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An Assessment of Environmental Impact on Offshore Decommissioning of Oil and Gas Pipelines

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Abstract: There has been a steady growth in the length of pipelines over the past 45 years, with over 6000 operating platforms extracting oil. Several facilities would reach their operational life, which can no longer be economically viable for their production and will eventually undergo the decommissioning procedure. Almost 3000 petroleum industries will likely be decommissioned worldwide in the next 17 years. By 2030, the total cost of decommissioning globally amounted to about USD 104.5 billion. The choice to decommission the offshore oil and gas sector is considered complicated and crucial as it must evaluate numerous variables such as cost, health and safety, and environmental consequences. This review paper aims to assess the decommissioning activity, specifically on pipelines in the oil and gas industry. The purpose of this study is to understand and evaluate significant environmental impacts associated with decommissioning of oil pipelines and to propose mitigation measures to address the challenges of decommissioning. Waste disposal, a threat to biodiversity and air pollution, is a major environmental concern in decommissioning oil and gas pipelines. Among the decommissioning measures, leave in-situ has the lowest environmental impact while repurposing and recycling, with the application of environmental impact qualitatively and quantitatively by integrating 3D information models, mathematical models embedded in hydrodynamic models look promising for decommissioning.

Keywords: biodiversity; decommissioning; environmental impact; gas; noise; offshore; oil; pipeline; sea bed

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1. Introduction

In the oil and gas industry, pipelines are a very crucial infrastructure to transport oil and gas, even from offshore oil and gas platforms. The pipelines are commonly preferred transport for oil and gas compared to other modes of transport such as waterways. Smaller diameter pipelines are used as gathering and feeder pipelines, while larger diameter pipelines are used for transmission and distribution. The sizes of these pipelines vary from 5 mm up to 1420 mm (Small—5 to 102 mm, medium—102 to 426 mm, and large—above 426 mm) and are usually made from steel with concrete or polymer external coatings. Throughput is a crucial criterion by which all pipes are distinguished. The diameter of the pipes, the inner wall properties, the number of bends, and other factors all directly affect throughput. Transporting oil and gas through pipelines has been considered the safest and most convenient approach, despite having millions of kilometers of stretched pipelines crossing regions and countries. Hence, there has been a steady growth in the length of pipelines over the past 45 years [1], with over 6000 operating platforms extracting oil [2].

The geographical and climatic conditions of the operation of pipelines are very diverse. Pipelines are laid through swamps, permafrost soils [3], mountainous areas with large elevation changes [4], places with seismic activity, forest areas, arable land [5], deserts, as well as densely populated and industrialized areas. It requires a variety of technical solutions for the operation and repair of pipelines. OST 153-39.4-027-2002 technology is recommended as a standard procedure for dismantling the linear part of the main oil pipelines [6].

The decommissioning process of structures is inevitable when the life cycle of a structure ends as the life extension and replacement techniques are no longer technically or economically viable. It is not economically justified due to very low oil production capacity and when operating costs are no longer profitable. Offshore oil and gas facilities and their supporting infrastructure typically have a service life of between 15 and 50 years [7]. Several facilities would reach their operational life where they can no longer be economically viable for production and will eventually undergo the decommissioning procedure [8–11]. Almost 3000 petroleum industries are likely to be decommissioned worldwide in the next 17 years [12]. Just in the US Gulf of Mexico, about 100 platforms annually have been taken out of operation since 1985 [11]. Other than wells, there is also a high abandonment of unused equipment for which companies will spend higher costs in getting rid of the equipment than constructing and developing new wells by 2025. The high cost of decommissioning includes high technology, machinery, and experts in the field, such as divers and robotic submarines to remove steel and other metal components, pipeline cleaning, and seabed surveys. Globally, by 2030, the total cost of decommissioning cost will be about USD 104.5 billion [11].

The choice to decommission the offshore oil and gas sector is considered complicated and crucial as it must evaluate numerous variables such as cost, health and safety, and environmental consequences. Additional difficulties are brought on by the compatibility of decommissioning activities with maritime protected zones. Offshore pipelines used in the oil and gas industry are usually either laid on the surface of the seabed or placed in a trench where it will either be backfilled or left open [13].

The process of decommissioning varies from site to site and from facility to facility. All decommissioning approaches involve a certain degree of dismantling and the generation of waste that will require proper management. The structures linked to the production of offshore or onshore petroleum includes platforms rigs, steel frame, wells, and oil pipelines that require high consideration of environmental, economic, human safety, and engineering factors to be considered during decommissioning [14,15]. It is recommended that decommissioning activities should have minimal impact on the surrounding marine organisms, with no contaminants released into the environment [16]. As the pipelines are laid over a long distance, covering both populated and industrialized areas, the process of decommissioning the pipelines is critical and has to be evaluated carefully [1,17]. A failure in the process will inevitably pose major risks to the community nearby and the surrounding environment [17].

