning options for structures (Techera & Chandler, 2015). Acknowledgement of contaminants as a key consideration within global decommissioning frameworks is vitally important in the governance process of national decision-making in the oil and gas sector.

3.4.3. Decommissioned infrastructure as artificial reefs

A large proportion of artificial reefs from offshore petroleum structures are created for increasing potential habitat for marine fauna, fisheries, prevention of trawling and ecological restoration devices. In current offshore decommissioning regulations, the permission for artificial reef creation from offshore installations and structures left in marine environments is only permitted in the United States. Half of the US coastal states' guidelines and criteria are based on guidance from the National Artificial Reef Plan (amended in 2007), yet there is no federal coordination or oversight regulating the Rigs-to-Reef (RtR) program in US waters (Paxton et al., 2020). However, in 2010 California passed a bill to mandate the conditional partial removal of offshore platforms; California Marine Resources Legacy Act, with the inactivation of the RtR legalization (Meyer-Gutbrod et al., 2020). The application of the RtR program in Australia is mentioned, yet it is still not an option due to the absence of reliable research and evaluation. Under the OSPAR convention, all North Sea participating countries are not permitted to abandon structures to be converted to artificial reefs. As there is no clear constitution on what classifies as a net benefit to the ecological community from the RtR program (further to excluding joint pipelines), it is difficult to come to a consensus.

Decision analyses should apply the novel ecosystems concept, predominantly based on the ecology identified from *in situ* offshore platforms (Bond et al., 2018; Gates et al., 2019; Macreadie et al., 2018; McLean, Parsons et al., 2020; van Elden et al., 2019). Current literature on global decommissioning processes and regulations called for incorporating an ecosystems-based approach (Sommer et al., 2019; van Elden et al., 2019). Bull and Love (2019) also briefly mentions this, however the review is focused on the United States and the RtR program. The creation of artificial ecosystems from converted oil platforms have been shown to support reef habitat for diverse marine biota with examples of increased fish production in California and increased biodiversity of reef communities in West Africa (Claisse et al., 2015; Friedlander et al., 2014). There is substantial unpredictability and uncertainty regarding the effectiveness of artificial reefs, considering the variability and complexity of global marine ecosystems (Ounanian et al., 2020). Furthermore, the effective use of decommissioned platforms and rigs as artificial reefs requires a multidisciplinary approach to monitor and confirm that the health of the local marine ecosystem has been improved following abandonment of the infrastructure.

The long-term marine ecological implications from leaving a pipeline *in situ* or via partial disposal on the seabed are unknown. Available information on the extent to which decommissioned pipelines support marine fauna communities or a new ecosystem has only emerged in the last five years (Macreadie et al., 2018; McLean, Parsons et al., 2020). These rely on current and historical remote-operated vehicle (ROV) data to understand the impacts of *in situ* structures (including jackets, pipelines, wells) on the local marine ecology (Bond et al., 2018; Gates et al., 2017; Macreadie et al., 2018; McLean et al., 2018). As to whether *in situ* decommissioning will benefit or harm the marine environment long-term, multiple experts including marine biologists engineers, lawyers, social scientists and health professionals, are needed to communicate the likely risks (Techera &

Chandler, 2015). This brings into focus the need for research and worldwide policies to incorporate a combined environmental and ecological-based approach for decommissioning options for pipelines.

4. Research gaps

4.1. Environmental monitoring pre- and post- decommissioning

Quantifying environmental concentrations of petroleum-associated contaminants during operation is difficult as produced water and cutting piles can dilute in seawater. None of the eight studies in this review analyzed the environmental media (water, sediment) at the decommissioning stage, most likely due to a lack of adequate chemical analysis of environmental media at postoperations and the decommissioning stage. Additionally, the ability to detect radionuclides in offshore structures with appropriate tools is limited, and therefore radioactive contamination may go unnoticed during the planning and execution of decommissioning. Using estimates of organism effects and contaminant concentrations based on risk modeling and outdated data is unlikely to be accurate and reliable. Baseline or background level data are still lacking in the public domain for the vicinity of offshore installations that can not be easily monitored for decommissioning conditions (Joye et al., 2011, 2016).

Long-term monitoring of contaminants in the deep sea (e.g. >2000 m) associated with oil and gas developments is extremely limited (Cordes et al., 2016; Harman et al., 2011). Temporal monitoring and surveying of contaminants is important because metals and NORM have the potential to accumulate beyond the postdrilling stage, as illustrated by the studies in this review. This has implications for the decommissioning process and structures to have residual contaminants (Kennicutt et al., 1996). The changing environmental conditions and the slow recovery of ecosystems over time is important to consider, during the continual monitoring of contaminants at decommissioned structures (Barreyre et al., 2012). Environmental monitoring may be required for years in the absence of guidelines that described acceptable levels of risk in the environment.

