Review article

Effects of crude oil pollution on aquatic ecosystem: A review

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SUMMARY

Crude oil, a highly hazardous chemical, is composed of up to 10,000 distinct hydrocarbons, posing significant risks to aquatic life. This review focuses on assessing both short- and long-term impacts of crude oil on aquatic ecosystems, including its effects on diversity, food webs, and ecological balance. The review also highlights sources of crude oil, its composition, and its transportation and fate within aquatic environments. Major sources of oil spills in aquatic ecosystems stem from oil exploration, transportation, and refineries. Various factors, such as oil weathering processes (e.g., evaporation, dissolution, emulsification, biodegradation, sedimentation, and photooxidation), physio-chemical changes (including partitioning, adsorption, sorption, hydrolysis, oxidation, volatilization, and emulsification), and environmental conditions (like oxygen levels, sediment presence, water currents, salinity, wave action, and temperature), influence the fate and transport of crude oil within aquatic ecosystems. In Nigeria, short- and long-term impacts of crude oil spills include immediate environmental damage, loss of livelihoods, degradation of ecosystems, disruption of food webs, and loss of aquatic biodiversity. Remediation efforts primarily rely on physical, chemical, and biological methods to mitigate the effects of oil spills. The damages inflicted by crude oil on human health and ecological systems are manifold, encompassing respiratory problems, skin irritations, cancers, neurological effects, habitat destruction, disruption of food chains, and loss of ecosystem services. These consequences highlight the urgent need for effective prevention, response, and remediation strategies to safeguard aquatic environments and human well-being from the adverse effects of crude oil contamination.

Keywords: Crude oil, Pollution, Freshwater, Marine

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INTRODUCTION

Continuous monitoring of the aquatic environment aims to enhance understanding of pollution effects and mitigate their impacts. The consequences of crude oil spills on marine ecosystems are extensively documented, with the severity of impacts influenced by spill volume, receiving water characteristics, and the nature of the petrochemical involved. Lighter petroleum products exhibit less persistence in the environment compared to crude oil [1].

Following the 1989 Exxon Valdez oil spill in Prince William Sound, Alaska, mortality of marine invertebrates resulted from a combination of chemical toxicity and smothering. It is estimated that 100,000–300,000 birds died from exposure to oil. However, long-term effects persist due to the unexpected persistence of toxic subsurface oil and chronic exposures, affecting wildlife even at sub-lethal levels [2].

Weathered oil in aquatic environments poses a significant threat to lifeforms, as toxic effects can cascade across trophic levels. Ecologically, crude oil can alter the structure and function of both freshwater and marine food webs (e.g., through mortality, retarded succession, and retrogression)

Research on crude impacts on freshwater invertebrates is limited but suggests similar impacts to marine environments [3]. Previous studies by Woodward *et al*., [4] primarily focus on acute spills in temperate streams or laboratory toxicity tests. These studies indicate high sensitivity of stream invertebrate assemblages to petroleum products, with significant reductions in abundance and taxonomic richness downstream from spills. Recovery following clean-ups occurs within a year for species assemblage assessments, but individual species' recovery is slower.

Woodward *et al*., [4] also reported certain freshwater invertebrates, such as Baetis and Isoperla, exhibit high sensitivity to oil exposure, with significant mortality observed at low concentrations. Studies on petroleum spill effects in tropical aquatic ecosystems are scarce, but reductions in benthic invertebrate abundance and diversity have been reported in Nigerian streams affected by refined petroleum spills. Similar findings are noted for small spills in the Niger Delta ecosystem [5]. This review focus on assessing the short- and long-term impact of crude oil on aquatic diversity, food web and ecological diversity of the aquatic ecosystem. In addition, we highlighted crude oil sources, its composition, and it transport and fate in the aquatic ecosystem.

Sources of crude oil pollution in Aquatic ecosystem

Crude oil pollution in aquatic ecosystems can occur through various sources and can have detrimental effects on the environment. Anthropogenic activities such as oil exploration, transport, and manufacturing in refineries near coastal regions contribute to oil pollution in marine ecosystems [6]. The spill of crude oil from both artisanal and government-owned refineries is a recurrent issue in areas like the Niger Delta, leading to devastating effects on the aquatic ecosystem [7]. Industrial wastewater from the oil industry can also contain organic toxic compounds such as polycyclic aromatic hydrocarbons (PAHs) and phenolic compounds, which pose a danger to the aquatic ecosystem [8]. Additionally, contamination of soil and aquatic ecosystems by petroleum hydrocarbons (PHs) is a serious global issue, with PHs being highly toxic, mutagenic, and carcinogenic in nature [5].

