

Advanced sorbents for oil spill cleanup: materials, methods, and future perspectives

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Abstract: Oil spills are a vital environmental problems for animals, plants, and even the economy. As more companies search for oil in the ocean, the number of pests' increases. Therefore, we need to find ways to clean up the pollution quickly. One way to do this is to use special materials that absorb oil. These materials are easy to use, can absorb large amounts of oil, and are not too expensive. They also work well in a variety of environments. This article will review the advances in the development of these special materials, or oil sorbents. It will discuss the different types of materials, how they are made, and how well they work. Some of these materials come from nature, while others are man-made. To improve their performance, scientists use various techniques, such as modifying or shrinking their surface properties. The good news is that these advanced materials can remove oil from water very effectively. However, more research is needed to make them even better. This includes creating materials that are a combination of different substances, finding environmentally friendly ways to manufacture them, and ensuring that they last a long time. In this regard, it is important to develop materials that can clean up oil spills effectively and efficiently. We must continue to work on improving these materials to protect the environment from spills.

Keywords: oil spillfc remediation; oil sorbent materials; natural and synthetic sorbents; hybrid sorbent materials; sustainable remediation technologies; oil-water emulsions.

1. Introduction

Oil spills are a serious environmental problem. Over the past few years, numerous accidents and leaks have harmed our oceans and wildlife. We need to find more effective ways to clean up spills and prevent them from happening again. Just a few years ago, a large oil tanker named Sanchi sank in the East China Sea, causing a massive spill that damaged the marine ecosystem (Duarte et al., 2024). Then, in 2019, someone spilled oil all along the coast of Brazil, damaging numerous protected areas and ecosystems. In 2020, a large diesel fuel tank collapsed in Russia,

spilling thousands of tons of fuel into rivers and the Arctic environment. Around the same time, the MV Wakashan ran aground off the island of Mauritius, causing a major oil spill that damaged coral reefs and coastal wildlife (Chang et al., 2014). Similar accidents continue to occur. For example, most recently, a tanker sank in Manila Bay, spilling millions of liters of industrial oil into the water (National Transportation Safety Board, 2019). This is bad news for fish, coastal ecosystems, and people living nearby. All of these incidents demonstrate that we need to improve oil spill prevention and response (Soares et al., 2020). We need new technologies and strategies to protect the environment from the dangers of oil transportation and storage. The problem is not going away, and we need to take action to stop it. Oil spills can happen anywhere, anytime, and they can have devastating consequences for the environment (Astakhova et al., 2021). We must be prepared and equipped with the necessary tools and methods to respond quickly and effectively. This is a huge task, but we cannot afford to wait. We must work together to find solutions and protect our planet from the harm caused by oil spills. We must learn from the past and use this knowledge to create a better future (Ragoonaden et al., 2021). By learning about the impacts of oil spills and how to prevent them, we can make a real difference. It's time to take responsibility and do right by the environment. We owe it to ourselves, our children, and the future of our planet to take action against oil spills and protect the beauty and wonder of our oceans and wildlife (Philippine Coast Guard, 2024).

Increased oil exploration, transportation, and refining have led to increased oil pollution of our waters and land. This is due to the constant release of oil-containing waste from industrial processes. Oil spills and oil-contaminated wastewater pose a threat not only to our aquatic resources and the animals living in them but also cause long-term damage to the environment and the economy. This is because oil can remain in the environment for a long time and is toxic, meaning it can harm living organisms (Zodiatis, 2017; Fingas, 2016; Prince et al., 2015). Furthermore, oil dissolves very quickly in water, forms a film on the surface, and gradually sinks and accumulates in sediments. Currents and winds tend to cause even more rapid spread, leading to the degradation and even disappearance of large areas of marine life and the environment (Fodrie, 2011 & D'Andrea et al., 2013). In combination with the above conditions, a number of physicochemical parameters such as temperature and salinity can also determine the rate of spread of oil spills in a natural water body. (Fingas, 2011 and Zekri et al., 2005). Figure 1 shows that the most significant volume of oil entering the water comes from ships (25%), tankers (20%) and tank barges (15%), with an additional percentage coming from refineries, terminals (25%) and platforms (15%). The most commonly encountered types of oil are crude oil (35%), diesel fuel (20%), marine oil (10%), gasoline (8%) and oil condensates (3%).

