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REVIEW

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A review of oil spill dynamics: Statistics, impacts, countermeasures, and weathering behaviors

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Abstract

Oil spills pose significant threats to marine and freshwater environments, impacting ecosystems and drinking water sources. The present review incorporated an up-to-date statistical analysis of the oil spills globally including the types and sources of oil spills and the main habitats affected by the past incidents. It presented immediate and long-term effects on aquatic organisms and habitats highlighting the necessity for action to protect the aquatic environment. The paper also elucidated a range of effective remediation and cleanup methods, presenting a comprehensive toolkit to mitigate ecological damage. Noticeably, the review identified crucial knowledge gaps in the literature: (i) the absence of marine plastic pollution in studies on oil spill impacts and (ii) the absence of a modeling framework that considers the presence of microplastics in the spillage region and their impacts on the overall weathering rate. From synthesizing essential knowledge on oil spill dynamics and identifying the knowledge gap in the literature, this review aims to enhance understanding and guide future research.

KEYWORDS

aquatic ecosystems, crude oils, dispersion, evaporation, hydrocarbon, microplastics, oil spills, weathering

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1 | INTRODUCTION

Over the years, thousands of oil spills have occurred due primarily to massive transportation between the major oil-producing nations and the major oil consumers.[1] Oil spills include crude oils and a wide range of refined products such as diesel, gasoline, kerosene, lubricating oil, jet fuels, etc. Oil enters seawater via accidental spills or deliberate discharge.[2] Most frequently, marine environments are susceptible for the oil and petroleum product spillages; however, spills can occur in the lakes, on the shore, or in rivers that flow into the coastal waters.[3]

While oil spills on seawater can destroy marine lives, spills occurring on lakes, rivers, streams, estuaries, and wetlands can significantly cause the pollution of drinking water.[4] Some major oil spills on seawater include the Deepwater Horizon (DWH) oil spill (210 million gallons) in the Gulf of Mexico in April 2010, which became one of the largest offshore oil spills in the history of the United States, posing a catastrophic threat to the entire Gulf and Atlantic coastline,[5] which cost British Petroleum (BP) more than $60 billion[6] in cleanup costs and legal fees. Between the years 1992 and 2006, the US Outer Continental Shelf had experienced 39 blowouts.[7,8] The spill incident of approximately ∼ 4750 t of crude oils occurred on the northwest coast of Australia in August 2009, due to the blowout of the Montara H1 oil and gas well,[9,10] which cost Australia $319 million by November 2010 for cleanup expenses.[11] Before the Monatara incident, the Australian offshore industry had encountered six blowouts.[7,8] Spills Arctic Lake Pyasino and surrounding rivers experienced a diesel (fuel) oil spillage of 20 000 t in May 2020.[3] A large spill of 10 300–126 000 t of oil occurred in the Arctic zone of the Russian Federation as a result of a pipeline leakage in 1994. Subsequently, this oil spill entered the tributaries of the Pechora River, namely, the Kolva and Usa rivers.[12,13]

Once oil is released onto a water body, it can pose catastrophic damage to the vitality and balance of that environment. Each oil has a unique "fingerprint" chemical composition; thus, it is important to understand the petroleum chemistry of each oil spill to predict its hazard and determine suitable remediation approaches.[14] For example, numerous distinct toxic substances are reported in crude oil such as aliphatic and polycyclic aromatic hydrocarbons (PAHs), polar chemicals, heavy metals, and persistent volatile compounds.[15] PAHs are genotoxic and can cause cancer in both humans and animals by impairing liver and kidney function.[16] Once oil is released into a water body, various weathering processes take place including evaporation, dispersion, emulsification, dissolution, sedimentation, and oxidation, which significantly alter the properties of the oil over time.

Many studies have been published over the past few decades regarding oil spills and their environmental impacts are discussed in the next section. Noticeably, Ansell et al reported specific problems identified from their experience involving in more than 150 actual oil spills.[17] The paper also proposed effective response performance and equipment to the spillages. The review of Saadoun reported statistics on major oil spills and their impact on different marine habitats.[18] Keesing et al provided a statistical record of significant oil spills in Australia between 1970 and 2012, which focused the impact of marine oil spill on invertebrates and macrophytes. The review of Chen et al[19] investigated the response performance of the shoreline oil spills where different treatment approaches were analyzed. Lovindeer et al[20] conducted a thorough review of oil spill effects on marine sharks, seabirds, and mammals with data collection for the Salish Sea. Data presented by the International Tanker Owners Pollution Federation Limited (ITOPF)[21] organization can promote effective responses to marine oil spills.

While oil spills are occasional accidents, plastic pollution presents a pervasive global issue that affects human daily life. It involves vast quantities of plastic waste polluting rivers, landfills, and oceans, with 10–20 million tons of plastic ending up in the ocean every year.[22] An economic cost between US$3300 and 33 000 per ton of plastic was estimated based only on marine natural capital.[23] Importantly, plastic waste degrades to small fragments forming microplastics in oceans, which varies the fate of the spilled oil and poses severe ecological harm on marine ecosystem due to their widespread distribution and ability to bioaccumulate toxins.[24]

However, it is found that none of the above review studies on oil spills has discussed the presence of microplastics in the spillage region, which was reported to significantly affect the dispersion process of the spilled oil.[25] Two distinct global issues, that is, oil spills and microplastics in oceans, converge into a single scientific inquiry: the interaction between microplastic particles and spilled oil in water and its impact on the fate of oil spills. This is identified as crucial knowledge gap in the literature, which demands urgent research attention.

The present review aims to contribute to the literature by focusing on the following knowledge gaps: (i) an up-to-date review on statistics of type and sources of oil spills and impacts of oil spills on aquatic organisms and (ii) the weathering processes with the presence of microplastics, which is absent in the above review studies.