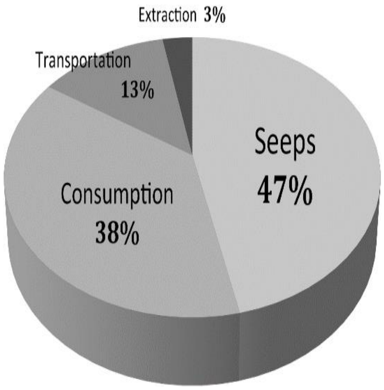

Fig.1. Sources of crude oil in the aquatic ecosystem
Source: (Michel and Fingas, 2016)

The Chemical composition of crude oil

Petroleum is a naturally occurring, toxic, heterogeneous, complex organic compound mixture of hydrocarbons. Its mass spectrometry revealed over 17,000 distinct chemical compounds, including cycloalkanes, mono- and polycyclic aromatic hydrocarbons, and general alkanes with different chain lengths and branch points. Some molecules have an abundance of sulfur, oxygen, and nitrogen, whereas phosphorus and heavy metals like nickel and vanadium are infrequently detected [2,9]. Their biodegradation capability and environmental fate fluctuate because to the significant variations in the chemical and physical characteristics of oil components (such as solvability, viscosity, capacity to absorb, and similarly variable in its toxicity and bioavailability).

Petroleum hydrocarbons are classified into four broad classes: Resins (Amides, Sulfoxides, Carbazoles, Quinolines, Pyridines), Saturated, Aromatics, and Asphaltenes (Porphyrins, Esters, Ketones, Fatty Acids, Phenols). The crude oil mixture was shown in Fig. 2. Light oils have larger concentrations of more polar chemical components such asphaltenes and resins as well as saturated and aromatic hydrocarbons [10].

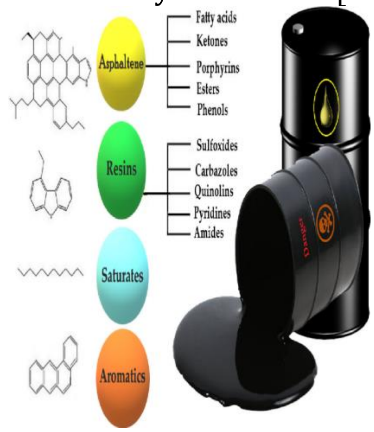

Fig. 2 The Chemical composition of crude oil
Source: (Hassanshahian *et al.*, 2020)

Transport and Fate of crude oil in the aquatic ecosystem

The mechanisms of transport and fate of crude oil in the aquatic ecosystem are influenced by various factors such as oil weathering processes, physico-chemical changes, and environmental conditions [11]. When oil is spilled, it undergoes weathering processes that determine its fate, including evaporation, oxidation, dissolution, spreading, accumulation, and biodegradation [8]. In marine environments, hydrocarbon fractions of spilled oil can selectively undergo evaporation, oxidation, and dissolution into the water table, as well as biodegradation by microorganisms [12]. The solubility behavior of hydrocarbons in seawater can lead to their dispersion in soluble, solubilized, and particulate states [13]. The transport and fate of crude oil in reservoirs can be simulated using proactive spill modeling methods, which consider dissolution trends and water quality impacts [14].

Impact of crude oil pollution on marine and fresh water bodies

Crude oil pollution has a significant impact on aquatic water bodies. It can lead to abnormal changes in the chemical, physical, and biological properties of the environment, affecting the ecological balance of nature [15]. Oil spills, especially in marine ecosystems, can have deleterious effects on aquatic organisms, including respiration, feeding, spawning, and thermoregulation [16]. The spillage of oil can also be lethal to humans, fish, birds, cattle, and wildlife, both through direct contact and consumption of polluted food [17]. Additionally, oil pollution can disrupt the global food chain and cause economic losses to farmers and governments [8]. The effects of crude oil pollution on macrophyte assemblages in rivers have been studied, with higher diversity and abundance observed in less polluted areas [18]. Petroleum hydrocarbons, such as total petroleum hydrocarbons (TPHs), are highly toxic and can cause sublethal and lethal effects on microorganisms, plants, and animals in both terrestrial and aquatic ecosystems.

