INTERNATIONAL JOURNAL OF RESEARCH AND TECHNOPRENEURIAL INNOVATIONS
(IJRTI)

P-ISSN: 3043-5722; E-ISSN: 3141-270X
Volume 3 Issue 1 (April 2026)

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E-mail: centralinstumentlaboratory@uniport.edu.ng
Website: www.ijrti.com.ng; https://ciluniport.com.ng/
https://doi.org/10.60787/ijrti.vol3no1.86

A Review on Advancement in Technological Innovation of Crude Oil Spill Identification and Remediation

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Dates: Received: 28 March 2026; Revised: 24 April 2026; Accepted: 28 April 2026

To cite this article:
Kpaduwa, S., Chukwu, N.P., Oritsebinone, E.I. and Amakoromo, T.E. Review on Advancement in Technological Innovation of Crude Oil Spill Identification and Remediation. *International Journal of Research and Technopreneurial Innovations*, 2026; 3(1): 143-160

Keywords:
Crude oil spill, Oil spill identification, Oil spill remediation, Technological innovation, Remote sensing, Bioremediation, Oil spill detection.

ABSTRACT

Petroleum spills constitute one of the gravest environmental challenges confronting marine and terrestrial ecosystems worldwide, carrying substantial economic and social ramifications. Although spill frequency has shown considerable decline in recent decades with incidents exceeding 700 tones decreasing by roughly 90% since 1970. The persistent threat of catastrophic events remains evident, exemplified by the 2010 Deepwater Horizon incident that discharged approximately 600,000 tons of petroleum into Gulf of Mexico waters. This review examines the evolutionary trajectory of technological innovations spanning historical, contemporary, and emerging approaches to oil spill detection and remediation. Detection methodologies have progressed from conventional remote sensing techniques toward sophisticated integrated multi-sensor platforms incorporating Synthetic Aperture Radar (SAR), UAV-mounted hyper spectral imaging, fluorescence-based imaging coupled with deep learning algorithms, and artificial intelligence-enabled data synthesis. Remediation strategies have similarly advanced, with conventional mechanical and chemical approaches now complemented by emerging biotechnological solutions. Particular emphasis is placed on next-generation sorbent materials demonstrating remarkable performance metrics, including polycaprolactone-based porous sorbents achieving absorption capacities of 45 g/g with reusability exceeding 15 cycles, alongside biochar-supported Fe_3O_4 nanoparticles enabling enhanced biodegradation capabilities.

1. INTRODUCTION

Petroleum remains one of the primary non- renewable energy resources globally and serves as a foundation for modern industrial and economic development. However, activities associated with the petroleum industry; including exploration, extraction, transportation, refining, and storage, present significant environmental risks due to the potential release of hydrocarbons into surrounding ecosystems [1],. Oil spills are defined as the accidental discharge of crude oil, refined petroleum products, or other hydrocarbon substances into terrestrial or aquatic [2].

Oil spills are among the most harmful environmental disasters because they can cause extensive ecological damage, particularly to marine and coastal ecosystems. These incidents threaten biodiversity, disrupt food chains, affect human health, and negatively impact economic activities such as fisheries and tourism [3]. Although marine environments are commonly affected, oil contamination can also occur on land through pipeline failures, storage tank leaks, transportation accidents, and industrial activities, leading to long-term environmental degradation (International Maritime Organization, 2020).

Principal causes encompass offshore drilling mishaps, pipeline system failures, tanker collisions, leaks from industrial installations, and acts of sabotage [4]. The historical record of oil spills extends to the early twentieth century; however, landmark incidents including the 1989 Exxon Valdez spill, the 2010 Deepwater Horizon catastrophe, and the 1983 Castillo de Bellver incident have starkly demonstrated the imperative for robust containment and response frameworks [5]. The Deepwater Horizon event alone released approximately 4.9 million barrels (780,000 cubic metres) of crude oil into the Gulf of Mexico, inflicting extensive ecological devastation and economic losses amounting to billions of dollars. Similarly, thes Exxon Valdez spill contaminated over 1,300 miles (2,100 kilometres) of coastline, resulting in mortality among thousands of marine organisms and persistent damage to fisheries. These catastrophic occurrences have catalyzed substantial advances in oil spill containment and response technologies. While conventional approaches such as mechanical recovery (booms and skimmers), chemical dispersant application, and bioremediation remain widely employed [6]. Contemporary innovations, including nanotechnology-based absorbents, magnetic separation techniques, and AI-enabled spill monitoring are significantly enhancing response efficiency and speed. The effectiveness of oil spill countermeasures depends on multiple variables, including the nature and volume of oil released, meteorological conditions, oceanographic currents, and response timeframes [7]. An effective spill response system necessitates integration of early detection technologies, rapid deployment of containment measures, and comprehensive environmental restoration strategies. The imperative for enhanced oil spill response has additionally driven international regulatory frameworks, notably the International Convention on Oil Pollution Preparedness, Response and Cooperation (OPRC 1990) and the U.S. Oil Pollution Act (1990), which mandate stringent prevention and response measures [8]. As petroleum exploration and transportation continue expanding particularly into offshore Arctic regions and deep-sea drilling sites, oil spill risks are anticipated to increase commensurately, underscoring the critical importance of sustained research and innovation in spill containment and response.