Olsgard and Gray (1995) suggested trace metals in old cutting piles will become the main source of environmental impacts, thus following decommissioning, cuttings piles are likely to become a future source of episodic contamination. Even though toxicity is still assessed from a determination of hydrocarbon concentrations under many regulatory guidelines, biodegradation of drilling mud and the presence of barite scale with metals and NORM constituents is likely to occur years beyond cessation of operations. Cuttings piles are vulnerable to physical disturbances that cause dispersion of contaminated material; thus, erosion and uncovered pipelines may uncover layers and enhance leakage and dispersion of contaminants into the benthic environment and water column. For example, the determination of Ba is important considering its low solubility and precipitation in the presence of sulfates and carbonates (Church & Wolgemuth, 1972; Crecelius et al., 2007). Therefore, for metals and NORM, the dissolved fractions (i.e. soluble products upon contact of the scale with surrounding seawater) should be considered as highly relevant for ecotoxicological assessments in decommissioning.

4.2. Characterization of petroleum scale and NORM components

Successful decommissioning of subsea oil and gas infrastructure requires an effective and safe approach to assessing and managing chemical and radiological residues. Little work has been done to define the characteristics and properties of scale, considering the variability of matrixes, environmental features such as the local geology and operational methods employed (i.e. cleaning, formally termed 'pigging', of the pipelines, residuals left in pipelines and wells after pigging, injection of produced water).

4.3. ERICA radiological dose assessments

Research investigating radiological impacts to marine biota often employ the ERICA screening tool and minimal laboratory experiments (Figure 2). The applicability of the ERICA tool and other radiological dose models to subsea infrastructure is limited, due to the lack of suitable homolog organisms in the ERICA database that are likely to inhabit or grow on the infrastructure. This creates uncertainties in assessing realistic estimations of exposure to marine biota. Limited data available on acute and chronic irradiation from NORM indicates there is inconsistent evidence and a lack of for any effects at dose rates below the 4 μGyh^{-1} benchmarks (Fuller et al., 2015). The heterogeneity in the endpoints assayed, together with different types of radiation emitted from the radionuclides and the variety of species exposed, makes it difficult to compare the results obtained in these studies to reference organisms. In this review, the studies measuring dose rates in exposed organisms to radiation lower than the benchmark value of 10 μGyh^{-1} did not examine or indicate detrimental effects including mortality, reproductive capacity or morbidity (Andersson et al., 2008).

Furthermore, extrapolation to populations is difficult due to the multitude of physicochemical interactions. The availability of only two International Commission on Radiological Protection (ICRP) Reference Animals; crab and flatfish, to radiological dose assessments presents challenges to a more general understanding of how NORM impacts all marine phyla. For decommissioned subsea structures, the benthic and pelagic communities comprising of species from mollusks to marine mammals do not have an appropriate reference organism for radiological dose assessments. For example, little is known about what constitutes a lethal acute or chronic radiological dose to cartilaginous fish, marine mammals or migrating marine reptiles (e.g. turtles). This implies there is uncertainty in applying the ERICA screening tool or similar dose assessment tools toward species of animals often not considered when it comes to research on the effects of IR. From the few studies on acute exposure of ^{210}Po in tissues of marine organisms from diverse taxa confirms the large variability in concentrations of the dose received between tissues and as a whole-body. For example, effective dose-equivalent rates for benthic crustaceans were calculated to range from 0.3 to 3.0 mSv y^{-1} in muscle and 130–750 mSv y^{-1} in hepatopancreas (Cherry & Heyraud, 1982; Fowler, 2011; Fowler & Fisher, 2005; Heyraud et al., 1987; 1994). Thus, determining radiation doses received by exposed individuals in the population of a species and then relating absorbed dose to biological effects needs to be carefully interpreted because of the high interspecies and tissue variability. A meta-analysis of research measuring the effect of chronic low dose radiation on indicators of oxidative stress (markers of oxidative damage, enzymatic and non-enzymatic antioxidants) found significant heterogeneity in effect size across species and tissues (Costantini & Borremans, 2019). This suggests selection for organisms able to cope with IR (e.g. upregulation of DNA repair mechanisms, antioxidants). This knowledge gap needs to be filled through more comprehensive research or inclusion of a diverse range of marine organisms to accurately predict organism responses and low-dose stressor exposure.