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2 | STATISTICS, IMPACTS, AND COUNTERMEASURES FOR OIL SPILLS

2.1 | Statistics

2.1.1 | Map of major oil spills

Oil spills can occur in different parts of the world. However, certain areas are prone to experiencing frequent spills due to their significant involvement in oil production, transportation, and related activities. Figure 1 depicts the magnitude of the oil spills recorded in aquatic environments globally. Most of the recorded spills can be attributed as large-scale oil spills. The Gulf of Mexico is a significant hub for oil exploration and production. As a result, it experienced several notable oil spills including the Ixtoc I oil spill (1979) and the DWH oil spill (2010), which released millions of barrels of oil into the sea water. According to the ITOPF, there is a downward trend in the frequency of oil spills per decade.[21]

2.1.2 | Classification for crude oil based on EPA

The oil industries classified crude oil into different groups based on its density as heavy or light and sulfur content as sweet or sour. Therefore, oil can be grouped into six categories such as heavy/sweet, heavy/sour, medium/sweet, medium/sour, light/sweet, and light/sour.[26] On the contrary, the Environmental Protection Agency (EPA) employs toxicity levels and alterations in oil states to classify oils (Table 1), which has gained much attention.[27] However, following US EPA classification can be subject to change for spilled oil as the behavior of crude oil and refined petroleum products in the environment is significantly influenced by climate and temperature in the water body. For example, class B oil might turn into class C oil as the volatiles evaporate, while class C oil may become class D if a significant temperature drop occurs. The class D oil can change back to a class C oil as it warms up. Typically, crude oil consists of four main hydrocarbon classes including saturates (i.e., alkanes), aromatics, asphaltenes, and resins.[28,29] In most cases,

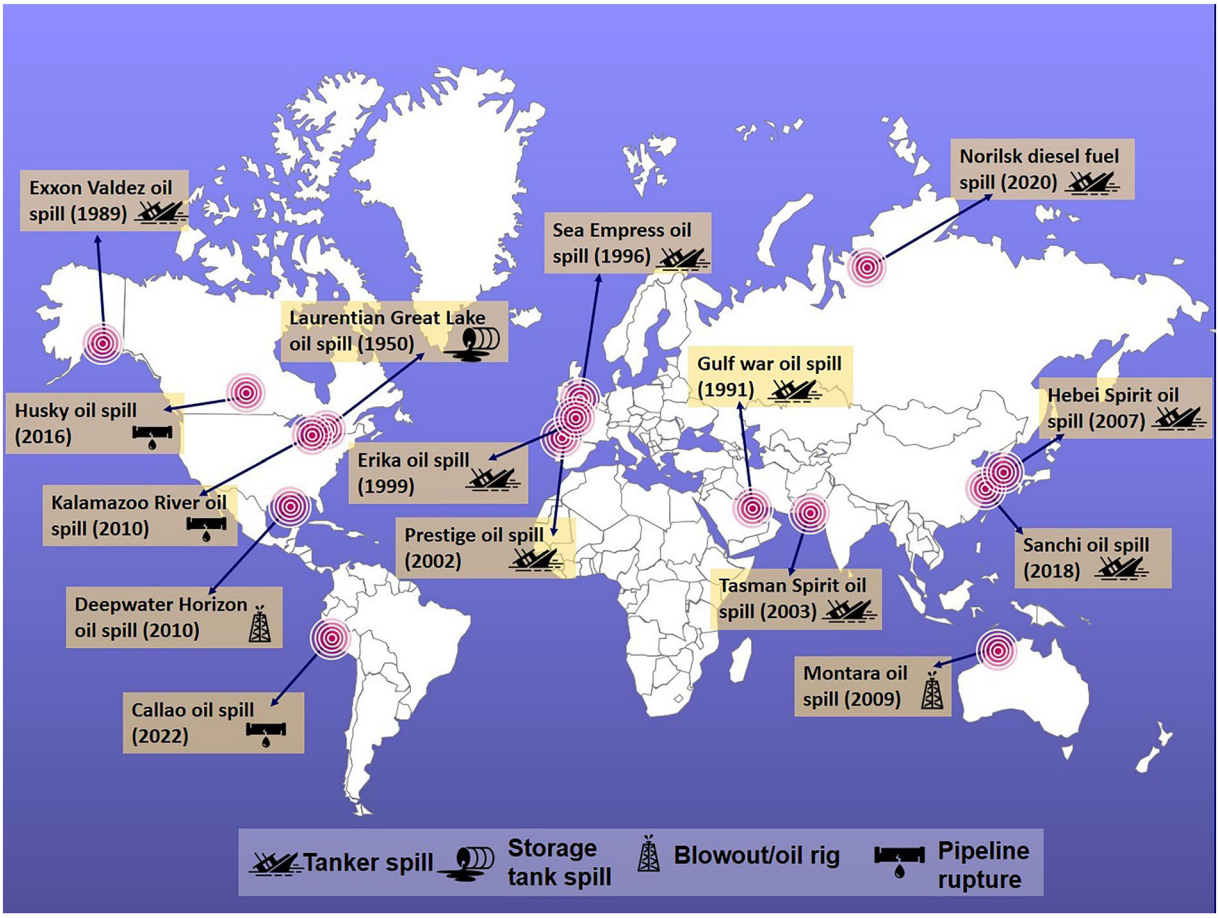


FIGURE 1 Significant oil spills occurred in aquatic environments recorded in the history.

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TABLE 1 Classification for crude oil based on EPA.[27]

Oil classification	Example	Remark
Class A oil (Light, volatile oils)	High-quality light crude oils Refined products such as gasoline and jet fuel	Light; easy spreading; strong odor, most toxic but least persistent
Class B oil (Non-sticky oils)	Lower-quality light crude oils Refined products such as kerosene and other heating oils	Less toxic than class A oils, more prone to adhering to surfaces, capable of causing prolonged contamination, highly flammable, and capable of burning for an extended duration compared to class A oils
Class C oil (Heavy, sticky oils)	Most types of crude oil Bunker B and bunker C fuel oils Residual fuel oils and medium to heavy crudes	Adheres strongly to surfaces; does not easily dilute and disperse
Class D oil (Non-fluid oils)	Residual oils Heavy crude oils Some high paraffin oils Some weathered oils	Solid and exhibiting minimal toxicity, these oils can melt when heated, forming a coating on surfaces that renders cleanup challenging
Non-petroleum oil	Synthetic oils Oils derived from plant or animal fats	Resistant to degradation and adept at infiltrating soil, these oils can inflict enduring harm on the affected area

saturates and aromatics are in greatest concentration in the crude oil.

2.1.3 | Types and sources of major oil spills

Oil spills can be classified into two primary sources: natural occurrences, like climatic events and geological processes, and human activities, such as drilling and transportation accidents. Natural oil spills result from phenomena like hurricanes and seismic events, while anthropogenic causes include negligence during drilling, deliberate spills, and transportation leaks. Human error accounts for an estimated 30%–50% of oil spills.[30] Numerous significant oil spill incidents are documented in Table 2.

The bar chart shown in Figure 2 presents an overall statistic of the reported oil spills from tanker incidents from 1979 until 2023. It is worth noted that a density of 900 kg/m^3 was used to estimate the amount of oil spill in tons for any data in volume reported unit. The data are highest in the period 1991–1995 due to the incident Gulf war in Kuwait Sea Island in 1991.