Effects crude oil pollution on aquatic organisms

Fish

Exposure to crude oil can lead to haematological changes in fishes, such as a decrease in red blood cell count, packed cell volume, haemoglobin, and an increase in mean corpuscular haemoglobin concentration [19]. It can also cause a decrease in white blood cells, making fishes more susceptible to stress and infection [20]. Additionally, crude oil exposure can result in histopathological alterations in the heart of fishes, leading to cardiac dysfunction [21]. Furthermore, fishes in oil-polluted water can accumulate Polycyclic Aromatic Hydrocarbons (PAHs) in their flesh and organs, posing a high health risk for consumers [22]. Larval and juvenile fishes exposed to crude oil may experience developmental defects, growth stunting, and suppressed immunity, with limited ability to recover even after being transferred to clean water [23].

Aquatic invertebrates

The release of oil into the environment, especially in marine ecosystems, can have severe impacts on the survival and functioning of aquatic invertebrates [15,24]. Oil spills can disrupt the buoyancy of surface-dwelling aquatic insects, such as water striders, which rely on fine-hair microstructures to remain buoyant [25]. The toxicity of petroleum hydrocarbons (PHs) in aquatic systems can be particularly harmful to benthic organisms, including mussels, oysters, crabs, and cockles, which ingest oil-bound particulates [8]. The bioavailability of PHs plays a crucial role in their toxicity, with hydrophilic PHs being more bioavailable and causing sublethal or lethal effects in organisms [26].

Plankton

The pollution caused by crude oil has substantial impacts on the populations of plankton, which are critical organisms in aquatic ecosystems. At the time of crude oil and gas condensate spills happening in marine sediments, they create a sequence of alterations in the characteristics of the sediments themselves. These spills result in raised amounts of organic carbon and heightened concentrations of polycyclic aromatic hydrocarbons (PAHs), which are harmful substances derived from crude oil [27]. In addition, the spills also have a detrimental effect on the biomass of benthic autotrophic microbes, which are indispensable for the ecological balance of the sediments. Interestingly, the abundance of heterotrophic bacteria remains unaffected by the spills, while their production actually increases. This finding suggests that the spills may have a selective impact on different microbial groups within the sediments [28].

A study conducted in the Gulf of Mexico has revealed that crude oil exposure has profound effects on phytoplankton communities, which serve as critical primary producers in marine ecosystems. The exposure to crude oil changes both individual phytoplankton species and the overall community structure. Diatoms, a type of phytoplankton, appear to exhibit better tolerance to crude oil compared to dinoflagellates, another type of phytoplankton [29]. This observation highlights the differential responses of different phytoplankton groups to crude oil pollution. Furthermore, the exposure to crude oil triggers the activation of reactive oxygen species within phytoplankton cells, leading to oxidative stress and damage to lipid structures. This oxidative stress can have detrimental effects on the overall health and functioning of phytoplankton, which are essential for maintaining the stability of marine ecosystems [30].

In oligotrophic coastal waters, the addition of crude oil has been found to have contrasting effects on different components of the microbial community. Specifically, the addition of crude oil leads to a decrease in phytoplankton biomass and production rates. This decrease can be attributed to the toxic effects of crude oil on phytoplankton cells, as well as the reduced availability of nutrients due to the presence of oil [31]. However, in contrast to the negative impact on phytoplankton, the abundance and production of heterotrophic bacteria actually increase in response to the addition of crude oil. This increase in bacterial activity may be attributed to the availability of organic carbon and other compounds derived from crude oil, which serve as an energy source for bacteria [31].

Birds

Particularly in aquatic environments, birds are frequently the most noticeable members of the biota impacted by oil spills. Fouling of feathers and ingestion are the two main ways that birds are exposed to oil. When birds come into touch with oil slicks on the ocean or along shorelines, their feathers get contaminated [32]. For seabirds, this is especially harmful since greasy feathers reduce insulation and buoyant capabilities. Once greased, a bird rapidly loses body heat, particularly at sea, potentially leading to death. Oiled sea birds may remain on land, where their temperature loss is less severe. Birds may clean their plumage by preening and, in doing so, may ingest some of the oil; birds may also ingest oil by eating oiled prey. Three categories of toxic effects can result from oil ingestion: (1) reduced reproduction; (2) destruction of red blood cells leading to anemia; and (3) increased stress resulting in an increased susceptibility to disease. By doing so, however, the birds are removed from their source of food and may die of starvation or predation [33].

Birds that have been contaminated may provide oil to their eggs or young. It has been discovered that the young in an egg may be killed with just a few droplets of fresh oil. Even in cases when birds consume very little oil, they may cease to produce eggs or deposit fewer of them. The eggs' capacity to hatch may also be impacted by a tiny bit of oil. The birds that spend a lot of time in the water, dive for food, migrate and overwinter in dense flocks, congregate in nesting colonies, or have small populations (thus classified as endangered or threatened) are the most vulnerable to the effects of oil spills [34].