Despite the environmental significance of marine fauna and their ongoing exposure to radionuclides through contaminants, fewer than 100 publications exist on the effects of IR on marine invertebrates and none measure effects from petroleum-associated scale. Internal and external doses arise from the relatively low activity concentrations of the NORM in scale, but also from natural environmental background levels of the radionuclides (Hosseini et al., 2012). Carvalho et al. (2011) described an assessment of absorbed radiation doses from low-level radioactive waste dumpsites in pelagic planktivorous sardine and the blue marlin in the Northeast Atlantic Ocean, which indicated most of the radiation dose was from NORM. However, there is minimal information available about radioactivity in the continental shelf surrounding petroleum reservoirs and the resulting radiation exposure of inhabiting biota to the naturally occurring radionuclides (Carvalho et al., 2011). The relative contribution of IR dose rates from exposure to scale-based NORM from petroleum is difficult to monitor and discern from the variability observed in natural marine systems, as the total acquired by marine fauna are from natural background sources (Fowler, 2011; Hosseini et al., 2012). Therefore, it is crucial to have a thorough understanding of separating exposure from environmental background levels to scale-based NORM in pipelines and other decommissioned infrastructure. In terms of petroleum scale contaminants and exposure of marine biota to IR, dose rates emitted from scale, the form of radiation (α, β, γ) and the effect thresholds that signal potential benchmark toxicity are currently unknown.

5. Future directions

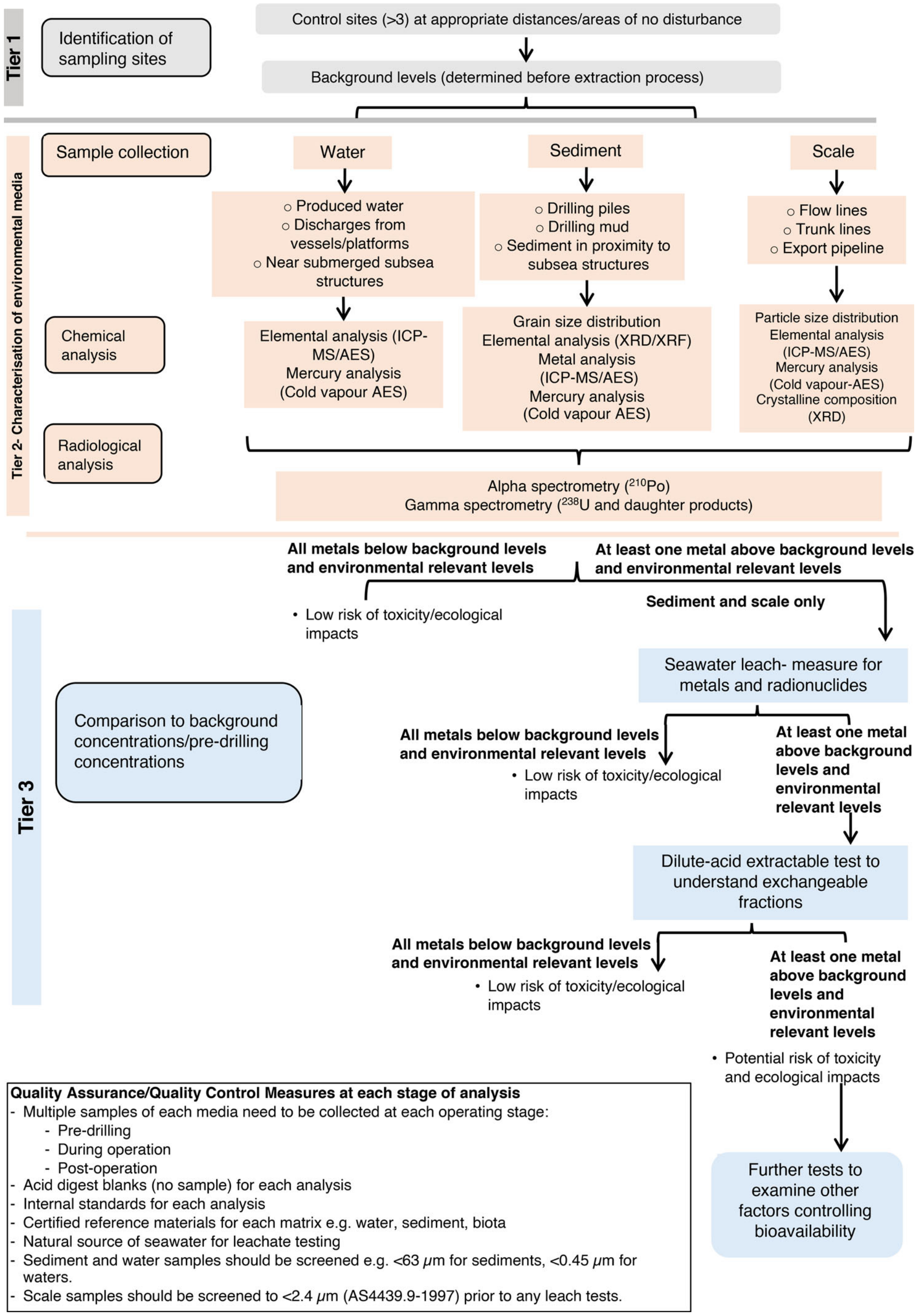
5.1. Framework for standardized environmental monitoring pre- and post-decommissioning