2.2 | Impacts of oil spills on aquatic organisms and their habitats

Oil spills in aquatic environments damage diverse microbial, flora, and fauna life, depending on toxicity in the oil. Chemicals in oil can enter organisms through different pathways, disrupting ecosystems and food chains.[72] Oil layers disrupt oxygen exchange, sunlight penetration, and phytoplankton photosynthesis, affecting marine productivity. Effects include direct lethal and sublethal impacts and indirect consequences.[73] A schematic picture of the impacts of spilled oil on aquatic ecosystems is sketched in Figure 3.

For immediate impacts, marine life faces immediate threats following oil spills, with certain species more vulnerable based on habitat depth.[74] Oil slicks on the water's surface disrupt underwater ecosystems, preventing sunlight penetration and harming sea plants and animals. Spilled oil primarily harms marine life through physical fouling, ingestion of toxic substances, and toxic effects from burning. These immediate impacts often lead to high mortality rates, reflecting the direct lethal effects of oil spills.[73] For instance, oil coating can immobilize bird wings and strip sea otters of their insulating fur,[75] increasing the risk of hypothermia. Many marine animals decease due to oil spills, which can disrupt their defense mechanisms. Notably, the *Exxon Valdez* spill (1989) killed thousands of seabirds, seals, and sea otters, while the Prestige spill impacted numerous bird species. Certain fish, like kelp greenling, develop liver abnormalities when exposed to oil, and pink salmon embryos face mortality after the Exxon Valdez incident. Sensitivity to oil varies by fish life stage, with salmon eggs being particularly vulnerable.[72] Planktonic species, especially those near the water's surface, face acute vulnerability to oil spills due to their proximity to concentrated oil compounds.[73] Zooplankton is generally more

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TABLE 2 Major reported incidents of oil spills in aquatic environments.

Spill name	Country/location	Date	Habitat	Oil type	Amount (tons except noted)	Cause/incident	Ref.
Atlantic Empress	Off Tobago, West Indies	1979 July	Marine	Crude oil	3.5 million barrels	Two-vessel collision	31
Po river	Po river, Italy	1980 Apr	Freshwater	Crude oil	663	Bursting pipeline	32
—	Shoal Creek, a Gasconade River tributary near Vienna, Missouri, USA	1988 Dec	Freshwater	Crude oil	3.3 ML	Pipeline rupture	33
Exxon Valdez	Prince William Sound, Bligh Reef, Alaska, USA	1989 Mar	Marine	Crude oil	41 ML	Ship hit a rock and grounding	34
Gulf war	Kuwait, Sea Island	1991 Jan	Marine	Crude oil	~1749 ML	Sinking of oil tankers	35
—	Cat Lai, Vietnam	1994 Oct	Port	Diesel Oil	~1864	Neptune ship collision with port	36
North Cape	Moonstone Beach, South Kingstown, Rhode Island, USA	1996 Jan	Marine	No. 2 fuel oil	2700	Wreck	37
Sea Empress	Milford Haven, UK	1996 Feb	Marine	Forties blend crude oil Heavy fuel oil	72 000 480	Grounding	38
Erika	North Atlantic Ocean, Brittany, France	1999 Dec	Marine	Crude oil	~ 22 ML	Vessel wreck	39,40
Jessica	Shiavioni reef at the entrance of Wreck Bay, Isla San Cristóbal, Galápagos	2001 Jan	Marine	Intermediate Fuel Oil 120 (IFO 120, or bunker fuel) Diesel oil #2	280 400	Grounding	41
Formosa One	Ba Ria-Vung Tau Province, Vietnam	2001	Bay	Diesel oil	~ 750	Collision between two ships	36
Prestige	Off Galicia, Spain	2002 Nov	Marine	Heavy fuel oil	63 000	Sinking of the 26-year-old, structurally deficient oil tanker	42
Tasman Spirit	Karachi Port, Pakistan	2003 Jul	Marine	Iranian light crude oil	35 000	Grounding	43
Jiyeh	Jiyeh power station, Lebanon	2006 Jul	Marine	Heavy fuel oil	15 000–20 000	Military attack	44,45

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TABLE 2 (Continued)

Spill name	Country/location	Date	Habitat	Oil type	Amount (tons except noted)	Cause/incident	Ref.
Kinder Morgan spill	Burnaby, British Columbia, Canada	2007 Jul	Estuarine	Albian heavy synthetic crude oil	0.224 ML	Pipeline rupture	46
Kerch Strait	Kerch Strait, Russia	2007 Nov	Marine	Heavy fuel oil	1300	Vessel wreck	47
Hebei Spirit	Coast of Taean, South Korea	2007 Dec	Marine	Crude oil (UAE Upper Zakum, Kuwait export crude, Iranian heavy crude)	12.547 ML	Collision between the oil tanker, MV Hebei Spirit and a barge carrying a crane	48
Pacific Adventurer	East of Cape Moreton, Queensland, Australia	2009 Mar	Marine	Bunker fuel oil	270	Damage of fuel tank and bunker tank due to a cyclone	49,50
Montara	Timor Sea off the northwest coast of Australia	2009 Aug	Marine	Crude oil	4000	Blowout	10,51
Deepwater Horizon (DWH)	Gulf of Mexico, USA	2010 Apr	Marine	Sweet crude oil	600 000	Oil drilling rig explosion	5,52
Kalamazoo River	Marshall, Michigan, USA	2010 July	Freshwater	Diluted bitumen crude oil (dilbit)	3.2 ML	Pipeline rupture	53
Xingang	Dalian Xingang, Yellow Sea, China	2010 July	Marine	Crude oil	1500	Oil tank explosion	54
Mumbai	Mumbai Harbour, India	2010 Aug	Marine	Fuel oil	800	Two-vessel collision	55
Bohai	Bohai Bay in China	2011 Jun	Marine	Oil	~0.115 ML	Blowout	56–58
The Texas City "Y" (TCY)	Galveston Bay near Texas City, Texas, USA	2014 Mar	Marine	RMG 380 (marine fuel oil/special bunker) oil	~0.636 ML	Vessel collision with the oil tank-barge	59
MV Marathassa vessel	English Bay (Vancouver), Canada	2015 Apr	Marine	Intermediate Fuel Oil 380	0.0028 ML	Leak in the ship's hull	60,61
Husky	North Saskatchewan River, Canada	2016 Jul	Freshwater	Heavy crude oil	0.225 ML	Pipeline rupture	62
Chennai	North of Chennai city in South India	2017 Jan	Marine	Heavy bunker fuel oil	75	Two-vessel collision	63