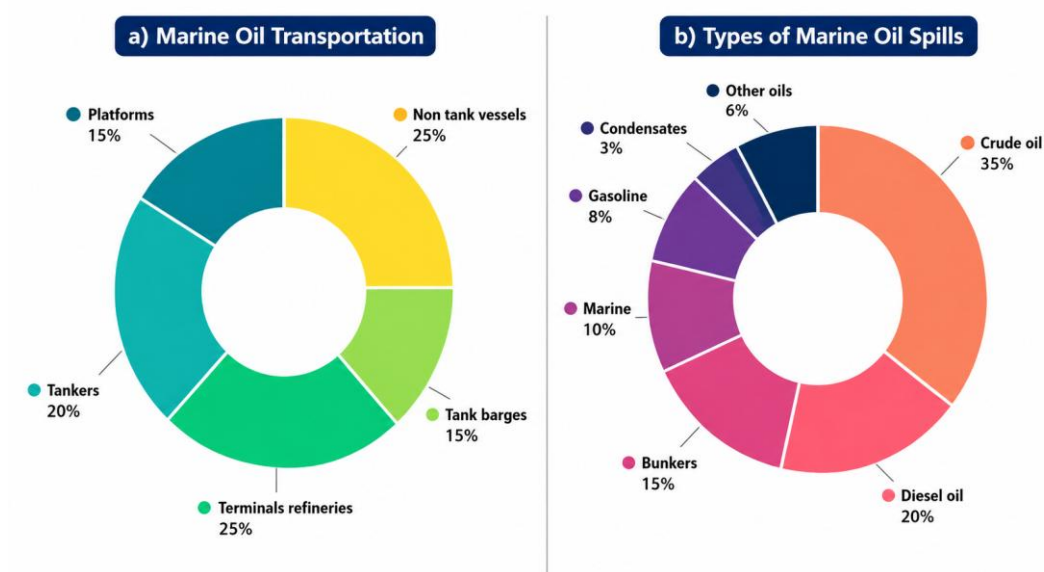


Figure 1. (a) Percentage (%) of oil spill origins in water. (b) Percentage (%) of oil types (adapted from Zamparas et al., 2020)

Traditional oil-water separation technologies, such as gravity separation, oil skimming, flotation, and membrane filtration, often suffer from inherent limitations, including low separation efficiency of fine emulsions, high energy and operating costs, membrane fouling, and the potential formation of secondary contaminants during treatment processes (Yang, 2022; Juraij et al., 2025). These drawbacks are particularly pronounced in complex industrial wastewaters, where small oil droplet sizes and stabilizing surfactants hinder efficient phase separation. As a result, extensive research has shifted toward advanced oil-sorbent materials as effective and environmentally compatible alternatives. Oil sorbents operate primarily through adsorption and absorption mechanisms, which are governed by physicochemical interactions such as surface wettability and capillary forces and affinity between the oil phase and the sorbent substrate (Pi, 2024; Sivashunmugam et al., 2021). Recent studies have identified a wide range of new sorbent materials, including hydrophobic/oleophilic polymer foams, biomass-derived porous absorbents, and functionalized nanostructured materials, which exhibit enhanced oil absorption, selectivity, and reusability compared to traditional methods (Liang, 2024; Hailan, 2025; Chen et al., 2024). These advanced sorbents promise to improve oil-water separation efficiency while reducing environmental impacts and operating costs. Figure 2 shows that traditional methods used in oil spill response techniques.

In recent years, organic oil sorbents, such as biomass-derived materials and synthetic polymer networks such as aerogels, foams, and electrospun fiber mats, have attracted considerable attention due to their inherently low density, high oil absorption capacity, and tunable surface chemistry (Abu, 2025; Li et al., 2024). Sorbents made from natural biomass (such as agricultural waste and plant fibers) and engineered polymer foams or fibers offer high sorption capacity and environmental benefits, bringing promise for oil spill response (Salim, 2018; Sarbatli et al., 2016). However, these materials often suffer from limited mechanical strength, poor recyclability, and stability issues, which may hinder large-scale deployment (Dehmani et al., 2023).