The lack of standardized methods and toxicity tests designed for NORM from offshore oil and gas operations makes assessing the effects of decommissioning methods difficult. Thus, the BACI approach can be integrated into environmental assessments as a technique to indicate if contaminants are elevated postoperations, to see if ecotoxicological effects are likely to occur in marine organisms. Environmental quality guidelines specifically for contaminated environmental media (produced water, cutting piles, scale) associated with offshore oil and gas structures and by-products would benefit from the inclusion of contaminants of primary concern in risk assessments. The development of guidelines must consider risks during operations of onshore or offshore human activities and those that might exist during closure. This is a crucial step in terms of whether they are applicable for decommissioned offshore structures.

As there are currently no globally prescribed guidelines or protocols to assess subsea infrastructure associated contaminants or scale, a tiered assessment framework for the assessment of contaminated sediments and water is needed (Figure 3). The ideal framework would be applied to monitor the contaminants entering the marine environment through decommissioning procedures and submerged infrastructure scale. Frameworks need to be generalized, but then applied to site-specific conditions accounting for the type of infrastructure-associated contaminants and concentrations, along with depth, pH, temperature and local ecology (ANZG, 2018; Brack et al., 2017; Simpson et al., 2005).

5.2. Elemental and radiometric analyses of petroleum scale and NORM components

We recommend industry to use available elemental and radiometric techniques to identify and classify the chemical composition and radioactivity levels of scale. This can include, but not be limited to, using inductively coupled mass-spectrometry/optical emission spectrometry and x-ray fluorescence to quantify inorganic elements and major ions in the scale.



Quality Assurance/Quality Control Measures at each stage of analysis

- Multiple samples of each media need to be collected at each operating stage:
  - Pre-drilling
  - During operation
  - Post-operation
- Acid digest blanks (no sample) for each analysis
- Internal standards for each analysis
- Certified reference materials for each matrix e.g. water, sediment, biota
- Natural source of seawater for leachate testing
- Sediment and water samples should be screened e.g. <63 μm for sediments, <0.45 μm for waters.
- Scale samples should be screened to <2.4 μm (AS4439.9-1997) prior to any leach tests.

Figure 3. A generalised three-tiered framework for the continual assessment of contaminated water, sediment and scale from offshore petroleum structures and processes. Framework is recommended for the ongoing monitoring of contaminants entering the marine environment through decommissioning procedures and submerged infrastructure scale. Assessment should be followed before, during and after offshore operations in preparation for the decommissioning process. Quality assurance and control measure for sampling and analyses procedures are provided in the textbox. Adapted from Simpson et al. (2005).

Gamma-ray spectrometry is the ideal technique for quantifying the activity concentration of radionuclides (Cresswell et al., 2017, 2020; Joel et al., 2017). Care must be taken to interpret the reading of radioactivity relative to where the gamma measurement is positioned on the piece of infrastructure e.g. if on the external surfaces of pipes, attenuation of the signal by the steel and how it is placed on the outside of the infrastructure are important to consider. However, gamma spectrometry will not detect alpha-emitting radionuclides such as ^{210}Po. This analytical technique will require samples of the scale to be collected and brought onshore as analysis of alpha-emitting radionuclides cannot be conducted in-situ. High-purity detectors have been developed and are extensively utilized in environmental studies to detect radioisotopes of contaminated waste. Therefore, gamma and alpha spectrometry can be used to measure the uranium and thorium radioisotopes and their decay products. Due to environmental and operational differences between petroleum operators, collection, analyses and characterization need to be conducted on several different sources of pipe scale. It is therefore recommended that scale samples are recovered from subsea infrastructure for analysis, either by cutting and lifting pipelines and then recovery of scale mechanically or by analysis of pigging dust/solids. For the latter, it is important to note that pigging solids represent a homogenous sample of scale from the entirety of the pipeline pigged and will not provide information on potential hotspots of contaminants along the pipe. Early detection will enable petroleum regulators to develop and utilize thresholds at which issues may occur in marine biota (Cordes et al., 2016). This will eventually lead to new opportunities for management and repair of contaminated past or historical decommissioning processes.