2. LITERATURE REVIEW

Oil spill containment and response encompass an integrated combination of mechanical, chemical, and biological approaches designed to prevent, control, and mitigate the impacts of discharged oil on marine and terrestrial environments. Technological advancements over recent decades have substantially enhanced the efficiency of these methods, reducing response times and improving oil recovery rates.

2.1. Origins and Classification of Oil Spills

Oil spills arise from diverse natural and anthropogenic factors, including [9]:

a) Tanker Incidents: Collisions and groundings involving oil tankers can precipitate massive spills, such as the 1989 Exxon Valdez disaster, which discharged 260,000 barrels of crude oil into Alaskan coastal waters.
b) Pipeline Ruptures: Corrosion, mechanical damage, or operational errors can cause pipeline failures. The 2017 Keystone Pipeline spill released 210,000 gallons of oil in South Dakota following a pipeline rupture.
c) Offshore Drilling Accidents: Blowouts, explosions, and equipment failures during offshore drilling operations have produced some of history's largest spills, including the 2010 Deepwater Horizon catastrophe, which released approximately 4.9 million barrels of oil into the Gulf of Mexico.
d) Sabotage and Unauthorised Discharges: Oil infrastructure in certain regions, notably Nigeria's Niger Delta faces frequent vandalism, causing extensive environmental pollution.
e) Natural Phenomena: Hurricanes, earthquakes, and extreme weather events can damage oil platforms and storage facilities, resulting in leaks.

2.2. Oil Spill Categorization by Magnitude

Oil spills are classified according to volume and potential impact:

1. Minor Spills: Less than 25 barrels in inland waters or less than 250 barrels on land; offshore or coastal discharges that do not threaten public health or welfare.
2. Medium Spills: 250 barrels or less in inland waters or 250 to 2,500 barrels in offshore and coastal waters.
3. Major Spills: Over 250 barrels in inland waters or offshore/coastal waters.
4. Catastrophic Spills: Uncontrolled well blowouts, pipeline ruptures, or storage tank failures posing imminent threats to public health or welfare.

2.3. Classification by Type and Location

Oil spills can be categorized based on the following criteria [10].

2.3.1. Oil Type Classification:

a) Light Crude: Rapidly spreads and evaporates but exhibits high toxicity.
b) Heavy Crude: Less volatile yet persists in the environment and proves difficult to clean.
c) Refined Products: Gasoline, diesel, and lubricants present unique challenges due to their distinct chemical properties.

2.3.2. Spill Location Classification:

a) Offshore Spills: Affect marine ecosystems, fisheries, and coastal economies.
b) Onshore Spills: Contaminate soil, groundwater, and agricultural land.

2.3.3. Size and Extent Classification:

a) Small-scale Spills (<100 barrels): Typically, containable using conventional methods.
b) Large-scale Spills (>10,000 barrels): Require advanced response strategies.

2.4. Chemical Composition of Crude Oil

Crude oil comprises organic compounds, heteroatom species (sulphur, nitrogen, oxygen), hydrocarbons (carbon and hydrogen), metallic elements (nickel, vanadium, iron), and inorganic compounds (sodium, calcium, chloride). Hydrocarbons compounds composed solely of carbon and hydrogen constitute the largest group of organic compounds in petroleum, potentially encompassing several thousand distinct hydrocarbon species. Hydrocarbon compounds conform to the general formula C_xH_γ, where x and y represent integer values.

Hydrocarbons are broadly categorized into four groups: (1) paraffin's, (2) olefins, (3) naphthalene's, and (4) aromatics. Among these groups, paraffin's, olefins, and naphthalene's are sometimes collectively termed aliphatic compounds, distinguishing them from aromatic compounds. The lightest hydrocarbon occurring as dissolved gas is methane (CH_4), the primary constituent of natural gas. Olefins are not typically found in crude oils but are generated through various refining processes.

2.5. Crude Oil Fingerprinting Methodology

The "oil fingerprinting" process involves disassembling crude oil into its constituent components using analytical procedures based on the sample's unique chemical composition, enabling identification of specific oil samples. This technique has been historically employed to trace the origins of crude oil or petroleum spills. Following sample preparation, whole oil gas chromatography employing GC-FID on both the spilled oil and suspected source oils initiates the chemical fingerprinting analysis in laboratory settings. Any differences between the two oils become apparent through this procedure. The resulting data established a foundation for sample characterization by calculating the total carbon range of the spilled oil and generating acyclic isoprenoid ratios readily assessable through GC-FID (total hydrocarbon distribution including n-alkanes C10-C40). The total carbon range of the spilled oil was thereby identified.