Therefore, consideration of the Environmental Impact Assessment (EIA) to mitigate the severe impact on the environment and ecosystems is essential for decommissioning activities. Thus, this review paper aims to assess the decommissioning activity, specifically on pipelines of the oil and gas industry. This EIA aims to understand and assess significant environmental impacts associated with the decommissioning of oil pipelines and propose mitigation measures to address the challenges of decommissioning pipelines. The study finds that leaving the pipelines in situ is the most suitable and cost-effective approach compared to fully or partially removing the pipelines.

2. Framework and Regulations

Most countries embrace EIA as a part of their legislation and regulations or requirements from funding agencies for investment. Decommissioning projects are regulated by either national or international law, in which the latter part has an important role in providing standards and a framework for the decommissioning process [18–20]. The regulatory requirement for each country may vary for decommissioning and may be more stringent than others. At the international level, several regulatory frameworks were introduced in the decommissioning of oil and gas structures which includes the United Nations Convention on the Law of the Sea (UNCLOS), the Petroleum Act 1998, the NE Atlantic Protocol from OSPAR (Oslo and Paris Commission) 98/3 and OSPAR convention 2007 [16,19–21]. The comparisons between oil and gas decommissioning regulations in the USA and UK, along with its main regulator and authorization in converting structures into artificial reef sites, are shown in Table 1. Although decommissioning of oil and gas structures on the UKCS (United Kingdom Continental Shelf) is executed according to the Petroleum Act (1998), each decommissioning program is required to comply with the Offshore Petroleum Regulator for Environment and Decommissioning (OPRED) before the decommissioning operations can be conducted (Oil and gas: decommissioning of offshore installations and pipelines, 2013). Meanwhile, OSPAR derogation involves a formal international deliberation by the related government [21]. Commercial fishing for leave-in-situ offshore oil and gas rigs in the Gulf of Mexico was made possible due to National Fishing Enhancement Act and the National Artificial Reef Plan [10].

Table 1. Oil and gas decommissioning regulations in the USA and UK (Source: [11]).

	USA	UK
Main regulator	BSEE (Bureau of Safety and Environmental Enforcement)	DECC (Department of Energy and Climate Change)
Key regulation	NTL G05 "Decommissioning Guidance for Wells and Platforms"—October 2010	Regional: OSPAR Decision 98/3 on the Disposal of Disused Offshore Installations; National: The Petroleum Act 1998.
Conversion to artificial reef	Authorized	Prohibited, except for excessively heavy or concrete structures

3. Options for Decommissioning

The maintenance cost of aging oil pipelines and the reduction in oil production is one of the main reasons for decommissioning [19]. Most of the pipelines will undergo cutting activities, such as being cut into smaller sections to ease the process of transporting them to the shore, while the residual pipelines will be flushed and cleaned, and sealed using plugs and buried at the height of one meter below the mud line level [22].

There are three possible options or actions for decommissioning activities, as shown in Figure 1. The decommissioning options are (i) leave in-situ—the structures can only be left in situ after the necessary removal and cleaning of hydrocarbons; (ii) partial removal—the structures are being partially dismantled and buried onto the seabed within the zone of the operational structure and (iii) total removal or recovery—this option includes the removal and transportation of the structures to shore [23,24]. Upon arrival, the structures will be dismantled, re-processed, or sent to the landfill for further processing or burial. Ref. [20] suggested decommissioning options, including full and partial removal, trenching, and burial of the pipelines. The stability of subsea infrastructure is frequently improved over time as a result of changes in the strength and bathymetry of the seabed brought on by consolidation and sediment movement, which is a recurring issue in emergent research. When developed into trustworthy and widely used forecasting models, this discovery supports in situ decommissioning instead of removal.