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TABLE 2 (Continued)

Spill name	Country/location	Date	Habitat	Oil type	Amount (tons except noted)	Cause/incident	Ref.
Agia Zoni II tanker	Saronikos Gulf (city of Athens), Greece	2017 Sep	Marine	Heavy fuel oil (group IFO 380)	500	Tanker sinking	64
Sanchi	Off Shanghai	2018 Jan	Marine	Iranian oil	136 000 t of condensate; 2000 t of fuel oil	Vessel collision tanker oil spill	65
Mysterious	Brazilian northeastern coast	2019 Aug	Marine	Crude oil	~5–12 ML	Unknown	66,67
Norilsk diesel	Norilsk, Krasnoyarsk Krai, Russia	2020 May	Freshwater	Diesel fuel	17 000	Fuel tank collapse	68
MV Wakashio	Reef of Point d'Esny, off the coast of Mauritius	2020 Jul	Marine	Very low sulfur fuel oils (VSLFO; <0.5% S)	1000	Vessel split into two and grounding	69,70
REPSOL or Callao	Off La Pampilla Refinery, in central Peru	2022 Jan	Marine	Crude oil	1460	Pipeline rupture	71

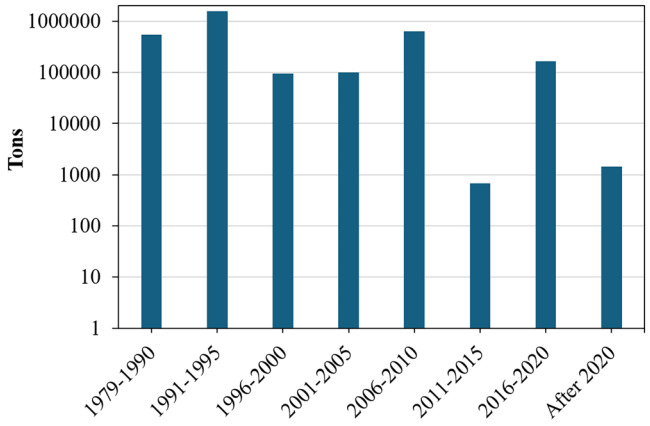


FIGURE 2 Quantities of reported oil spills from tanker incidents from 1979 to 2023. Density of 900 kg/m^3 was estimated for any reported data in volume unit

susceptible to oil pollution than phytoplankton, with observed mortality after oil spills like the Amoco Cadiz and Ixtoc I incidents.[76,77] Intertidal benthic organisms are at high risk of being coated and experiencing acute toxicity. Macroalgae and various invertebrates, including crustaceans and mollusks, often suffer high mortality rates.

Long-term ecological consequences of oil spills involve alterations in metabolism, growth, reproduction, behavior, and survival.[72] While not always fatal, these effects can impact the fitness of marine animals, known as sublethal effects.[78–80] In evaporation, the oils release carcinogens and aerosols, affecting air quality and potentially causing sublethal effects in sensitive seabirds. There are elevated aspartate aminotransferase (AST) levels in adult seabirds years after spills, indicating ongoing sublethal toxicity.[81,82] Inhalation exposure to oil mists disrupts wildlife hormonal systems. Even birds not directly in contact with oil may suffer from a contaminated diet, highlighting the need for comprehensive evaluation.[83] Research has found that egg-laying behavior of birds that have been exposed to oil contamination can cease or decrease the number of eggs. A little amount of oil exposure can affect the eggs' hatching ability. Contaminated birds can also pass oil to their offspring.[72] Long-term exposure of animals such as sea lions, seals, or walruses to the more volatile component of the oil when evaporating can result in permanent damage to their eyes.[72] Benthic communities can suffer acute toxicity for years, especially from sunken oil fractions. Indirect effects include habitat destruction, with recovery taking 1–3 years for most habitats and over a decade for mangroves.[84] Habitat loss can lead to starvation, impacting wildlife as severely as direct oil exposure. Oil toxicity can also disrupt the ecological balance, promoting algae

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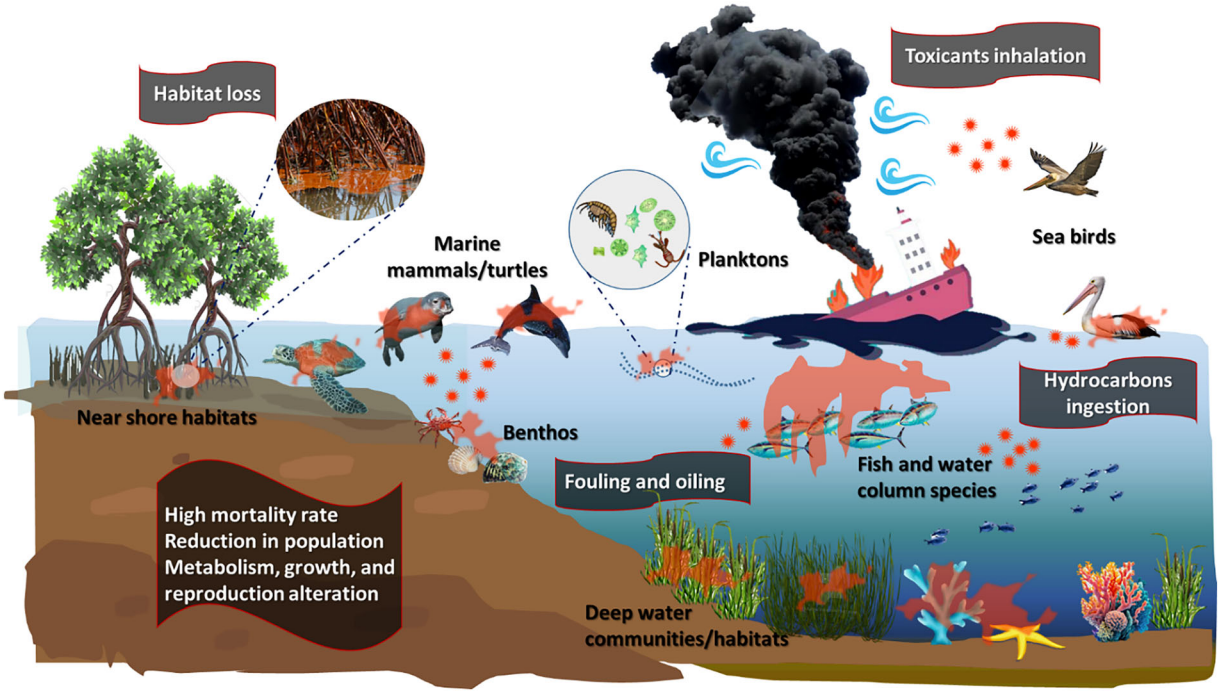


FIGURE 3 Schematic view of the impacts of spilled oil on aquatic ecosystems.