2.6. Petroleum Fingerprinting Analytical Techniques

Numerous analytical techniques have been employed for source identification and oil fingerprinting, including thin layer chromatography (TLC) [11]. Among these methods, gas chromatography-based approaches (GC-MS and GC-FID) predominate due to their superior sensitivity, selectivity, resolution, and isotopic biomarker identification capabilities, providing enhanced oil fingerprinting tools. Comprehensive quality assurance and quality control procedures have optimized analytical data accuracy and precision, while advances in computer technology have augmented laboratory data processing capabilities. [12]., employed a combination of multi-statistical analysis, gas chromatography-flame ionization detection, and gas chromatography-mass spectrometry to identify the source of an oil leak in China's Bohai Sea. Additionally, [13]., conducted compositional analysis utilising GC-FID to investigate an oil spill in the Niger Delta (Agbada-1) using fingerprinting technology. The investigation revealed that the leaked oil originated from the same source as the hydrocarbon contamination, with substantial hydrocarbon contamination identified in the vicinity. Numerous evaluations of analytical techniques for oil hydrocarbon characterisation and differentiation have been published, synthesising findings from multiple earlier investigations [14,11].

Alternatively, aromatic compound analysis may be enhanced using gas chromatography coupled with mass spectrometric detection (MSD), particularly when operated in selected ion monitoring (SIM) mode. This approach provides more detailed compound identification and enables detection of compounds present in complex matrices at very low concentrations, provided the target compound possesses a prominent fragment ion at a mass distinguishing it from other hydrocarbon compounds [15].

2.7. Oil Spill Characterisation and Source Attribution

Characterisation refers to the process of identifying oil's distinctive attributes distinguishing it from other oils, encompassing physical and chemical property determination through source examination. Subsequent research may be conducted in laboratory, mesoscale, or field settings to investigate how oil properties change upon environmental exposure and weathering processes following discharge. Characterization constitutes a vital instrument in operational practice and contingency planning, proving valuable in accidental environmental releases.

Oil characterization using fingerprinting methods is crucial in environmental release scenarios for the following reasons:

- Understanding oil properties facilitates both rapid response decision-making and ensures response effectiveness.
- Physical and chemical property data enables informed estimation of environmental damage and ecological impact.

Recent instrumentation hardware and software advances, combined with enhanced understanding of chemical processes in terrestrial and aquatic environments, have led to widespread adoption of target hydrocarbon fingerprinting methods [16]. Key analytes include chemical biomarkers such as steranes and triterpanes, alongside specific saturated hydrocarbons, n-alkanes, and isoprenoids. Alkyl homologues of principal PAHs, sulphur-heterocyclic aromatic hydrocarbons, nitrogen heterocyclic aromatic hydrocarbons, oxygen heterocyclic aromatic hydrocarbons, total petroleum hydrocarbons, carbon isotopes, and product additives also play significant roles in hydrocarbon fingerprinting processes.

3. HISTORICAL APPROACHES TO OIL SPILL IDENTIFICATION AND REMEDIATION

3.1. Early Identification Methods: Sensory and Physical Property Analysis

Prior to the advent of sophisticated laboratory techniques, oil spill identification relied predominantly on direct human observation. Experts would visually examine oil appearance, noting color, thickness, and characteristic sheen patterns on water surfaces. The distinctive olfactory properties of various crude oils provided additional identification clues, as different petroleum sources possess unique chemical signatures detectable by odour. Early investigators also conducted basic physical tests measuring density, viscosity, and boiling point ranges to distinguish between oil types [17].

3.1.1. Visual and Olfactory Inspection

The initial line of defense comprised simple observation. Experts would document oil appearance (color, thickness, sheen), odour (different crude oils exhibit distinct smells), and behavior on water surfaces. For instance, "rainbow sheen" indicates a very thin layer, while darker, thicker patches suggest heavier, more weathered oil. This constituted the initial "fingerprint" prior to any testing.

3.1.2. Basic Physical Property Testing

Following sample collection, earliest laboratory tests aimed to measure fundamental physical characteristics, including density (relative weight compared to water), viscosity (thickness or flow resistance), and boiling point range. Comparing these properties against known reference samples enabled analysts to make preliminary judgments regarding oil type, distinguishing between light diesel and heavy bunker fuel.

3.1.3. Advent of Chromatographic Fingerprinting

The mid-twentieth century development of gas chromatography (GC) revolutionized oil spill identification. Early GC techniques represented the first powerful "molecular fingerprinting" tools, functioning by vaporizing an oil sample and passing it through a long, coiled column that separated the mixture into individual hydrocarbon components. The resulting peak pattern on a chart recorder chromatogram functioned as a unique fingerprint for specific oil types, enabling analysts to match unknown spill samples to suspected sources with unprecedented accuracy [18].