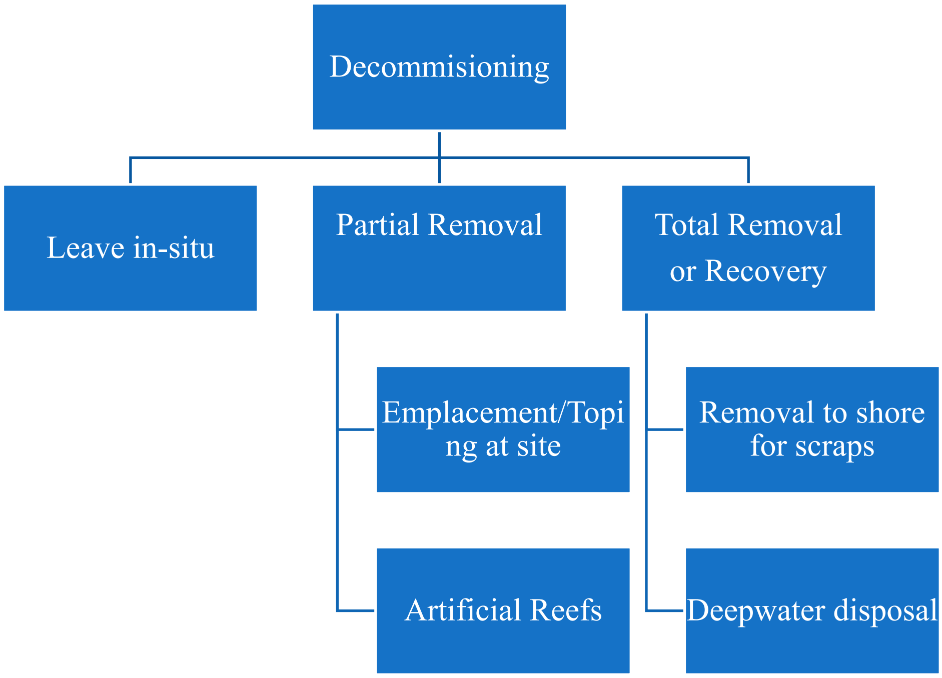

Figure 1. Decommissioning types (Source: Authors).

In some cases, pipelines that are left in situ or cannot be dismantled should be sealed with nitrogen or through filling slurry [25–27], controlled low-strength material (CLSM), as what has been performed in Mainland China [27]. Moreover, [20] stated that facilities with no hazardous effect on the environment could be disposed of in deepwater, and the structures can also be modified into artificial reef habitats. The offshore structure underneath in deep water can be left as it is, and it can become a breeding ground for aquatic habitats. With a leave in-situ rigs-to-reefs management strategy, offshore platforms can support ecological, sustainable, and economic consequences, as well as greatly benefit from lower CO_2 levels [28] and is considered a cost and time-effective decommissioning option [29]. However, in certain situations, some offshore structures may cause a hazard to sea activities such as fishing and navigation; hence, removing the structure and disposing of it onshore is preferable [30]. Gradual decommissioning of main gas pipelines may be accompanied by disturbances in the hydrodynamics of gas pumping [31]. Therefore, decommissioning options for pipelines depend on the state of the pipeline, the impacts it may pose, and stakeholder involvement in the process.

In order to conduct decommissioning programs, there are several procedures to be followed, such as to initiate the decommissioning operation before reaching its service life, which is to be approved by the OPRED (Offshore Petroleum Regulator for Environment and Decommissioning) and the Oil and Gas Authority (OGA) before the operation can be conducted. In the case of assessing HSE, OPRED is the responsible authority, while operators shall come up with several options to conduct decommissioning of the pipelines and to carry out the comparative assessment (CA) to compare which options give better outcomes. Pipelines to be left in situ will be considered with the condition that the pipelines to be buried or to undergo complete removal will eliminate the impacts on the seabed [31] (Offshore Safety Directive Regulator, 2021). As shown in Table 2, the success of decommissioning criteria can ensure the implementation and maintenance of the pipeline integrity management process.

Table 2. Decommissioning success criteria (Source: [32]).

	Success Criteria
Implementation and maintenance of pipeline integrity management process	• Adequate measures are in place to ensure the safe separation from live plants, including valve testing beforehand and continuous monitoring of the functionality of the valve (if appropriate). • Purging/cleaning of oil and gas in order to comply with environmental regulations. • Adjacent active pipelines in bundles/piggybacks and others are taken into account. • Establish an acceptable surveying and maintenance regime for pipelines in the IPR (Interim Pipeline Regime) until the official decommissioning program is approved. • As per the decommissioning program and PSR (Pipeline Safety Regulation, 1996) standards, make sure pipelines are either removed or left in a state where they will not pose a threat to people. • Ensure that the ultimate decommissioning of a pipeline is carried out in a regulated and safe way.

4. Environmental Baseline

If related environmental data is not readily available, an environmental baseline is often conducted before decommissioning begins. Because the baseline work is generally set in consultation with government authorities, requirements will vary from site to site. If seabed contamination is an issue, a complete seabed sampling program will be included in the environmental baseline to confirm the degree of contamination. The most common data collected for decommissioning is shown in Figure 2.

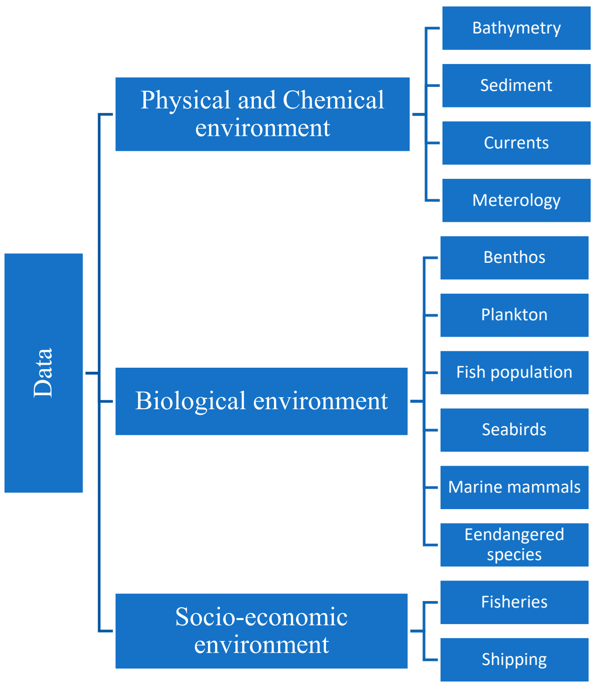

Figure 2. Data required for decommissioning (Source: Authors).