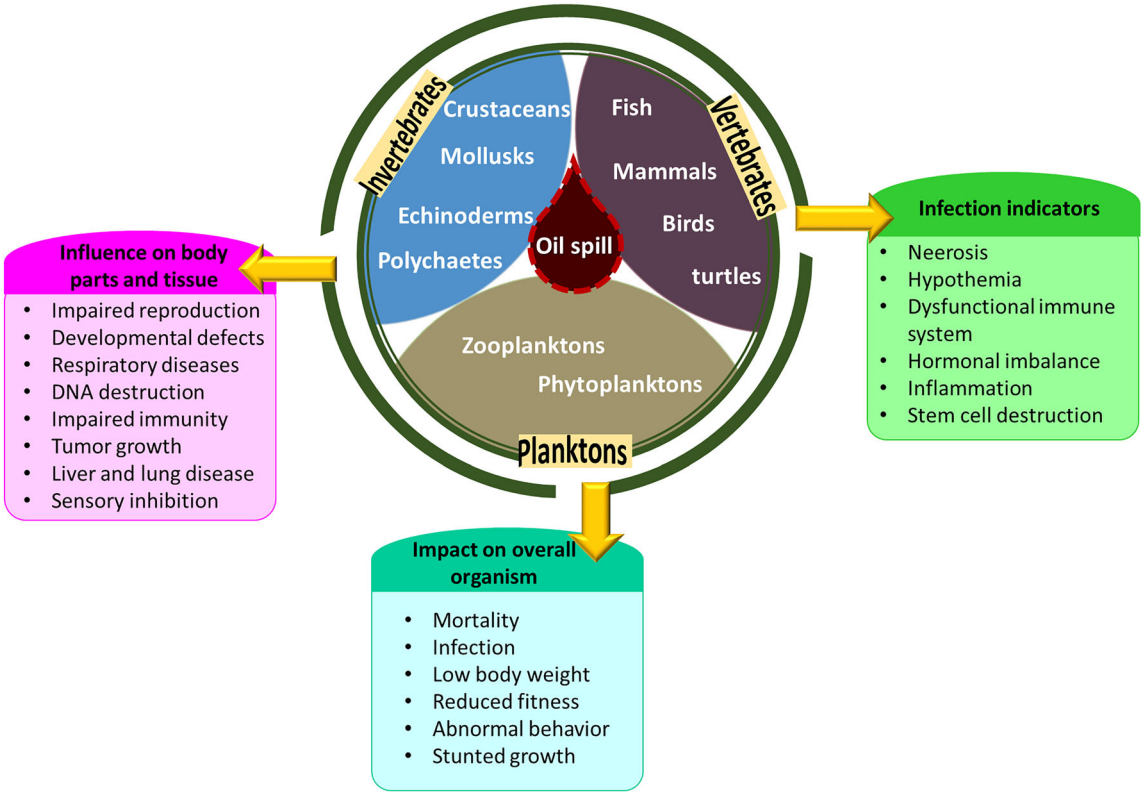


FIGURE 4 Classifications of the impacts on aquatic organisms. Data source from Adzigbli and Yuewen.[85]

growth and hindering organism recovery. A summary of the influence of oil spills on aquatic organisms is depicted in Figure 4.

Table 3 presents a summary of oil spill impacts on various aquatic species. It is clearly that there is no comprehensive study on the impacts of oil spills on aquatic

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TABLE 3 Impacts of oil spills on aquatic ecosystems.

	Species	Effect/impact	Ref.
Vegetation	Mangroves	Cause large diebacks and canopy gaps	86–88
		Seedlings death and leaf defoliation	89
	Avicennia marina and *Bruguiera gymnorrhiza*	Leaf wilting and aging, loss of foliage, malformed roots, diminished seedling survival rates due to suppressed seed germination, lowered efficiency of photosynthesis, ecological toxicity, and elevated mutation rates	90
Marine planktons	Phytoplankton and zooplankton communities	Bioaccumulation of oil-derived polycyclic aromatic hydrocarbons (PAHs) like anthracene, phenanthrene, and pyrene	91
	Scyphozoans and ctenophores	Sensitive to bioaccumulation	92
	Planktonic copepods	Immediate death, acute toxicity, diminished feeding, delayed egg laying, slow hatching, decreased swimming velocity, and reproductive irregularities	93,94
	Algal communities	Loss of species diversity and decrease in biomass	95
Benthic marine invertebrates	Amphipods	Irregularities in carbohydrate processing, elevated mortality levels, hindered growth affecting reproductive capabilities and hormonal rhythms, initiation of transcriptomic alterations	96
	Isopods, amphipods, and polychaete species	Decline in macroinfauna populations	97
	Grazers, amphipods, and isopods	Reduce in number of species and abundance	40
	Copepods	Reduced egg production, decreased rates of fecal pellet production, and hatching of eggs	98
	Mytilus galloprovincialis	Effects on biomarker, immune response, alteration of metabolism, failures of embryo-larval development, lower growth rates, and reduction in population abundance	80
	Marine crustacean	Impaired movement, reproductive failure, and death	85
Fish	Fish early life stages	Fish embryos are at risk even at very low concentrations of 0.5 μg/L, leading to lethal impacts including cardiac dysfunction, altered morphology like jaw and spinal curvature, abnormal kidney development, neural cell death, cardiotoxicity, heart circulation failure, and morphological imperfections	99,100
	Adult fish	Reduced aeration capacity, heart failures, decreased cardiovascular output, acute cardiotoxicity, and slower swimming speeds	101
		Decreased growth and feeding rates, genetic harm, mortality in fish eggs and larvae, heightened susceptibility to starvation, and impaired predator evasion	102
	Fish larvae	Decreased abundances, smaller larvae, elevated abnormality rates in embryonic development, spinal deformities, and yolk sac edema	103

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TABLE 3 (Continued)