Marine mammals

The effects of oil spills on marine and other aquatic mammals vary with species. A few factors that affect marine mammals' sensitivity to oil exposure are whether they rely on fur or blubber for thermoregulation, whether they form dense groups on land or in the water, how and what they feed, and the risk of inhalation. Seals, sea lions, and walruses are particularly vulnerable to oiling because they haul out, often in very large numbers, on the shorelines of small islands, rocks, or remote coasts with few options for new territory [32]. For instance, 30,000 walruses were hauled out on a 1.6 km stretch of beach in the Chukchi Sea, Alaska, in 2011. Young seals and sea lions that are externally oiled usually die from lack of coat development, which prevents them from being adequately insulated. Mothers may choose not to feed their children when they are greased since oil is frequently absorbed or consumed [10].

When whales, dolphins, and porpoises rise to breathe, they may come into contact with oil in the water column or on the surface. Despite this, it has been impossible to tell if these species died as a result of the spill. This is likely due to a combination of circumstances. However, most spills do not pose a substantial harm to these species. Oil does not attach to the skins of these creatures, and because they are very mobile, they are unlikely to be exposed for an extended length of time [35].

Polar bears are attracted to oil, particularly lubricating oil, which they will drink. They spend a lot of their time near or in water, swimming between ice floes and hunting seals, so there is a moderate risk of oiling. However, polar bears can ingest oil while grooming themselves, which can lead to death or severe illness. [32,36].

Long term impact of crude oil pollution the aquatic ecosystem

Impact on food web

Crude oil pollution can exert substantial impacts on the intricate networks of interactions that constitute food webs. Numerous research studies have illuminated the negative outcomes that exposure to crude oil can bring about in various organisms, including gelatinous zooplankton [37]. These creatures, which have a vital function in marine food webs, possess the capacity to accumulate PAHs from crude oil, potentially transferring these contaminants to higher trophic levels in the ecosystem [38]. Moreover, copepods, serving as yet another pivotal constituent of marine ecosystems, have been observed to ingest minute droplets of crude oil, thereby indicating that the pollution stemming from this resource can indeed infiltrate marine food webs through this particular pathway [39]. The use of stable isotopes and radioisotopes as analytical tools, is capable of providing invaluable insights into the occurrence of trophic shifts and the assimilation of petrocarbon within marine food webs [40].

Impact on ecological changes

Crude oil pollution has the potential to induce abnormal modifications in the chemical, physical, and biological properties of the surrounding environment, consequently yielding a discernible impact on the delicate ecological equilibrium that characterizes the natural world [15].Instances of oil spills, whether originating from oil exploration activities, transportation processes, or even artisanal refineries, inflict severe and devastating consequences upon the fragile aquatic ecosystem, with various organisms such as fish, crustaceans, mollusks, and other living entities bearing the brunt of such deleterious incidents [7]. The inherent toxicity associated with crude oil is instrumental in instigating sublethal and lethal outcomes for the aquatic organisms, thereby causing disruptions in their cell membranes and central nervous systems, which are vital for their overall functioning and survival [8]. Consequently, the introduction of oil pollution into the aquatic milieu inevitably disrupts the patterns pertaining to growth and reproduction within organisms, giving rise to anatomical complications, and elevating their susceptibility towards hypothermia, a potentially pernicious condition [41]. Both accidental land-based oil spills and those occurring within the marine environment prove to be highly detrimental to the intricate web of microbial communities, fish, invertebrates, seabirds, marine mammals, and phytoplankton, thereby threatening the overall stability and health of these ecosystems [24].

Remediation strategies

Physical methods

Physical strategies for remediating crude oil pollution in aquatic ecosystems encompass various approaches, one of which involves the utilization of nanomaterials such as pure anatase titanium nanoparticles (n-TiO_2) [42]. It has been determined that these nanoparticles possess the capacity to effectively diminish the levels of DNA damage that result from the presence of crude oil pollutants [43]. Another physical method employed in the remediation process is the application of biochar, a highly porous carbonaceous material, which can be combined synergistically with microbes and biosurfactants to enhance the overall effectiveness of bioremediation [44]. Notably, when biosurfactants and biochar are employed in conjunction with microbes, their combined effects have been demonstrated to significantly outperform their individual contributions in the context of bioremediation [45]. Furthermore, the integration of oleophilic microorganisms, which possess the remarkable ability to produce biosurfactants, into a bioremediation system has exhibited promising outcomes in terms of decontaminating aquatic environments afflicted by petroleum hydrocarbons and oil spills [46].