3.1.4. Gas Chromatography/Mass Spectrometry Integration

The combination of gas chromatography with mass spectrometry (GC/MS) represented a significant advancement in forensic oil spill identification. This integrated approach utilizes retention indices, relative response factors, and diagnostic ratios to identify and quantify pollutant compounds. Kao *et al*. [18] demonstrated that this methodology effectively distinguishes among gasoline and diesel oil products in commercial markets and establishes linkages between pollutant sources and contaminated environmental samples, even for aged spills with significant weathering effects.

3.2. Early Remediation Methods

Prior to the development of bioremediation or advanced chemical dispersants, cleanup efforts were largely mechanical and physical, focusing on containing and removing concentrated oil.

3.2.1. Mechanical Containment and Recovery

This approach remains the primary response for bulk oil removal.

Containment Booms: Floating barriers called booms served as the primary method for controlling oil spread. During the 1989 Exxon Valdez response, responders ultimately deployed more than 100 miles of containment boom of various designs to corral free oil on open water before it reached sensitive shorelines [19]. These booms were strategically positioned to prevent oil migration and concentrate slicks for recovery.

Skimmers and Recovery Devices: Following containment, various skimming devices removed oil from the water surface. These ranged from simple suction hoses and floating weirs to more complex oleophilic (oil-attracting) belt, disc, or drum skimmers that collected oil for subsequent scraping into collection barges [19],. Recovered oil required transfer to temporary storage pending final disposal.

3.2.2. Natural Sorbent Materials

Before widespread availability of synthetic sorbents, response crews utilised readily available natural materials to absorb spilled oil. Research has systematically evaluated numerous natural sorbents for crude oil and diesel cleanup effectiveness [20].

Types of Natural Sorbents: Natural organic sorbents include peat moss, straw, hay, sawdust, ground corncobs, feathers, wool, and other carbon-based products. These materials primarily function as absorbents, drawing oil into their structure; many can be wrung out for reuse or biodegrade after use. Natural inorganic sorbents consist of clay, perlite, vermiculite, glass wool, sand, and volcanic ash, typically functioning as adsorbents with oil adhering to external surfaces [21].

Comparative Effectiveness: Experimental studies comparing various natural sorbents for crude oil and diesel spill cleanup identified peat as the most suitable material for oil spill response on water surfaces [22]. Wool-based sorbents have also demonstrated particular merit due to natural availability, sustainable sourcing, and excellent absorption capacity, especially those formed from long fiber. The Lagergren model has been adapted to predict the time interval required for sorbents to achieve maximum sorption capacity, providing a decision support tool for response operations.

3.2.3. In-Situ Burning

Under controlled conditions, contained oil can be ignited and burned directly on the water surface. This method rapidly removes large oil volumes by converting them to combustion byproducts. Effectiveness requires specific conditions, including sufficient oil thickness (typically >2-3 mm), appropriate weather conditions, and fire-resistant booms to contain burning oil [23]. While highly effective for oil removal, in-situ burning produces significant smoke plumes, requiring careful assessment of tradeoffs between water and air quality impacts.

3.2.4. Shoreline Cleanup Techniques

On beaches and rocky coastlines, early remediation efforts relied heavily on manual labour. Workers physically excavated and removed oiled sand and gravel, or used buckets, rags, and low-pressure hoses to wipe or wash oil from rock surfaces. The Exxon Valdez spill provided critical lessons about cleanup effectiveness: responders learned that high-pressure, hot water washing of gravel beaches actually increased injury to plants and animals and may have contributed to lingering oil deposits (National Oceanic and Atmospheric Administration [24]. This discovery led to more refined, less destructive shoreline treatment approaches.

4. CONTEMPORARY OIL SPILL IDENTIFICATION TECHNOLOGIES

Effective oil spill response begins with rapid, accurate detection and characterization. The past decade has witnessed significant advances in remote sensing technologies, progressing from single-sensor platforms toward integrated, multimodal systems enhanced by machine learning algorithms.

4.1. Satellite-Based Observation Technologies

Satellite remote sensing has become indispensable for large-scale oil spill monitoring, offering synoptic coverage and repeat-pass capability. Among available technologies, Synthetic Aperture Radar (SAR) has emerged as particularly valuable due to its all-weather, day-night operational capability [25].

SAR operates by transmitting microwave pulses and analyzing backscatter from the sea surface. Oil slicks dampen capillary waves, reducing backscatter and appearing as dark patches against brighter surrounding water. This physical principle enables reliable detection regardless of cloud cover or illumination conditions, a critical advantage in marine environments where optical sensors may be obstructed. The damping of ocean waves by surface films has been extensively characterized, with slick-covered areas exhibiting significantly reduced radar return compared to clean water surfaces [26].