	Species	Effect/impact	Ref.
Birds	Seabirds and shorebirds	Feather loss leads to drowning and hypothermia due to lost weatherproofing	104
	Migratory bird	Impairs flight, breeding, winter survival, and reproductive health. Feather coating damages navigation and flight, reduces insulation and buoyancy, leading to hypothermia and death	105
	Seabirds	Mass mortality, pathological lung, kidney, liver, and gland malformations, disruption of thyroid balance and metabolism, and immunotoxic anemia	106
	Shag and black guillemot	Reduced breeding numbers	107
	Birds	Wet feathers lose insulation, leading to death from cold; reduced mobility increases vulnerability to predators; cleaning interruptions cause starvation; coated feathers reduce buoyancy, leading to drowning; ingested oil causes intestinal lesions; clogged nostrils and throat can result in suffocation	108
	Yellow-legged gulls (*Larus michahellis*)	Sublethal toxicity in breeding	79
	South Polar skuas	Increased mortality rate among nestling, short-term disruption of normal parental attendance behavior	109
Mammals	Bottlenose dolphins (*Tursiops truncatus*)	Kidney abnormalities (hypoadrenocorticism, adrenal toxicity), lung diseases (alveolar interstitial syndrome, pulmonary masses), and widespread mortality	110
		Moderate to severe lung disease, underweight, excessive tooth loss, decreased survival and fecundity	111
Reptiles	Sea turtles	Toxic components smother and harm turtle eggs, affecting growing embryos	112
	Freshwater turtles (*Graptemys geographica*)	Decreases in population size and shifts in size distribution	53
Marine habitat	Coral reef	Tends to halt its growth, affecting invertebrates that rely on corals for survival	113
		Tissue loss and sclerite enlargement	114

organisms with the inclusion of marine plastic pollution, where with 10–20 million tons of plastic ending up in the ocean every year.[22] The plastic pollution itself is known to cause severe ecological harm to the aquatic environment due to their widespread distribution and toxin bioaccumulation.[24] Plastic waste degrades into microplastics in oceans. When these micro plastic particles interact with the oil droplets to form oil-plastic agglomerates, the impacts on marine organisms can be significantly worse, especially given the projected rapid rise in microplastic pollution in oceans. This is identified as a crucial knowledge gap in studies on the impact of oil spills on marine environment, which urgently requires further research.

2.3 | Countermeasures

Remediation and cleanup efforts are essential for mitigating the environmental impact and protecting affected ecosystems and coastal areas. Cleaning the spilled oil is difficult, depending on upon factors including the type of oil spilled, the types of waterfronts including shorelines, beaches, rivers, etc., and the weather conditions around the location. Remediation typically involves a combination of mechanical, chemical, and biological methods. These efforts aim to remove or break down the oil, restore affected ecosystems, and mitigate the long-term impact of the spill on marine life and coastal

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communities. The following sections provide a review of different remediation efforts which have been published in the literature.

2.3.1 | In situ burning

In situ burning, a common oil spill response method, targets removing oil slicks from water surfaces. It requires fresh oil with volatile hydrocarbons for ignition and specific environmental conditions for safety. Continuous monitoring controls the burn rate and emissions, although it releases smoke and PAHs, impacting air quality and posing health risks. Efficiency varies, with estimates around 85% for DWH and up to 95% for Exxon Valdez spills. Flame temperatures range from 900 to 1200°C.[115] In situ burning adheres to Clean Air Act regulations and EPA standards for air quality.

2.3.2 | Mechanical remediation

Common mechanical approaches for oil spill cleanup, known as physical methods, include booms, skimmers, vacuum trucks, adsorbent materials, and shovels. These methods[116–120] aim to remove oil without altering its properties. Booms are used to contain and control oil spread, but their effectiveness depends on sea conditions. Fence, curtain, and fire-resistant booms address different challenges. Skimmers, operating with booms, recover oil from the water surface without altering it. Oleophilic skimmers absorb oil efficiently, while non-oleophilic skimmers separate oil and water using gravity. Suction skimmers transfer oil to storage tanks but are less effective with dispersants or in rough seas. The efficiency from using skimmers depends on sea conditions and oil characteristics.

2.3.3 | Chemical remediation

Chemical remediation, alongside mechanical methods, mitigates oil spill impacts by controlling oil spreading. Dispersants, emulsion breakers, herding agents, surfactants, and solidifiers break down oil into smaller droplets, preventing large slick formation.[121] They contain surfactants, solvents, and stabilizers to maintain effectiveness and stability. Dispersants were heavily used during the DWH incident. Solidifiers, like polymer sorbents and cross-linking agents, turn spilled oil into a semisolid phase for easier removal.[122] However, solidifiers may lead to toxic secondary pollution and therefore are restricted on a large scale to avoid worsening environmental impacts.[123]

2.3.4 | Biological remediation

Bioremediation has been identified as one of the most effective methods in oil spill remediation, according to recent studies.[124] It involves microorganisms, often aided by dispersants or bio surfactants, to break down the oil.[125–127] Other techniques, including surface modification, immobilization, bio-augmentation, and bio-stimulation, have enhanced the efficacy of bioremediation,[128–132] offering a low-cost, energy-efficient alternative to chemical methods or burning. Bacteria and fungi are favored for their efficient hydrocarbon degradation. Despite its advantages, successful marine bioremediation requires addressing challenges such as adapting microorganisms to marine conditions and mitigating factors hindering their activity.

2.3.5 | Sorbent materials

Adsorbents, such as synthetic polymer-based materials, can efficiently remove oil spills by altering oil properties, making cleanup easier. They can be employed as a remediation technique for large oil spills or as a method to remove residual oil after using the above mechanical or chemical techniques.[133] Adsorbents include natural materials (such as rice husk, maple biochar, and gliricidia wood biochar) with limitations and synthetic ones with higher costs but superior performance. Polymer-based options, such as metal–organic framework (MOF) sponges and carbon nanotubes, offer high porosity, hydrophobicity, and chemical stability, making them effective and cost-efficient for oil spill cleanup.[134] Numerous studies have been conducted using adsorbent materials for oil spill removal, as shown in Table 4.

3 | CHARACTERISTICS OF OIL SPILL

3.1 | Weathering processes

Once the oil is released onto the water surface, it undergoes eight different weathering processes: spreading, evaporation, emulsification, dispersion, dissolution, oxidation, sedimentation, and biodegradation. Early in a spill, spreading, evaporation, emulsification, and dispersion dominate the mass balance of the oil. Next,

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TABLE 4 Oil spills remediation techniques.