Chemical methods

Chemical remediation strategies employed for the mitigation of crude oil pollution in aquatic ecosystems encompass the utilization of chemical agents with the purpose of eliminating the pollutants from the affected environment. These strategies involve a myriad of approaches, among which chemical-physical methods stand out as they exhibit the ability to effectively eliminate a substantial proportion of the pollutants that have contaminated the ecosystem. For instance, the utilization of bioremediation by microorganisms has been recognized as an effective means of combating crude oil pollution [42]. The degradation of the toxic compounds present in petroleum can be accomplished through the deployment of microalgae and bacteria, whose symbiotic cooperation has been the subject of investigation when it comes to cleansing water that has been contaminated by hydrocarbons [46]. Furthermore, the bioremediation rate of petroleum hydrocarbons can be augmented by the inclusion of biosurfactants, which are secondary metabolites produced by microorganisms [42].

In addition to the aforementioned strategies, chemical dispersants are also employed for the purpose of addressing oil spills in marine environments. However, the effectiveness of these dispersants is contingent upon a multitude of factors, including but not limited to the specific type and quantity of dispersant utilized, the viscosity characteristics of the oil, and the salinity levels of the water [47].

Biological methods

Biological strategies involve the use of microorganisms such as bacteria, fungi, and microalgae, which possess the remarkable capability to break down and eliminate hydrocarbons from contaminated water sources [42]. The employment of bioremediation techniques involving microbial communities has demonstrated encouraging outcomes in the treatment of marine environments that have been adversely impacted by petroleum compounds [48]. Microalgae play a pivotal role in the bioremediation process through their facilitation of bacterial growth and their direct influence on contaminants via diverse mechanisms [46]. Another effective approach, known as bio stimulation, involves augmenting the hydrocarbon degradation activity of indigenous microorganisms, thereby significantly enhancing the breakdown of petroleum hydrocarbons. The utilization of biosurfactants, which are produced by microorganisms, represents a promising tool within bioremediation systems, as they have the potential to accelerate the rate at which petroleum hydrocarbons are remediated. These biological remediation strategies offer both environmentally friendly and highly efficacious means of mitigating the deleterious effects of crude oil pollution in aquatic ecosystems.

Table 2.1 Notable crude pollution incidents and lessons learned

Spill name/ Year	Size (tons ×1000)	Location	Oil type	Nature of spill	Some lessons learned
Gulf War Spill/ 1991	800	Arabian Gulf	Heavy crude	Act of war	— Largest marine spill; affected 800 km of shoreline — Long-term impacts in sheltered areas with no cleanup
Deepwater Horizon/ 2010	500	U.S. Gulf of Mexico	Light crude	Oil well blowout	— Behavior and fate of deep releases — Submerged oil mat behavior
Amoco Cadiz/ 1978	223	Brittany, France	Medium crude	Tanker grounding	— Contamination of nearshore sediments by natural oil dispersion — Aggressive cleanup of marshes slows recovery
Prestige/ 2002	63	North of Spain	Heavy fuel oil	Tanker breakup	— Long-term persistence very heavy fuel oil — Need safe havens for stricken ships
Ixtoc I/1979	470	Gulf of Mexico	Heavy crude	Oil well blowout	— First use of environmental sensitivity mapping — Value of oil spill trajectory models
Enbridge Pipeline/ 2010	4	Kalamazoo River, Michigan	Diluted bitumen	Pipeline rupture	— Diluted bitumen sinks after several days weathering — Many lessons on how to locate and recover sunken oil in rivers

Source: (Michel and Fingas, 2016)

Human Health concerns

The potential human health risks associated with crude oil spills in aquatic ecosystems encompass a range of detrimental consequences. These include the contamination of food sources, the direct interaction with the spilled oil, and the inhalation of petroleum compounds. When oil spills occur, they have the capacity to contaminate the delicate balance of the marine ecosystem, thereby impacting the flora and fauna that inhabit it. This includes fish and other vital aquatic organisms that serve as crucial links in the intricate food chain. The consumption of polluted food, particularly fish that have been tainted by the spill, can have harmful effects on both humans and wildlife alike [7]. Additionally, direct contact with the spilled oil can prove to be lethal for not only humans, but also for fish, birds, cattle, and wildlife in general [15]. Moreover, the inhalation of petroleum compounds has the potential to lead to various health disorders in humans [49]. Oil spills pose a significant risk to human health and necessitate the implementation of effective remedial measures that can effectively minimize their impact [8].