Recent evaluations indicate that SAR-based detection is recommended for regions with high sea states or persistent cloud cover, while neural network-based methods show particular effectiveness in high-risk areas requiring rapid response [27]. The integration of multi-sensor data combining SAR with optical and thermal infrared imagery has demonstrated promise in enhancing detection accuracy and reducing false positives from lookalikes (e.g., biogenic films, low wind areas).

4.2. Multimodal Fusion of SAR and Hyperspectral Imagery

While SAR provides excellent wide-area detection capabilities, it shows significant variance in distinguishing thin from thick oil, with accuracy discrepancies of approximately 6.41–56.98% depending on oil layer characteristics (Liu et al., 2025). Conversely, hyperspectral imagery (HSI) excels at identifying various oil types through characteristic absorption features in the shortwave infrared region (1000–2400 nm) corresponding to C-H bond vibrations, although HSI exhibits limited generalisation capabilities compared to SAR, as evidenced by Kappa reductions of approximately 7–45% when applied to unseen conditions [28].

To address these complementary limitations, researchers have developed multimodal fusion approaches combining the strengths of both sensing modalities. The SAR and HSI fusion network (SHNet) represent a significant advancement, achieving superior performance in oil type discrimination and overall oil spill detection through hierarchical feature extraction from both modalities [29]. This approach suggests that while SAR imagery remains optimal for rapid, large-scale detection, the fusion of HSI and SAR data provides more precise oil type estimation within identified spill areas.

4.3. Fluorescence Imaging and Deep Learning for Real-Time Assessment

Traditional oil spill assessment methods, including gas chromatography-mass spectrometry (GC/MS), satellite imaging, and visual surveys, face significant limitations. GC/MS requires costly, time-intensive sample collection and laboratory analysis, while satellite and remote sensing lack resolution for detailed characterization and are limited by environmental factors like cloud coverage [30]. Furthermore, visual identification of spills can be confounded by naturally occurring sheens from decaying plant material.

A significant breakthrough has emerged through the integration of fluorescence imaging with deep learning architectures. Fluorescence imaging capitalizes on the well-documented phenomenon that oil residues emit detectable fluorescence under specific light wavelengths, enabling non-destructive, real-time analysis with automation potential. Recent research has developed a lightweight convolution neural network (CNN) architecture trained on 1,530 fluorescence images from two distinct crude oil types: naphthalene crude oil (NACO) and aromatic naphthalene crude oil (ANCO), at concentrations ranging from 0 to 500 mg/L [31].

The proposed approach leverages MobileNetV3 for feature extraction coupled with a custom CNN regression model, demonstrating superior performance compared to both traditional machine learning models and more complex deep learning architectures. In cross-dataset evaluation (training on NACO, testing on ANCO), the model achieved an R^2 of 0.9767, while combined dataset evaluation yielded an exceptional R^2 of 0.9958 with a root mean square error (RMSE) of 9.28 (Poudel et al., 2025). The integration of adaptive conformal prediction provides real-time confidence intervals, while deployment through synchronized mobile applications and cloud-based databases enables rapid, on-site concentration assessment and data management. This approach democratises oil spill assessment, allowing field operators to perform accurate predictions using their own fluorescence images without specialised laboratory equipment.

4.4. UAV-Borne Hyperspectral Sensing

While satellite platforms provide wide-area coverage, they face limitations in spatial resolution and revisit time. Unmanned Aerial Vehicles (UAVs) equipped with hyper spectral sensors have emerged as complementary technology capable of bridging this gap, offering high-resolution, on-demand data acquisition. Recent demonstrations have established correlations between spectral signatures in the visible near-infrared (VNIR, 400–1000 nm) and shortwave infrared (SWIR, 1000–2400 nm) regions with oil film thickness and hydrocarbon degradation state.

The practical advantages of UAV platforms are substantial. Unlike aircraft or satellites requiring extended planning for deployment, UAVs can be launched from ships or rigs within minutes, enabling real-time data acquisition before significant emulsification or weathering occurs. This capability is particularly valuable for near shore and shoreline monitoring where rapid response is critical.

4.5. Artificial Intelligence and Machine Learning Integration

The proliferation of remote sensing data has created both opportunities and challenges for oil spill detection. Machine learning, particularly deep learning architectures, has emerged as a powerful tool for automating feature extraction and classification from complex, multidimensional datasets. Object detection models, including Faster R-CNN optimized with feature pyramid networks (FPN), have demonstrated reasonable accuracy for oil spill detection in both hyper spectral and SAR imagery [32]. The FPN network improved precision, recall, and average precision by approximately 0.1 compared to baseline models.