5. Potential Environmental Impacts

The EIA process requires a thorough understanding of the proposed decommissioning activities and the potential impact on the environment. The systematic identification of problems that may have an impact on the environment and also other users of the environment is crucial to the process. Once identified, these issues must be addressed to estimate the magnitude of potential environmental impact so that, if necessary, mitigation measures can be taken to avoid or minimize such effects. There are various potential sources of contaminants from offshore petroleum activities, such as by-products during the withdrawal process of oil and gas, accidental discharge from the vessels, mud drillings, as well as surface sediments or drill cuttings that have an adverse impact, as shown in Figure 3.

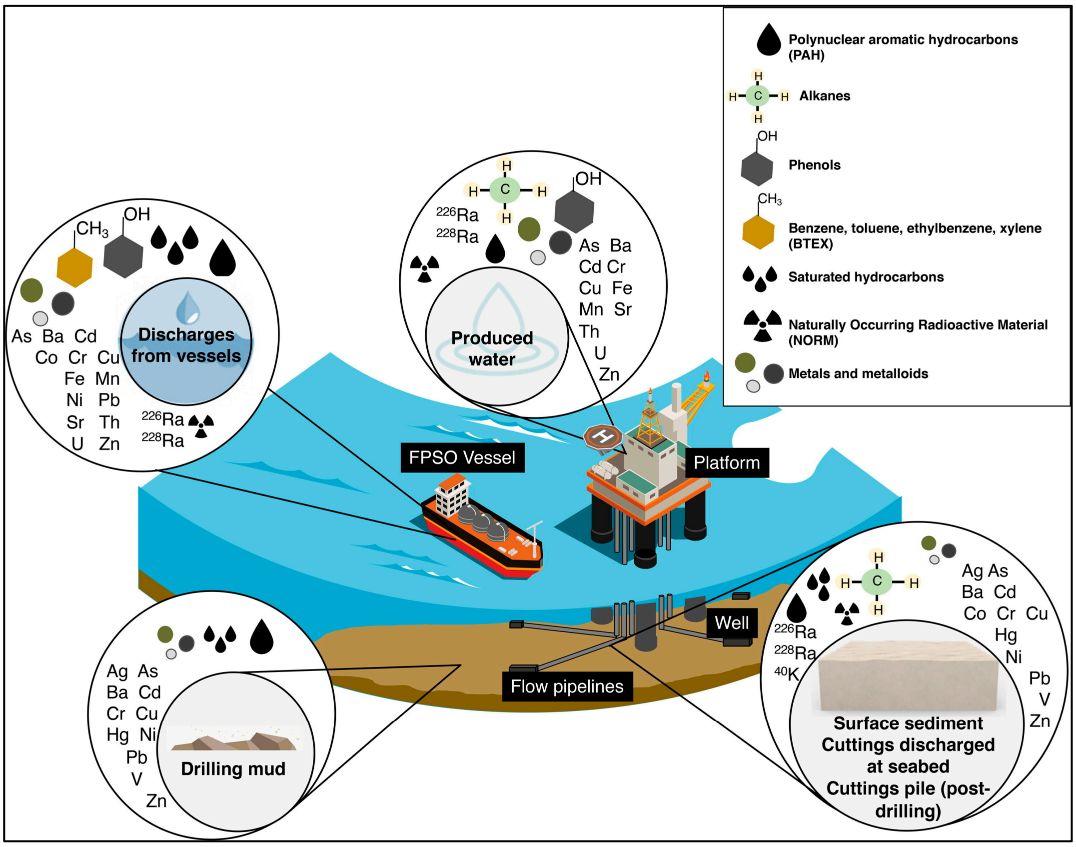

Figure 3. Contaminants accumulated or released due to activities related to offshore infrastructures (Source: [33]).

5.1. Noise Impact

Underwater noise pollution caused by human activities can endanger marine ecosystems. Generation of noise may have a significant impact on the behavior of marine mammals due to the elevated noise levels [33] Thames Area Decommissioning Environmental Impact Assessment, 2014). The possibility of fish being affected by various noise-emitting industries, for example, the oil and gas industry. The operation of vessels, underwater cutting, and other activities such as water-jetting and cutting tools cause noise pollution (148 to 180 dB with a frequency range of 200 to 1000 Hz) in the marine environment during the total decommissioning (above 120 dB), partial decommissioning (around 100 dB) and leave in-situ (less than 50 dB) process [34]. Thus, anthropogenic underwater noise has the potential to impact marine mammals [35–37] particularly for total or partial decommissioning. For example, cetaceans (a subset of marine mammals, including whales, dolphins, and porpoises) use sounds for communication, detection of prey, and navigation of their surroundings. The noise impact of decommissioning can influence those mammals to migrate to other places due to interference of noises during underwater cutting [38].