CONCLUSION

Oil spills will always occur, and will continue to have detrimental effects on the environment as long as we continue to explore for, produce, and consume oil. In order to mitigate the potential consequences of these spills, it is imperative to prioritize the development and implementation of strategies that can effectively counteract the detrimental effects they have on aquatic ecosystems and the overall health of individuals that rely on these ecosystems for sustenance and livelihood.

Declarations

Disclosure of Conflict of Interest

None

Ethical Approval and informed Consent

This review did not use human or animal subjects. Therefore, ethical consideration was not applicable.

Disclosure of Funding

This study did not receive any external funding

REFERENCES

1. Budiman, F., Ismardi, A., Hardinah, T., Muhammad, R., Hartaman, A., Nurhidayat, A., ... & Sutapa, I. D. (2023). Strengthening oil pollution monitoring system in aquatic environment through development of IoT-based Oil-Water Separator Device. *Ecohydrology & Hydrobiology*.

2. Perhar, G., & Arhonditsis, G. B. (2014). Aquatic ecosystem dynamics following petroleum hydrocarbon perturbations: A review of the current state of knowledge. *Journal of Great Lakes Research*, *40*, 56-72.

3. Woodward D.F, little E.E., and Smith L.M (1987) Toxicity of fiveshale oils to fish and aquatic invertebrates. *Journal Archives of Environmental Contamination and Toxicology* **16**: 239–246

4. Simister, R., Taylor, M. W., Rogers, K. M., Schupp, P. J., & Deines, P. (2013). Temporal molecular and isotopic analysis of active bacterial communities in two New Zealand sponges. *FEMS microbiology ecology*, *85*(1), 195-205.

5. Ifelebuegu, A.O., Ukpebor, J.E., Ahukannah, A.U., Nnadi, E.O., & Theophilus, S.C. (2017). Environmental effects of crude oil spill on the physicochemical and hydrobiological characteristics of the Nun River, Niger Delta. *Environmental Monitoring and Assessment, 189*, 1-12.

6. Butnariu, M. (2022). Aquatic pollution and marine ecosystems. In *Bacterial Fish Diseases* (pp. 1-29). Academic Press.

7. Gadirova, E. (2022). Pollution level of oil industrial water samples. *Water And Water Purification Technologies. Scientific And Technical News*, *34*(3), 57-63.

8. Luke, M. E., & Odokuma, L. O. (2021). Acute toxicity of crude oil from NNPC and artisanal refineries in Niger Delta on selected aquatic biota. *GSC Biological and Pharmaceutical Sciences*, *15*(3), 016-024.

9. Kuppusamy, S., Maddela, N. R., Megharaj, M., Venkateswarlu, K., Kuppusamy, S., Maddela, N. R., & Venkateswarlu, K. (2020). Ecological impacts of total petroleum hydrocarbons. *Total Petroleum Hydrocarbons: Environmental Fate, Toxicity, and Remediation*, 95-138.

10. Van Hamme, J. D., Singh, A., & Ward, O. P. (2003). Recent advances in petroleum microbiology. *Microbiology and molecular biology reviews*, *67*(4), 503-549.

11. Singh, D.S. (2024). A Comprehensive Analysis of Marine Life Pollution Using Machine Learning Techniques on historical shipping Pollutants data. *Interantional Journal Of Scientific Research In Engineering And Management*.

12. Dukhovskoy, D. S., Morey, S. L., Chassignet, E. P., Chen, X., Coles, V. J., Cui, L., & Wang, J. (2021). Development of the CSOMIO coupled ocean-oil-sediment-biology model. *Frontiers in Marine Science*, *8*, 629299.

13. Jeznach, L. C., Mohan, A., Tobiason, J. E., & Reckhow, D. A. (2021). Modeling crude oil fate and transport in freshwater. *Environmental Modeling & Assessment*, *26*, 77-87.

14. Boehm, P. D. (1977). The transport and fate of hydrocarbons in benthic environments.

15. Iskander, L., Khalil, C. A., & Boufadel, M. C. (2021). Fate of crude oil in the environment and remediation of oil spills. *STEM Fellowship Journal*, *6*(1), 69-75.

16. Thakur, A., & Koul, B. (2022). Impact of oil exploration and spillage on marine environments. In *Advances in Oil-Water Separation* (pp. 115-135). Elsevier.

17. Budiman, F., Ismardi, A., Hardinah, T., Muhammad, R., Hartaman, A., Nurhidayat, A., & Sutapa, I. D. (2023). Strengthening Oil Pollution Monitoring System in Aquatic Environment through Development of IoT-Based Oil-Water Separator Device. *Ecohydrology & Hydrobiology*.