For hyper spectral data, object detection models achieved precision, recall, and average precision exceeding 0.9 using pseudo-color images. For SAR imagery, the highest accuracies were achieved using the polarization characteristic parameter of anisotropy according to Journal of the Indian Society of Remote Sensing, 2025. These findings suggest that object detection models are superior to image segmentation models in application situations requiring binary determination of oil spill existence with real-time processing requirements and low false alarm rates. Such models are particularly suitable for daily surveillance of oil spills using airborne remote sensors and can be integrated with image segmentation algorithms to balance model efficiency with exact oil spill area extraction.

However, several challenges remain. The lack of ground truth data for algorithm validation, particularly for smaller spills limits model generalisability. Many published studies continue to rely on legacy datasets such as AVIRIS imagery from the 2010 Deepwater Horizon spill, raising questions about applicability to contemporary sensors and scenarios. Future research should prioritize the collection of validation data from controlled experiments and real incidents.

5. ADVANCEMENTS IN OIL SPILL REMEDIATION TECHNOLOGIES

Remediation technologies have evolved substantially from primarily mechanical recovery toward integrated approaches combining physical, chemical, and biological methods. Recent innovations have focused on improving efficiency, reducing environmental impact, and developing materials with enhanced sorption and regeneration capabilities

5.1. Conventional Methods: Status and Limitations

Traditional remediation approaches include mechanical recovery (booms, skimmers), chemical dispersants, and in-situ burning (ISB). Each method has well-documented advantages and limitations that influence its applicability to specific spill scenarios.

Mechanical recovery remains the most environmentally benign approach when feasible, as it physically removes oil from the water surface without introducing foreign chemicals. However, effectiveness is limited to moderate sea states and relatively thick oil layers. During the Exxon Valdez and Deepwater Horizon responses, mechanical techniques recovered only 15–25% of spilled oil. Booms require calm conditions for effective containment, while skimmers struggle with emulsified oil and debris.

Chemical dispersants, such as the 2 million gallons of Corexit™ applied during Deepwater Horizon, operate by breaking oil into small droplets that disperse into the water column, enhancing natural biodegradation. While effective at reducing surface contamination, dispersants have sparked controversy regarding aquatic toxicity and the "hidden" nature of the remediation approach, which relocates rather than removes contamination [33].

In-situ burning (ISB) can rapidly remove large oil volumes with high efficiency (50–95%) but requires rapid deployment before emulsification and raises air quality concerns. Recent research has examined the environmental impacts of ISB on marine plankton, with studies evaluating the acceptability of this mitigation option after major oil spills [34]. The emerging "Blue Whirl" phenomenon; a novel combustion regime characterized by soot-free, stable combustion which has been identified as a promising breakthrough toward achieving cleaner and more efficient in-situ burning in future applications [35]. This phenomenon represents a significant advancement, as traditional in-situ burning generates substantial black carbon and incomplete combustion products that contribute to air pollution.

5.2. Emerging Sorbent Materials

The development of advanced sorbent materials represents one of the most active areas of oil spill remediation research. Ideal sorbents combine high sorption capacity, rapid uptake kinetics, hydrophobicity/oleophilicity, buoyancy reusability, and environmental compatibility.

Natural fibre sorbents have gained renewed attention due to their low cost, biodegradability, and favourable performance characteristics. Cattail (Typha) fibre achieves exceptional oil sorption capacity ranging from 18 to 98 g of sorbate per gram of sorbent, depending on oil type and density. Industrial oil 120 A showed the highest capacity (96 ± 2 g/g), while crude oils ranged from 18–29 g/g based on density and resin content. The material's branched fibre structure and natural hydrophobic layer (lignin content up to 18%) contribute to sorption rates reaching approximately 2.7 g/(g·s) in the first seconds, more than ten times faster than known cellulose-based alternatives with buoyancy exceeding 30 days and regeneration potential over 50 cycles.

Polycaprolactone (PCL)-based porous sorbents represent a significant synthetic advancement. Researchers have developed hydrophobic porous sorbents using three types of porogens; solid (NaCl), liquid (mesitylene), and hybrid (polystyrene and toluene), to create optimized porous structures [36]. These PCL-based sorbents achieve absorption capacities of 45 g/g with no affinity for water, excellent reusability properties up to 15 cycles, and are synthesized through a solvent/catalyst/initiator-free method that supports environmental sustainability. The incorporation of NaCl, polystyrene, toluene, and mesitylene, all abundant and low-cost materials, not only enhances sorption efficiency but also significantly reduces material costs, making the approach economically attractive for large-scale applications. Advanced nanosorbents have been systematically reviewed for their potential in oil-water separation. Synthetic polymeric sorbents exhibit high oil sorption capacities, but their non-biodegradability raises ecological concerns, shifting research focus toward nature-friendly biodegradable polymeric sorbents [37]. However, these biodegradable sorbents often suffer from inherent hydrophilicity, limited oil selectivity, and low mechanical strength. Chemical surface modifications with hydrophobic materials such as carbon nanotubes, graphene oxide, and fluoro-alkanes have proven effective in improving water repellency but raise concerns regarding toxicity and environmental safety. Recent advancements focus on integrating natural fillers, biomimetic surface engineering, and functional biocompatible coatings to achieve superior oil-water separation performance while maintaining environmental safety.