Remediation techniques		Characteristics	Effectiveness/capacities	Ref.
Booms	Fence boom	Length 15 m height 8 m	Quick deployment; minimal space for storage	120
	Curtain boom	Length 150–500 m Diameter 100–500 m	Less affected by wind and currents	120
	Fire-resistant boom	Length up to 200 m	Burning area 1500 m^2 Tolerance >1000°C	119
Skimmers	Wire skimmers	Made of rotating drums, covered with oleophilic materials	Effective for low-viscosity oil	119,135
	Oleophilic skimmers	Wave resistant Hydrophobic nature	Removes >90%	136
	Suction skimmers	Operated with a vacuum mechanism	Removes all types of oils	136
Adsorbents	Micro-fibrillated cellulose fiber sponge	Excellent hydrophobicity Recyclability (30 times)	228 g/g[a]	137
	Populus seed fibers	Excellent hydrophobicity	182 g/g	138
	Hollow carbon fibers of natural cotton	Reusability up to 8 cycles	77 g/g	139
	Super-hydrophobic kapok fibers	Reusability up to eight cycles Up to 90% oil was removed	54.2 g/g	140
	Nanoporous polystyrene fibers	Higher sorption rate (within 15 min)	113.87 g/g	141
	Polypropylene fiber cut	Excellent hydrophobicity	48.4 g/g	142
	Polyvinyl alcohol formaldehyde sponges	Reusability up to 100 cycles	57 g/g	143
	Kapok fiber sponge	Excellent hydrophobicity Enhanced reusability	85 g/g	144
	CNT sponge	Excellent hydrophobicity	180 g/g	145
	Exfoliated vermiculite	Enhanced reusability up to 10 cycles	70.6 g/g	146

[a]The amount of adsorbate taken up by the adsorbent per unit mass of the adsorbent.

dissolution, oxidation, sedimentation, and biodegradation take place but do not play significant role on the fate of the oil but rather produce toxicity to the aquatic life. Throughout these processes, the oil undergoes various chemical breakdown and physical transformations.[147,148] Many of these processes occur simultaneously, causing difficulty in predicting the impact of each process individually.

3.1.1 | Evaporation

Considerable fraction of the spilled oil is lost due to the evaporation process where higher volatile components of the oil such as propane, hexane, and heptane evaporate in to the atmosphere first, leaving the less volatile components such as heavier hydrocarbons, bitumens, asphaltenes, etc., in the oil slick.[149,150] Lighter refined products such as gasoline or kerosene evaporate much faster than diesel or heavier hydrocarbons.

3.1.2 | Emulsification

Emulsification involves the incorporation of 60%–80% water to form a stable mixture known as an emulsion.[147] Water droplets are stabilized within the oil phase by amphiphilic molecules such as asphaltenes.[151] Development of water-in-oil emulsions contribute to persist in the maritime environment or along shorelines for a long time.[147] Emulsion considerably alters density and viscosity of the spilled oil. Much oil spilled into the environment eventually forms tarballs and brought ashore by waves and currents.[152]

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3.1.3 | Dispersion

Certain conditions such as water turbulence and wave enhance the efficacy and break up the spilled oil into small droplets.[153] The distribution and suspension of such droplets throughout the water column is referred to as the dispersion process. The microbes can more easily degrade the oil that has been dispersed.[154] Particularly, the dispersed oil can contaminate a broader range of marine life, which inhabit the sub-surface levels of the water.[155] Unlike other weathering processes, dispersion has no considerable impact on the physiochemical characteristics of the oil.[156]

3.1.4 | Dissolution

Dissolution is the process during which water-soluble components (contained in the spilled oil) from oil–water interface dissolve into the water body.[155] Dissolution rate depends on the oil's composition and the oil/water surface area. Similar to evaporation, the dissolution is accelerated by the spreading process, which increases the oil/water contracting area. Crude oils have a small content of water-soluble hydrocarbons. However, the oxidation tends to create highly hydrophilic groups such as phenol and hydroxyl, thus increasing the water solubility.[157]

3.1.5 | Photo-oxidation

Crude oil exposed to ultraviolet (UV) radiation usually undergoes oxidation through two processes, namely, photo-oxidation and microbial enzymatic oxidation (or biodegradation).[158] Photo-oxidation refers to the oxidation of petroleum hydrocarbons catalyzed by light, resulting in the formation of oxygenated products, which may possess more toxicity and water solubility than the original composition.[155,159] Nevertheless, the derivatives generated from photo-oxidation have more resistance to biodegradation and may persist in the ecosystem.[155]

3.1.6 | Sedimentation

Oil sorption to suspended sediments causes sedimentation, which causes the oil aggregates (flocs) that are denser than water to gradually sink out of the water column and deposit on the bottom.[158,160] Emulsification or dispersion causes alterations to the physical characteristics of oil.[155] The ingestion of this kind of oil flocs can cause toxicity issues for filter-feeding animals, whereas long-term consequences on marine biodiversity can arise when they accumulate on seabed.[161] A significant portion of the spilled oil by the DWH spill made its way to the seafloor through a substantial sedimentation characterized by the deposition of oil aggregates referred to as oil snow.[162]

3.1.7 | Biodegradation

Microbial oxidation, also known as biodegradation, is a process where microbes, primarily bacteria and fungi, break down the hydrocarbons in the oil and those derived from photo-oxidation into simpler compounds. Biodegradation takes place at the oil–water interface with the presence of oxygen. Warmer climate is favorable for microbial activities, thus prone to accelerate the breakdown process of the spilled oil, resulting in a high biodegradation rate. Marine waters host a diverse array of microorganisms capable of utilizing hydrocarbons as an energy source, leading to the partial or complete degradation of oil into water-soluble compounds, and producing carbon dioxide and water.

3.2 | Weathering rate and the presence of microplastics

Crude oils comprise hundreds of compounds ranging from less volatile components including heavy hydrocarbon, bitumen, asphaltenes, resins, and waxes to light or higher volatile components including gasoline, heptane, hexane, propane, etc.[150,163] Crude oil also contains various harmful components such as aliphatic and PAHs, polar chemicals, heavy metals such as nickel and vanadium, and volatile compounds (VOCs; e.g., benzene, toluene, ethylbenzene, or xylene) that exhibit persistent characteristics in the environment and are grouped under persistent organic pollutants (POPs).[15,113,164,165] These characteristics play a significant role on the fate of an oil spill.

The "weathering" processes cause the oil's physical and chemical properties to change over time. Among the above processes, evaporation, dispersion, and emulsification are identified as the primary contributors to the weathering rate. The behavior of these processes depends on various factors such as physical, chemical, and biological properties of the oil; the environmental and hydrometeorological conditions such as wave, winds, currents, water turbulence, air temperature, and humidity.