18. Eke-John, H., Owoleke, V. A., & Komi, G. W. (2022). The effect of crude oil pollution on macrophyte assemblage in Kporghor River, southern Nigeria. *Scientia Africana*, *21*(1), 223-232.

19. Sarkhel, R., & Ganguly, P. (2022). Oil pollution and municipal wastewater treatment: issues and impact. *Advances in Oil-Water Separation*, 57-64.

20. Zitte Leelee, F., Ikiomogha, M., & Sikoki Francis, D. (2023). Heamatological Changes Associated with Exposure of Catfish (Claria gariepinus) to Crude Oil. IDOSR Journal of Applied Sciences, 131-134. doi: 10.59298/idosr/2023/12.1.7903

21. Jin, F., Wang, Y., Yu, F., Liu, X., Zhang, M., Li, Z., & Wang, J. (2023). Acute and Chronic Effects of Crude Oil Water-Accommodated Fractions on the Early Life

Stages of Marine Medaka (Oryzias melastigma, McClelland, 1839). *Toxics*, *11*(3), 236.

22. Akankali, J. A., & Nkeeh, D. K. (2022). Effects of Oilfield Chemicals, Herbicides, Pesticides and other Pollutants on Fisheries Resources in Nigeria. *Asian Journal of Fisheries and Aquatic Research*, *16*(5), 45-55.

23. Orowe, A. U., & Ikponmwen, E. G. (2022). Concentrations of polycyclic aromatic hydrocarbons (PAHs) in the African catfish (Clarias gariepinus) juveniles exposed to crude oil contaminated water. *Chemistry of the Total Environment*, *2*(1), 10-16.

24. Ireland, K. S., & Milligan-Myhre, K. (2021). Effects of crude oil on juvenile three spine stickleback somatic and immune development. *bioRxiv*, 2021-11.

25. Jha, S., & Dahiya, P. (2022). Impact analysis of oil pollution on environment, marine, and soil communities. In *Advances in Oil-Water Separation* (pp. 99-113). Elsevier.

26. Black, T. A., Hanson, M. L., Palace, V. P., & Rodriguez-Gil, J. L. (2021). Surface-dwelling aquatic insects in low-energy freshwater environments are highly impacted by oil spills and the surface washing agent Corexit EC9580A used in oil spill response. *Environmental Toxicology and Chemistry*, *40*(5), 1298-1307.

27. Hook, S. E., Strzelecki, J., Adams, M. S., Binet, M. T., McKnight, K., Golding, L. A., & Elsdon, T. S. (2022). The Influence of Oil-in-Water Preparations on the Toxicity of Crude Oil to Marine Invertebrates and Fish Following Short-Term Pulse and Continuous Exposures. *Environmental Toxicology and Chemistry*, *41*(10), 2580-2594.

28. Kababu, E., Angel, D. L., Sisma-Ventura, G., Belkin, N., Rubin-Blum, M., & Rahav, E. (2022). Effects of crude oil and gas condensate spill on coastal benthic microbial populations. *Frontiers in Environmental Science*, *10*, 1051460.

29. Ozhan, K. (2014). *Phytoplankton Response to South Louisiana Crude Oil Exposure: Determining Impacts at Individual, Community, Toxin Production, Enzymatic-Activity and Gene-Expression Levels*. Louisiana State University and Agricultural & Mechanical College.

30. Shai, Y., Rubin-Blum, M., Angel, D. L., Sisma-Ventura, G., Zurel, D., Astrahan, P., & Rahav, E. (2021). Response of oligotrophic coastal microbial populations in the SE Mediterranean Sea to crude oil pollution; lessons from mesocosm studies. *Estuarine, Coastal and Shelf Science*, *249*, 107102.

31. Putzeys, S., Juárez-Fonseca, M., Valencia-Agami, S. S., Mendoza-Flores, A., Cerqueda-García, D., Aguilar-Trujillo, A. C., & Pech, D. (2022). Effects of a light crude oil spill on a tropical coastal phytoplankton community. *Bulletin of Environmental Contamination and Toxicology*, *108*(1), 55-63.

32. Michael, C., Miller., Vera, Alexander., Robert, J., Barsdate. (2016). The Effects Of Oil Spills On Phytoplankton.

33. Michel, J., & Fingas, M. (2016). *Oil Spills: Causes, Consequences, Prevention, and Countermeasures. Fossil Fuels, 159–201.* doi:10.1142/9789814699983_0007

34. Osborne, O. E., Willie, M. M., & O’Hara, P. D. (2022). The effects of oil spill dispersant use on marine birds: a review of scientific literature and identification of information gaps. *Environmental Reviews*, *31*(2), 243-255.