5.3. Direct organism exposure assessment scenarios

This review has identified new directions for ecotoxicological research in the offshore decommissioning field to improve understanding about the biological effects of NORM. Performing laboratory studies by exposing a variety of marine species to infrastructure-associated NORM contaminants will create refined estimates of contaminant bioavailability, radiation dose and subsequent assessments of effects from NORM and IR, combined with metals. Radiotracing techniques can provide new perspectives on the pathways and rates of uptake (e.g., bioaccumulation) and biomagnification processes of radioactive and non-radioactive contaminants (Cresswell et al., 2020; Lanctôt et al., 2017). Laboratory studies are needed to investigate the radiation-induced effects from NORM contaminants associated with petroleum scale. Furthermore, quantifying the bioavailability of inorganic contaminants and radionuclides within scale will increase certainty around the potential for biological impacts to occur. Direct dietary and water exposures of scale material and their dissolution products to a series of benthic and pelagic marine organisms under different environmental scenarios would allow for a better understanding of the potential for organism bioaccumulation, potential effects and food chain transfer. Organisms should be selected to represent active sediment feeding behaviors (i.e. worst-case scenario of ingestion of scale mixed with sediment) and ideally should include organisms targeted for fisheries (e.g. prawns and commercial fish) to understand the potential for human consumption and subsequent implications.

5.4. Radiological dose modeling assessments

It is recommended simplified radiological dose modeling using the ERICA assessment tool and seawater leachate tests are conducted to estimate the potential radiological doses and effects to model marine organisms inhabiting subsea tubular infrastructure. This is due to benthic organisms colonizing the exterior of structures being exposed to significant activity concentrations of NORM. As ERICA is limited in its ability to characterize the external dose and interior dimensions of a pipeline, a range of scenarios of pipeline degradation (from non-degraded operational use to fully degraded pipeline mixing with surficial sediments) need to be adapted to account for the circular source and shielding from pipes.

5.5. Collaboration with industry, government and research agencies

From this review, it is clear there is a lack of data transparency relating to the presence and concentration of contaminants associated with decommissioned infrastructure and potential biological interactions with marine biota. To improve data transparency, multistakeholder collaboration can provide the opportunity to create open-source datasets (Murray et al., 2018). Data collection is part of routine operations and provides important information about the ecology of offshore structures, however external parties and scientists still have the challenge of inaccessibility to environmental and contaminant data (Birchenough & Degraer, 2020; Burdon et al., 2018). Acquisition of environmental data is recommended for decommissioning decisions, as access to industry datasets can expand understanding of the legacy impacts of the offshore industry (Levin et al., 2019). Decisions need to incorporate sufficient scientific knowledge to predict environmental as well as socioeconomic impacts, with an acceptable degree of uncertainty. In general, trust between participating stakeholders can be an ongoing barrier to data sharing. Maintaining long-term communication through collaborations can help to build trust and develop working relationships to the development of reliable and invaluable data sharing agreements. Partnerships between the oil and gas industry, government and research agencies are encouraged to improve data transparency, through overcoming barriers limiting data accessibility and effective communication (McLean, Parsons et al., 2020; Todd et al., 2020).

Efforts should be made to increase collaboration with national and international regulators, operators (industry) and academic stakeholders to expand decommissioning policy frameworks (Fowler et al., 2019; Lacey & Hayes, 2020). Such collaborations should seek to perform radiological dose-response experiments to understand thresholds associated with acceptable levels of environmental risk. These can be inputs of biological data to multicriteria decision analyses used by operators to select the preferred closure outcome for their subsea facilities. Providing segments of pipelines or recovered scale for analyses provides the opportunity to do ecotoxicological studies, that enables an understanding of the potential ecological and environmental impacts associated with the planned decommissioning scenarios. This will communicate the presence of NORM and interactions with marine organisms during the decommissioning of offshore seabed infrastructure to stakeholders. Collaboration between science and industry will strengthen the relationship, to demonstrate the importance of environmental protection and the formation of risk assessments. Communicating environmental science and its importance to expand the limited global knowledge on the potential effects of NORM contaminants associated with decommissioning will ensure a more robust and transparent decommissioning process.

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Declaration of interest

All authors have no conflict of interest to declare.

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Data availability

The data that support the findings of this study are openly available in figshare at https://doi.org/10.6084/m9.figshare.13174808.v1.

CRediT author statement

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