5.2. Seabed Disturbance

Oil and gas platforms may require the use of explosives to remove the supports that are buried inside the seabed. If the pipelines are buried deep inside the seabed, explosives might be used [10]. For partial decommissioning of the platform, it does not require any explosives. Even so, partial removal still destroys cryptic fish and sessile invertebrate species on the upper section of the platform. Some fishes might move down to the platform or seek a new inshore shallow habitat that will increase competition for resources [10]. In the end, removing the buried pipeline from the seabed may not be feasible since it has a more detrimental effect on the environment and requires expensive technology or equipment [39]. Not only will the seabed be disturbed, but the habitat will also be destroyed. Moreover, the removal of subsea structures may cause potential damage to rhodoliths and deepwater corals [40]. Although the natural habitat will eventually be restored after decommissioning, the protection of the de facto fisheries exclusion will be reversed. In other words, with the fishing communities going back to business, the seabed will still be disturbed. A lot of aquatic species can also be found on the pipelines as the pipelines provide additional habitat for low mobility (epifaunal) species [13,41,42]. The benthos surrounding numerous oil and gas rigs in the North Sea has experienced significant ecological alteration as a result of disturbed seabed from drill cuttings. The toxicity of disturbed sediments from the area surrounding the North West Hutton platform is shown in Table 3. Due to decommissioning, the concentration of contaminants on the seafloor of an offshore oil and gas platform is shown in Table 4.

Table 3. Maximum concentrations of disturbed sediments in the Northwest Hutton sediments (Source: [43]).

Metal	Maximum Concentration in Sediments (μg/g)
Ba	484
Cr	22
Cu	46
Fe	14,320
Mn	628
Pb	195
Zn	927
THC	17,211

Table 4. Concentrations of contaminants associated with offshore petroleum above the Australian and New Zealand sediment quality guidelines; highlighted in bold [44].

Contaminant	Origins of Contaminant	Pre-Drilling Mean Concentration (mg/kg dw)	During Operations Mean Concentration (mg/kg dw)	Post-Drilling Mean Concentration (mg/kg dw)	ANZG Sediment DGV (mg/kg dw)	Reference
PAH	Discharges from the platform to the seabed	55	-	**48**	10	[45]
Ba	Discharges from the platform to the seabed	752	-	862	NA	
Pb	Drilling cuttings	-	**1926**	-	50	
Ni	Drilling cuttings	-	67	-	21	
Zn	Drilling cuttings	-	**1346**	-	200	

5.3. Waste Disposal

During the process of the decommissioning activity, most of the unwanted materials from the cut pipelines are brought to landfills for disposal. Alternatively, the materials could be recycled or reused for other purposes. However, many South-East Asian countries face problems regarding insufficient ground for processing the wastes. It has also been found that the crude oil found in these countries contains higher mercury as compared to other parts of the world [46]. Moreover, the dismantling of pipelines cannot be undertaken if the pipelines contain residue of toxic substances and trace metals [33], where cleaning is found to be difficult and impossible [27]. In addition, other wastes can have an adverse impact on the environment, such as hydrocarbons and industrial materials and chemicals known as polychlorinated biphenyls (PCBs) [46]. Such wastes can have a detrimental impact on the environment, especially biodiversity. This chemical damages the DNA and decreases the survival rate of the species increasing species mortality [47]. In addition, a high number of solid materials resulting from drill cuttings and mud chemicals, also referred to as seabed deposits, is a major threat to biodiversity [22]. This has been an ongoing issue for decades as accumulated solid materials have increasingly been disposed of into the ocean, which will gradually disrupt the ecosystem of the marine environment.

5.4. Biodiversity

According to [48], in Santa Barbara Channel, Southern California, it is reported that the diversity of the fish population is seven to six times greater on pipelines compared to the adjacent seafloor. It is also reported from other studies in North Western Australia, with a high diversity of fish populations on offshore pipelines. An example of fish species includes groupers of epinephelids and lutjanids (snappers). It was observed that higher diversity of fish was near the 'more than half-exposed pipeline from seafloor' and 'spanning above the seafloor pipeline or exposed pipeline above seafloor.' Further study shows that offshore oil and gas platforms can provide a healthy environment for a wide variety of sessile invertebrates and fish, including some that are valuable for commerce and recreation and have excellent potential for preserving natural resources [49,50]. Subsea equipment, pipelines, and other equipment should be appropriately cleaned and flushed before being left in place to provide additional habitats (substrate) for reef-like animals, allowing other deep-sea marine life to gather around these reef-like organisms and preventing potential damage by human disturbance. Keeping the pipeline in place might thus have major ecological benefits in the long run. In reality, leave-in-situ oil and gas platforms can operate as "stepping-stones" in habitats with a lot of soft sediment by allowing fish and invertebrate species to live there that might not otherwise [51]. A variety of advantages from these leave-in-situ decommissioning options have been revealed in recent research, including the creation of artificial reef habitats that improve marine biomass and biodiversity [15].