Studies on the prediction of evaporation are often conducted using empirical models, in which the

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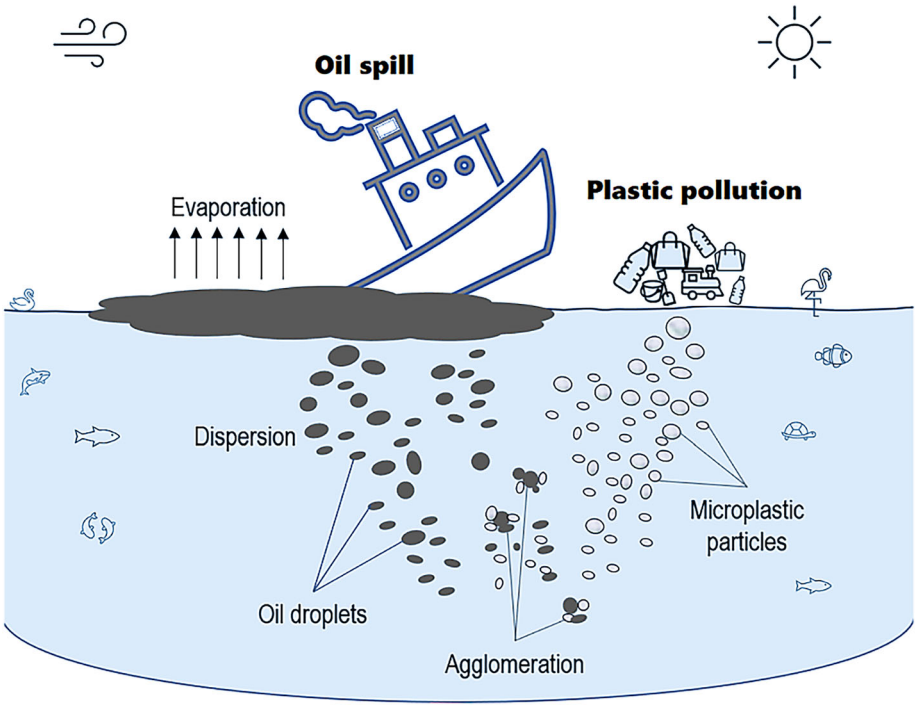


FIGURE 5 Oil spill weathering with the presence of plastic pollution.

experimental framework is similar to that of surface water evaporation.[166] According to many experimental studies of Fingas,[167,168] the evaporation rate of the rate of emulsion formation is exponential with respect to time. Gasoline can evaporate up to 90% within a day under warm weather. For diesel fuel, evaporation can reach about 60% in 3 days in warm water, whereas dispersion contributes to a large extent in turbulent waters. Light crude oil evaporates about 40% in 2 days and disperses depending on saturate content. For heavy crudes, evaporation can reach about 15% with negligible dispersion due to high asphaltene and resin content. Residual oils experience minimal evaporation and limited natural dispersion due to their composition. More than half of the light cargo oil (diesel) spilled during the grounding of the fuel tanker Jessica at Galapagos Islands in 2001 evaporated due to high solar radiation, leaving behind only patches of the remaining fuel oil from the cargo.[41,159] Approximately 30% and 40% of the spilled oil were lost due to evaporation during Exxon Valdez oil spill (1989) and Amoco Cadiz oil spill (1978), respectively.[159] Similarly, at least 25% of spilled oil by the DWH incident is estimated due to evaporation or dissolution.[169]

Obviously, dispersion plays a significant role in the overall weathering rate of oil spills. It also occurs during the evaporation process, which is known to contribute the most to the fate of an oil spill. Studies on the oil spill evaporation and dispersion model are well developed, as recorded in the recent comprehensive review paper.[170] The widely used weathering rate model utilizes a computer software package called Automated Data Inquiry for Oil Spills (ADIOS), available on the website of the National Oceanic and Atmospheric Administration (NOAA) of the United States. The program can be employed to predict evaporation and dispersion rates, requiring a range of conditional inputs and characteristics of the spilled oil. However, none of the published oil spill models have accounted for the influence of microplastics even though recent research has shown that the interaction between oil and microplastics (to form oil–plastic agglomerates) significantly alters the dispersion behavior, as sketched in Figure 5.

Gui et al[171] reported a considerable increase in the dispersion rate of microplastic particles with the presence of oil in seawater. A recent publication by Yang et al[172] proposed that the interaction between oil droplets and microplastics results to reducing efficiency of oil dispersion. Yang et al[173] found that the agglomerates formed by oil and microplastic considerably reduced the dispersion efficiency over a range of turbulence mixing energy levels of the water body and its salinities. Yan and Tan[174] reported the absorption behavior of oil varying with different types of plastics and temperatures of the seawater. The experimental study[175] of Gao et al reported that increasing salinity from 15% to 35% resulted in a 10% and 13% increase in oil dispersion rate, while raising the seawater temperature from 10 to 25°C led to respective increases of approximately 16% and 13% in dispersion rate for polyethylene and polystyrene microplastics. It is noted that these studies only reported the impact of

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microplastics on the dispersion behavior of either the oil droplets or the oil–microplastic agglomerates. Dispersion can occur simultaneously with evaporation, which plays the utmost role in the fate of an oil spill. However, there is no study investigating the impact of microplastics on the overall evaporation rate of the oil slick.

With the above research evidence, the limitation in the weathering modeling framework on the absence of microplastic could render the existing prediction tools inaccurate, considering the anticipated rapid increase in microplastic pollution in oceans in the near future.[176]

The presence of microplastic particles introduces a new layer of complexity to the evaporation and dispersion dynamics of spilled oil. Understanding how these particles interact with oil droplets and influence the overall weathering rate is crucial for effective spill response strategies to mitigate adverse environmental and ecological impacts. Future study is expected to quantitatively assess the variation in evaporation and dispersion rates due to the presence of microplastics across real-world concentrations.

4 | CONCLUSION

In conclusion, this present review provided an up-to-date statistical analysis of oil spills, identifying the oil types, leading causes, locations, and the main affected habitats of the past incidents globally. The review identified the devastating consequences of spilled oil on aquatic organisms and their habitats, from immediate impacts to long-term ecological ramifications, emphasizing the imperative need for action in protecting the aquatic environment. The review also elucidated the commonly used remediation and cleanup methods, presenting a comprehensive toolkit to mitigate ecological damage. Discussion on various weathering process taking place simultaneous was presented, causing difficulty in predicting the impact of each process individually. The review identified the absence of microplastics in studies on the impact of oil spills on marine organisms and the absence of a modeling framework that includes the impact of microplastic particles on the weathering rate, which could potentially cause existing prediction tools inaccurate. These identified knowledge gaps suggest an urgent need for corresponding research on oil spills in the presence of microplastics.

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