5.3. Bioremediation and Integrated Approaches

Bioremediation utilizes microorganisms to degrade petroleum hydrocarbons, offering a low-impact, cost-effective approach for treating oil-contaminated shorelines and soils. Naturally occurring hydrocarbon-degrading bacteria, including species of Pseudomonas, Alcanivorax, Marinobacter, and Rhodococcus, can be stimulated through nutrient addition (biostimulation) or supplemented through culture introduction (bioaugmentation).

Advanced biochar-based bioremediation represents a significant innovation in this field. Researchers have isolated an efficient petroleum-degrading strain, Rhodococcus hoagii S4, from petroleum-contaminated sediment [38]. Systematic evaluation of various biochar types demonstrated that corn straw biochar, pyrolyzed at 350°C enhanced oil degradation. Subsequently, an innovative Fe_3O_4/biochar-immobilised bacteria (S/FBC) system was developed, achieving an oil degradation efficiency of 61.64% with enhanced salt tolerance.

Mechanistic investigations revealed that the S/FBC composite stimulated biosurfactant production and substantially upregulated alkylB expression, the primary gene responsible for alkane terminal hydroxylation—with increases of 61.89% and 44.24% relative to free bacteria and biochar-immobilised bacteria, respectively. Gas chromatography/mass spectrometry (GC/MS) analysis demonstrated that S/FBC greatly facilitated the degradation of medium- and long-chain alkanes and polycyclic aromatic hydrocarbons (PAHs). This research clarifies the interaction mechanisms between nano materials and microbes, advancing the development of immobilized multifunctional bioremediation for marine oil spill control.

Biodegradable polymer composites with natural fillers have emerged as another promising direction. Research has demonstrated the potential of combining biodegradable polymers with natural waste materials to achieve effective and reusable sorbents for oil-contaminated wastewater remediation, via increased surface area with fillers [39]. Three-dimensional fibrous structures based on polylactic acid (PLA) and biomass wastes have been developed for fat, oil, and grease (FOG) wastewater treatment, offering sustainable and reusable solutions.

5.4. Arctic and Ice-Covered Waters Response Capabilities

Renewed political and commercial interest in Arctic resources, combined with the reduction in sea ice extent and thickness, has prompted renewed examination of oil spill countermeasures for cold environments [40]. This review provides an overview of present oil spill response capabilities and technologies for ice-covered waters, covering three main areas: oil weathering and modeling, oil detection and monitoring, and oil spill response techniques. The unique challenges of Arctic response, including extreme temperatures, limited daylight, ice cover, remote locations, and limited infrastructure, invalidate many conventional approaches and necessitate specialized technologies. Key research results from laboratory tests, field programs, and modeling work over many decades have been synthesized to inform future capability development. Quantitative comparison reveals that no single method is optimal for all scenarios. The choice of remediation approach depends on oil type and volume, sea state, distance from shore, environmental sensitivity, and time elapsed since spill.

6. FUTURE DIRECTIONS IN OIL SPILL IDENTIFICATION AND REMEDIATION (2026–2030)

6.1. Next-Generation Identification Technologies

6.1.1. Advanced AI Architectures for Satellite and Remote Sensing

The cornerstone of future detection lies in sophisticated deep learning models trained on increasingly large, validated datasets. The SOSeas (Searching for Oil Spills on Sea Surfaces) project exemplifies this shift, proposing a two-stage AI framework that uses the Damping Ratio (DR) as a primary feature [41]. DR is more robust to variations in incidence angle and wind speed than the traditional Normalized Radar Cross Section (NRCS), providing a more consistent and reliable basis for slick characterization.

Similarly, the NOS-Net model, designed for the Lower Congo Basin, integrates a Residual Convolution Block Attention Module (RCBA) within a U-Net architecture to achieve an IoU of 61.27% for oil spills, outperforming baseline models by over 7% [42]. The DeepSegFusion architecture, combining SegNet and DeepLabV3+ with attention-based feature fusion, has demonstrated the ability to reduce false detections by 64.4%, achieving an overall accuracy of 94.85% on diverse SAR datasets [43]. Furthermore, the OilSAM2 framework is being developed for scalable, memory-augmented segmentation of SAR data [44].

6.1.2. Integrated IoT, Unmanned Vehicles, and Digital Twins

Future detection systems will be characterized by the integration of multiple sensing platforms within a unified digital architecture. A framework combining IoT sensors, Saildrone USVs, and transfer learning has achieved up to 98.3% accuracy on drone images for spill detection (2026, Next-gen marine safety). This multi-layered system provides real-time data acquisition at the physical layer, edge processing for low-latency response, and cloud-based deep learning for classification. A Digital Twin of the Ocean (DTO) in the Cretan Sea automates an end-to-end workflow: it ingests Sentinel-1 SAR data, uses an FCOS and U-Net combination for detection, and automatically triggers downstream oil spill transport models like MEDSLIK-II to forecast spill evolution [45].