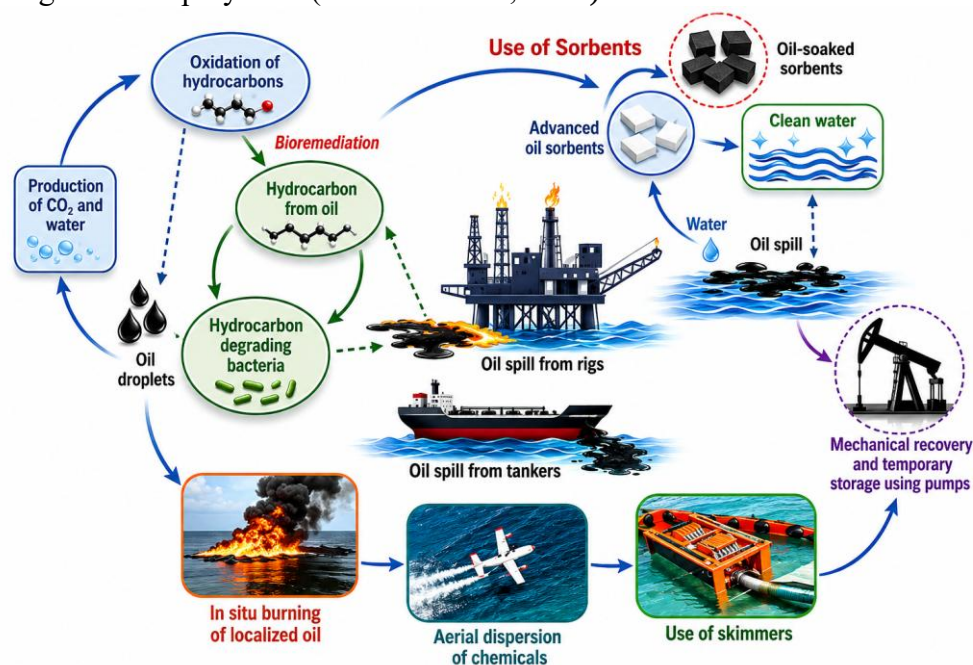


Figure 2. Traditional methods used in oil spill response (reprinted from Gote et al., 2023)

Conversely, inorganic oil sorbents, including clays, silica-based materials, metal oxides, zeolites, and carbon nanostructures, offer superior thermal and chemical properties, stability, and structural strength, which can enhance performance in harsh environments (Gao et al., 2024). These materials can exhibit lower oil selectivity, higher density, and more difficult recovery or regeneration

in practical applications (Wu et al., 2014). To overcome these limitations, organic-inorganic hybrid sorbents have emerged as a promising class of materials. By integrating organic components (providing hydrophobicity and flexible surface chemistry) with inorganic phases (providing durability and functionality), these hybrids can achieve synergistic improvements in surface area, hierarchical porosity, controlled wettability, and regenerability, resulting in enhanced oil sorption efficiency and practical utility (Zamparas et al., 2020). Recent advances in surface functionality, nanostructuring, magnetic modification, and green synthesis strategies have further enhanced the performance and sustainability of oil sorbent materials (Ge et al., 2016). However, significant challenges remain in terms of scalability, regeneration efficiency, environmental safety, and cost-effectiveness.

The widespread problem of oil spills and industrial pollutant emissions requires the development of highly efficient and sustainable remediation technologies (Wu et al., 2014). Traditional methods often fail to cope with the complexity and scale of pollution, prompting an urgent shift to advanced sorbent materials (Elgarahi et al., 2025). This includes a growing focus on innovative adsorbents that provide improved performance and minimize environmental impact compared to traditional remediation processes such as chemical precipitation or membrane filtration, which often incur high costs and generate secondary pollutants (Akhtar et al., 2024). The development of new sorbents, especially those derived from renewable resources, represents a promising direction for cost-effective and environmentally friendly remediation (Liu, 2025; Hailan et al., 2025). The urgency of developing practical solutions is highlighted by the severe impacts of oil pollution on the environment and human health, including coral reef bleaching and hypothermia in aquatic species (Ghobashi and Gaed, 2024). Consequently, significant research efforts have been focused on the development of advanced sorbent technologies for rapid and efficient oil recovery, recognizing their crucial role in remediation processes (Askari et al., 2025). These sorbents are crucial for addressing oil spill and contaminated wastewater issues by efficiently removing oil layers to produce purified water (Hoang et al., 2021). This focus includes the synthesis of eco-friendly adsorbents and the analytical information gained from their application, offering a more sustainable and economically viable approach to water treatment (Odoom et al., 2024). Indeed, various methods exist for oil spill control, such as mechanical containment, in-situ burning, bioremediation, and chemical dispersal (Gogol and Rahmati, 2024). However, physical adsorption using modern materials has proven to be a particularly attractive and simple method for cleaning up oil and solvent spills due to its ease of application and high efficiency (Gote et al., 2023).