35. Monti, F. (2020). Oil Contamination of Osprey (Pandion haliaetus) in the Mediterranean Sea: An Underestimated Threat for the Species?. *Journal of Raptor Research*, *54*(3), 322-325.

36. Ouyang, Z. (2023). Impacts of sea pollution on marine animals. *Theoretical and Natural Science*.

37. Wilson, R. R., Perham, C., French-McCay, D. P., & Balouskus, R. (2018). Potential impacts of offshore oil spills on polar bears in the Chukchi Sea. *Environmental pollution (Barking, Essex : 1987)*, *235*, 652–659. https://doi.org/10.1016/j.envpol.2017.12.057

38. Steven, A., Murawski., Martin, Grosell., Cynthia, Smith., Tracey, T., Sutton., Kenneth, M., Halanych., Richard, F., Shaw., Charles, R., Wilson. (2021). Impacts of petroleum, petroleum components, and dispersants on organisms and populations. Oceanography, 34(1):136-151. doi: 10.5670/OCEANOG.2021.122

39. Rodrigo, Almeda., Zoe, Wambaugh., Zoe, Wambaugh., Chao, Chai., Chao, Chai., Zucheng, Wang., Zucheng, Wang., Zhanfei, Liu., Edward, J., Buskey. (2013). Effects of crude oil exposure on bioaccumulation of polycyclic aromatic hydrocarbons and survival of adult and larval stages of gelatinous zooplankton. PLOS ONE, 8(10):74476-74476. doi: 10.1371/JOURNAL.PONE.0074476

40. Rodrigo, Almeda., Sarah, Baca., Sarah, Baca., Cammie, J., Hyatt., Edward, J., Buskey. (2014). Ingestion and sublethal effects of physically and chemically dispersed crude oil on marine planktonic copepods. Ecotoxicology, 23(6):988-1003. doi: 10.1007/S10646-014-1242-6

41. William, F., Patterson., J., Chanton., David, J., Hollander., Ethan, Goddard., Beverly, K., Barnett., Beverly, K., Barnett., Joseph, H., Tarnecki. (2020). The Utility of Stable and Radioisotopes in Fish Tissues as Biogeochemical Tracers of Marine Oil Spill Food Web Effects. 219-238. doi: 10.1007/978-3-030-12963-7_13

42. Waikhom, D., Ngasotter, S., Soniya Devi, L., Devi, S., & Singh, A. S. (2020). Role of microbes in petroleum hydrocarbon degradation in the aquatic environment: a review. *Int. J. Curr. Microbiol. Appl. Sci*, *9*, 2990-2903.

43. Radice, R. P., De Fabrizio, V., Donadoni, A., Scopa, A., & Martelli, G. (2023). Crude Oil Bioremediation: From Bacteria to Microalgae. *Processes*, *11*(2), 442.

44. Guidi, P., Bernardeschi, M., Scarcelli, V., Lucchesi, P., Palumbo, M., Corsi, I., & Frenzilli, G. (2022). Nanoparticled Titanium Dioxide to Remediate Crude Oil Exposure. An In Vivo Approach in Dicentrarchus labrax. *Toxics*, *10*(3), 111.

45. Gaur, V. K., Gupta, S., & Pandey, A. (2021). Evolution in mitigation approaches for petroleum oil-polluted environment: recent advances and future directions. *Environmental Science and Pollution Research*, 1-17.

46. Agyei-Tuffour, B., Gbogbo, S., Dodoo-Arhin, D., Damoah, L. N., Efavi, J. K., Yaya, A., & Nyankson, E. (2020). Photocatalytic degradation of fractionated crude oil: potential application in oil spill remediation. *Cogent Engineering*, *7*(1), 1744944.

47. Zahed, M. A., Matinvafa, M. A., Azari, A., & Mohajeri, L. (2022). Biosurfactant, a green and effective solution for bioremediation of petroleum hydrocarbons in

the aquatic environment. *Discover Water*, *2*(1), 5.

48. Onokare, E. P., Tesi, G. O., Odokuma, L. O., & Sikoki, F. D. (2022). Effectiveness and toxicity of chemical dispersant in oil spill aquatic environment. *Asian Journal of Water, Environment and Pollution*, *19*(2), 41-46.

49. Sun, X., Fu, H., Bao, M., Zhang, F., Liu, W., Li, Y., & Lu, J. (2023). Preparation of slow-release microencapsulated fertilizer-Biostimulation remediation of marine oil spill pollution. *Journal of Environmental Chemical Engineering*, *11*(2), 109283.