6.1.3. Emerging Sensing Modalities and Fluorescence Imaging

The operational use of fluorescence imaging is advancing, with a 2025 study demonstrating a mobile application capable of real-time oil concentration assessment. The system achieved an R^2 of 0.9958 and an RMSE of 9.28, providing a rapid, cost-effective field tool that democratises spill assessment [46]. Meanwhile, the PACE mission is exploring polarimetry for ocean surface refractive index detection, a novel physical approach [47].

6.2. Advanced Remediation Technologies

6.2.1. Autonomous and Robotic Systems

A new class of small, autonomous robots is emerging for active spill recovery. The "Electronic

Dolphin," a dolphin-shaped minibot, uses a bio-inspired sea urchin filter to recover oil with over 95% purity [48]. This autonomous system can be deployed in risky, hard-to-reach areas without human intervention. Furthermore, researchers have developed a vision-based autonomous UAV platform for real-time oil spill sample collection, capable of autonomous navigation, simulated sampling, and precision landing using fiducial markers, enabling rapid unmanned incident response [49].

6.2.2. Innovative Sorbent Materials

Material science is delivering sorbents with unprecedented functionality. A carbon dots/loofah sponge (P-CLS) offers solar-driven recovery, with its surface reaching 55°C under 1 sun irradiation to accelerate oil absorption and achieve a self-releasing efficiency of 41.67% [50]. Researchers have also developed square-wettability patterned, recyclable polyolefin elastomer sorbents that combine rapid absorption, magnetic responsiveness, and fluorescence properties for tracking and recovery [51]. Other promising materials include halloysite nanotube-coated melamine sponges with 99.99% separation efficiency and ultrafine sorbents fabricated via gas-assisted melt electrospinning (GAME).

6.2.3. In-Situ Combustion and Fire Whirls

In-situ burning is being reinvented with the "Blue Whirl" phenomenon, a soot-free, stable combustion regime that could significantly reduce air pollution from burn operations. A first-of-its-kind, large-scale experiment demonstrated that fire whirls burn oil 40% faster, cut soot emissions by 40%, and consume up to 95% of the fuel compared to conventional fire pools, all while producing less smoke [52].

6.2.4. Advanced Bioremediation

Bioremediation is transitioning from passive seeding to active nanomaterial-enhanced strategies. Researchers have developed a Fe_3O_4-biochar-immobilised bacteria system (S/FBC) using Rhodococcus hoagii S4, which achieved 61.64% oil degradation efficiency. The system upregulated the alkB gene expression by 44.24% compared to non-immobilised bacteria, facilitating the breakdown of medium- and long-chain alkanes and polycyclic aromatic hydrocarbons [53]. Another study successfully used a dual-strain consortium (Novosphingobium sp. and Alcanivorax sp.) immobilised on rice husk biochar for synergistic hydrocarbon removal.

6.2.5. Integrated Future Frameworks and Challenges

The future of oil spill response lies in integrated, autonomous, and intelligent systems. The global oil spill management market is projected to reach USD 192.61 billion by 2030. However, significant challenges remain, including: (a) the transition of novel materials from lab to industrial scale, (b) the need for real-time thickness estimation over large areas, (c) the development of robust cold-water bioremediation, and (d) the integration of these diverse technologies into a cohesive, fail-safe operational framework.

4. CONCLUSION

The evolution of crude oil spill response represents a narrative of progressive refinement driven by catastrophic events, scientific discovery, and technological innovation. From the earliest industrial spills of the late nineteenth century to the autonomous systems envisioned for the 2030s, each generation has learned from the mistakes of its predecessors. The journey from shovels and straw to quantum sensors and fire whirls illustrates humanity's adaptive capacity in addressing environmental challenges.

The increasing global reliance on offshore oil extraction, deep-sea drilling, and pipeline transportation has heightened the risk of oil spills, making effective containment and response strategies critical to environmental sustainability. Over the past few decades, major oil spills such as Exxon Valdez (1989), Deepwater Horizon (2010), and the Prestige oil spill (2002) have demonstrated the devastating consequences of inadequate response mechanisms. These incidents have catalyzed significant technological innovations, regulatory improvements, and the development of best practices in oil spill management.

The future, if realized, will be one where a major spill triggers not a frantic, dirty, and prolonged cleanup, but a swift, coordinated, and nearly invisible restoration of the marine environment. The integration of AI-powered detection systems, autonomous recovery vehicles, advanced sorbent materials, and nanomaterial-enhanced bioremediation promises to transform oil spill response from reactive damage control to proactive environmental stewardship.

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