The oil pipelines underneath seas are rich in biodiversity due to the build-up of sediment transport and scouring processes. The pipelines are favorable places for the refuge of various species of fish, having good accessibility to food. Additionally, it is found that natural reefs of a hard substrate with coral cover and/or macroalgae and sand with patchy epibenthic create colonies for sponges and gorgonians [52,53]. A colony of Australian fur seals, Arctocephalus pusillus doriferus, in the Bass Strait, south-eastern Australia flourished due to the existence of fish and fauna at subsea pipelines [48]. Hence, offshore decommissioning activities, such as removing underwater pipelines, will interrupt the existing coral and fish species living on the pipelines. The fish stock that is supported by the reef ecosystems developed on subsea infrastructure also has a commercial value [13,49]. This is particularly observed in the North Sea, where commercial fishing around pipelines often occurs [54].

5.5. Water Pollution

The decommissioning of offshore oil and gas platforms can significantly impact water quality, especially if the process is not managed appropriately. The potential discharge of oil and other hydrocarbons from the platform is one of the key worries. These might escape either during decommissioning or because of mishaps or spills. According to [43], there is a high correlation between concentrations of Cu, Fe, Mg, Mn, Pb, Zn, and total hydrocarbons, as well as the percentage of marine sediments with a diameter of less than 63 mm. The correlation patterns show that these coarser sediments were mixed with finer metal and hydrocarbon-contaminated sediments from drill cuttings, particularly after total and partial removal. The total or partial decommissioning can increase the resuspension of contaminants in local sediments and the subsequent effects on marine organisms exposed to these contaminants [55].

5.6. Air Pollution

There is a challenge to mitigate air pollution emissions from platform decommissioning caused by diesel engines, as they operate in almost all phases and activities. During the removal process of excavating out the pipelines, several types of machinery will be used, such as an excavator, leveling machine, and backhoe, while other equipment, such as hydraulic plate shear and high-pressure welding machines, are used for cutting and welding pipelines [27]. The degradation of air quality during the decommissioning activity is closely related to the types of machinery and equipment used. The air quality is mainly affected during the excavation process, where accumulated dust can be observed as well, especially during transportation. For instance, an hour of idling for a backhoe loader machinery contributes to CO emissions of 65 g, CO_2 emissions of 6848 g, and PM_{10} (Particulate Matter less than 10 µm) emission of 13 g. Meanwhile, an on-road truck contributes a CO_2 emission of 6848 g and a PM_{10} emission of 2 g [56]. Annabel and Audrey Fields Decommissioning Project (2017) reported that 44% of the total energy use is due to the direct energy required by support vessels, and the decommissioning activities account for 42% of the associated atmospheric emissions. Moreover, flora and fauna in the form of algae and plankton (bioorganic decomposition), along with dirty water runoff from anthropogenic activities and oil spills from tankers, can pollute the air. Total removal of the topsides of the offshore oil and gas platform creates approximately 6.75 times more air pollution than partial decommissioning to a depth of 85 feet below the surface of the water [57]. The level of air pollution caused by comprehensive decommissioning is the highest of the three options. This is because the removal of the platform's structures and apparatus can generate significant quantities of dust, fumes, and other pollutants. These pollutants can travel great distances and have negative effects on human health and the environment, whereas partial decommissioning, which involves removing only a portion of the platform's structures and equipment, generates less sediment, fumes, and other pollutants. Leave-in-situ decommissioning, in contrast, requires no machinery to dismantle the platform. The platform will eventually degrade naturally, generating some air pollution, but this pollution will be significantly less than that generated by the other decommissioning methods.

5.7. Potential Economic Impact

The decommissioning cost is varied depending on each project. Around 2500 platforms and 35,000 wells in the Asia Pacific might cost up to $100 billion to decommission [12]. In the shallow water of the Gulf of Mexico in the United States, the average inflation-adjusted pipeline decommissioning cost was $187,000/km and $1660 per cubic meter [58]. The average annual cost of decommissioning oil and gas platforms in the Gulf of Mexico exceeds USD 1.5 billion [24]. The cost usually depends on how complex the decommissioning work is. A damaged pipeline due to events such as natural disasters or leakage will be three to four times more expensive than an undamaged pipeline [58]. The decommissioning works are also known to be unique, and currently, there is no universal standard practice to address the decommissioning works [40] fully. According to estimates, the cost of decommissioning wells, platforms, and pipelines in Australian water will be $40.5 billion by 2050 [59]. Decommissioning work for pipelines is relatively cheaper compared to the decommissioning of oil and gas platforms, where it involves the removal of large and complex residues. The uncertainties regarding the timing of decommissioning works creates difficulties in establishing an effective marketplace for service, which was found to be the limiting factor to investing in innovative cost-saving technologies for decommissioning [60]. As more oil and gas platforms will soon come to their lifespan, a lot of decommissioning works will need to be executed [39], as most of the regulation requires them to be removed at the end of their service life. Therefore, to achieve successful decommissioning of deep pipelines, the industry needs to develop an improved, safe, environmentally friendly, and cost-effective decommissioning strategy [20].

A multicriteria decision matrix has been suggested as a method for choosing a decommissioning option. According to [24,61,62] numerous such frameworks have been suggested and reviewed. Potential environmental impacts were analyzed using high = 3, medium = 2 and low = 1, neutral = 0, and positive impact were indicated by a "+" and negative impact was indicated by a "−" sign and compared among decommissioning options as shown in Table 5. Effective multicriteria analyses are, however, not possible due to the lack of quantitative data on the probable inventory of residual contaminants at the point of decommissioning (i.e., post-cleaning) and the likely environmental repercussions [61,63].

Table 5. Multicriteria decision matrix for decommissioning option.

Criteria		**Total Removal**	**Partial Removal**	**Leave In-Situ**
Environmental	Seabed disturbance	−3	−2	−1
	Air pollution/emission due to construction equipment	−3	−2	−1
	Waste disposal	−3	−2	−1
	Noise impact	−3	−2	−1
	Water quality	−3	−2	−1
	Biodiversity	−3	−2	−1
Social	Impact on fisheries/Livelihood of fisherman	0	0	1
Economic	Cost	−3	−2	−1
	Employment opportunities/recruitment of workforce	3	2	1
Safety	Risk to navigation	−1	−2	−3
	Risk to personnel	−3	−2	−1
Score		−22	−16	−9

The matrix analysis using the scoring method indicates that the leave in situ is the best option for decommissioning.

It is observed that based on the potential environmental impacts, the leave-in-situ method is the most suitable option for decommissioning offshore oil and gas platforms. This is further supported by the study carried out by [63] in which Multicriteria Approval (MA) for evaluating and comparing alternative decommissioning options across key selection criteria such as environmental, financial, socioeconomic, and health and safety were considered. [64] also demonstrated that using multicriteria decision analysis can be considered an adequate model for choosing options for decommissioning oil and gas assets, and leave in-situ is one of the most preferable options for decommissioning where a qualitative approach was applied.

6. Mitigation Measures

Mitigation measures are considered when potentially significant impacts are detected. The aim is for preventive measures to avoid, minimize, or manage such adverse effects to the point where they are not substantial. The key role of mitigation is to review project procedures and recommend specific guidance on practices, reducing impacts, avoiding, repairing the environment or compensating for adverse effects, or possibly enhancing the environment. A simplified version of the mitigation measures is shown in Table 6, considering different features of major environmental impacts due to the activity of decommissioning.

Table 6. Mitigation strategies for decommissioning.

Aspect	Mitigation Strategies
Noise	Machinery, tools, and equipment are to be in good working condition. The vessels' work activities will be carefully planned to optimize their use. Careful scheduling and selection of equipment with less noise level below 80 dB.
Air pollution, the carbon footprint of vessels	Fuel consumption to minimize by operational practices and power management systems for engines, generators, and any other combustion plant to reduce air emissions and minimize carbon footprint in the atmosphere. Decommissioning activities planned to minimize vessel use, such as optimization of vessel and helicopter schedules.
Seabed disturbance	Improving management in optimizing pipeline routing to minimize the amount of trenching will also minimize the unavoidable impacts of increased suspended sediment. Man-made chemicals such as Polychlorinated biphenyls (PCBs) that are detrimental to the water quality should be substituted with other chemicals that do not contribute to the damage to the water quality.
Biodiversity	Relocating species to other locations during the decommissioning process. Mitigating impact considerations by minimizing machine noise or suspended sediments (turbidity) or by avoidance of decommissioning activities.
Solid waste from decommissioning of pipelines	Reuse and recycling of pipelines or cut materials for post-decommission instead of throwing the potential materials into landfill. Conducting examination after decommissioning to ensure all cut materials are removed. Creating local waste treatment facilities and local decommissioning yards.

6.1. Data Transparency

Most of the cases involving decommissioning of pipelines require transparency between the stakeholders, as transparency is more of an issue with data sharing rather than technological capabilities [65]. Workshops or other cocurricular activities can be held to build trust between different stakeholders. Transparency in data collection and management can improve the investment climate for investors in decommissioning and improves budgeting and performance on benchmarking [11]. The data should be reviewed before publishing and should be shared among the stakeholders. The conflict between the fishermen and the oil and gas operator can be avoided by using GIS to identify the location of pipelines [66].

6.2. Utilizing Current Technology in Decommissioning Works

Although stakeholders' participation could resolve most issues, it is not always the case. This is because different stakeholders will have different opinions regarding this matter. The conflict will eventually take more time to resolve. Thus, [67] developed a framework based on supervised algorithms and dimensionality reduction techniques to solve decommissioning works with multicriteria problems [67]. The estimation of decommissioning environmental impact methodology can be applied qualitatively and quantitatively by integrating 3D information models and modified life cycle assessment (LCA) techniques [24]. The cost estimation will also be lowered with accurate cost estimation. The complexity of decommissioning oil and gas infrastructure at offshore facilities was examined using the recently developed DAPSI(W)R(M) problem structuring framework (covering Drivers, Activities, Pressures, State changes, Impacts (on Welfare), and Responses (as Measures), with the results feeding into the development of a novel database tool for Screening Potential Impacts of Decommissioning Activities (SPIDA) [16].

6.3. Mathematical Models

Meanwhile, [40] use hydrodynamic modeling to simulate the impact of the decommissioning works. However, more studies are required to obtain accurate estimates of sediment resuspension and layer deposition onto benthic organisms to support regulatory decision-making for decommissioning. The fleet sizing decision support model is used to analyze sets of pipelines to reduce the decommissioning work [68]. It aids in understanding and predicting sediment movement during decommissioning, which would help understand the impact on the ecosystem and marine species. The use of mathematical programming to construct and solve early-stage field development plans results in higher profit margins. The optimization model can calculate the drilling and production schedules and the ideal decommissioning period that results in the highest net present value for the project [69].

6.4. Decommissioning Forecast

Another method to reduce the cost is by decommissioning forecasts. [58] carried out three approaches to estimate the decommissioning works in the Gulf of Mexico. The approaches are lease status for the short term, gross revenue for the mid-term, and production forecast for the long term. The analysis provides a better understanding of future requirements and the expected timing of capital expenditure [58].

6.5. Revising the Framework for Decommissioning Pipelines

Decommissioning works are unique for each project. This is because the design of each oil and gas platform is designed differently. Moreover, most of the platforms constructed before 1998 are not meant to be fully removed at the end of their service [60] since no environmental impact assessment has been conducted during that time. This means there is no standard way for the decommissioning works. Therefore, the design for the oil and gas platform and pipelines should be standardized for future construction.

6.6. Repurpose

Since most of the regulations require the decommissioning works, alternatives to repurpose the oil and gas platform which will resolve the economic issues regarding decommissioning works. Ref. [34] proposed to convert the platform to produce fresh water through the desalination process, hydrogen power plants, and wind turbines. The existing pipelines can be used as an advantage to transport liquids. Ref. [3] proposed that offshore oil platforms be integrated into ocean wave power generation. Since wave energy is an inexhaustible source of clean, renewable energy, it will eventually reduce the dependency on fossil fuels and reduce costs. Most importantly, the platform conversion would provide continuous revenue to the industry. Nevertheless, all the proposed alternative platform reconversions present positive environmental effects in most impact categories compared to the standard decommissioning scenario [34]. Another example is rigged to reefs where oil and gas infrastructure is used for aquaculture [19]. It will save the environment, but rigs to reefs can also be viewed as a business opportunity.

6.7. Recycling or Reusing the Oil and Gas Pipelines

Kaiser, M. [27] proposed a new construction technology for the pipelines called the combined disposal scheme. The scheme is capable of eliminating safety and environmental risk and reducing costs. The pipelines should be first cleaned using a combined cleaning method before and after the decommissioning operation to avoid leakage of residual pollutants, destruction of the environment, and the restoration of the ground [27]. It is suggested that the oil and gas pipelines can be reused as a method of transportation for carbon dioxide. Not only will it reduce the cost of decommissioning works, but this could also be one of the methods to mitigate global warming. This approach will allow the reuse of oil pipelines, saving the manufacturing cost of new materials. Dismantled pipelines can be further reused for lower operating pressure, re-melting, and manufacture of other parts and raw materials. Offshore pipelines that are buried will remain in place. Jackets and topsides of offshore pipelines, pipelines' tie-in spools, and trench transition portions underwater must be removed, retrieved, and returned to shore for recycling.

7. Conclusions

The global exploitation of oil and gas resources has increased to meet the global energy demand. However, several facilities, especially oil pipelines, will reach their operational life, no longer be economically viable, and eventually undergo decommissioning. The methods for decommissioning pipelines are either partially removing the pipelines or leaving them in situ. The major environmental impacts involved with decommissioning include noise impact, seabed disturbance, biodiversity, waste disposal, water pollution, and air pollution, which must be identified, and corresponding mitigation measures must be taken to minimize the negative impacts during the project's life cycle of the decommissioning of the oil pipelines. Leave-in-situ decommissioning is the least disruptive and polluting method of decommissioning offshore oil and gas platforms. However, the best method of decommissioning will vary depending on a number of factors, including the location of the platform, the type of platform, and the environmental conditions. The final decision on the decommissioning method will be made based on having the lowest risk that fulfills the technical requirement. Decommissioning includes tools such as multicriteria decision analysis and the environmental impact matrix tool to assess the significance of impacts by considering criteria such as size and duration. Attention was drawn to the mitigation measures, which include advanced planning of work programs, involvement of experts, and specialized tools and technology to deal with the delicate marine environment. Furthermore, any actions and appropriate allocation of responsibility in addressing potential adverse impacts depends on complying with the legislation, standards, and guidelines provided by the government or international agencies.

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