These strategies improve the efficiency, selectivity, and environmental compatibility of oil sorbents, addressing the limitations of traditional materials. The integration of modern materials and innovative technologies is crucial for developing sorbents capable of effectively addressing oil spills and industrial pollutants. Key strategies and their implications are summarized below.

2. Methods

2.1. *Continental oil cleanup methods*

Physical response methods are the primary oil spill response mechanisms based on mechanical processes to contain, collect, and remove spilled oil from the affected environment (Sharma et al., 2024). These methods are particularly important during the initial phase of a response, when rapid containment can significantly reduce environmental damage (Zhong et al., 2023). Physical approaches include mechanical recovery systems, containment booms, skimmers, and manual collection methods. The selection and application of specific physical methods depends largely on the environmental and oceanic conditions at the spill site, including wave height, water temperature, wind speed, and proximity to sensitive ecosystems (Dhaka & Chattopadhyay, 2021). Additionally, artificial lift systems use various equipment designs to physically separate and collect oil from water surfaces. These systems include skimmers, vacuum devices, and specialized oil recovery vessels that utilize the difference in oil and water densities (Lee & Neff, 2018). Skimmers are the most widely deployed mechanical recovery technology, with designs ranging from barrage skimmers and

oleophilic drum skimmers to disc skimmers and rope mop systems (Khalil et al., 2022). Mechanical recovery efficiency is highly dependent on oil viscosity, sea state, and the presence of debris or ice (Chen et al., 2022). Recent advances have focused on improving skimmer performance through improved design features and automated operations (Dhaka and Chattopadhyay, 2021). Deployment strategies should consider spill trajectory modeling, shoreline protection priorities, and logistical constraints when assessing remote or challenging environments (Ekunke et al., 2025).

These floating barriers come in a variety of configurations, including booms, mounted booms, and fire-resistant booms for in-situ burn operations. Current velocity, wave action, and wind conditions significantly affect boom effectiveness, with failure occurring when these forces exceed the boom's holding capacity (Dhaka and Chattopadhyay, 2021). These labor-intensive approaches involve workers using shovels, rakes, absorbent materials, and hand-held equipment to remove oil-contaminated sediments and debris (Huynh et al., 2022). Shoreline cleanup operations must balance the need for thorough oil removal with the risk of causing additional environmental damage through excessive sediment disturbance. The effectiveness of onshore response operations is significantly influenced by the oil characteristics, substrate type and environmental sensitivity of the affected area (Keramea et al., 2026).

2.2. Chemical treatment methods

Chemical treatments use synthetic compounds to modify the properties of oil, improve dispersion, or facilitate degradation processes (Vu & Mulligan, 2023). These approaches include dispersants, curing agents, surface cleaners, and chemical oxidizers, which alter the physical and chemical characteristics of spilled oil. Although chemical methods allow for rapid cleanup of large spill volumes and access to areas inaccessible by mechanical means, concerns about the toxicity of treatment agents and their long-term environmental impacts have limited their use (Farahani & Zheng, 2022). The decision to use chemical treatments involves a complex tradeoff between immediate cleanup effectiveness and potential secondary environmental impacts.

Dispersants are the most widely used chemical treatment method, which act by reducing the interfacial tension between oil and water, promoting the formation of small oil droplets that disperse throughout the water column (Adofo et al., 2022). Modern dispersant formulations typically contain blends of surfactants and solvents designed to enhance effectiveness across a variety of oil types and environmental conditions (Farahani and Zheng, 2022). Application methods include aerial spraying from aircraft, ship-based spray systems, and underground injection into wellheads (Fernandes et al., 2019). However, the use of dispersants remains controversial due to concerns about increased bioavailability of toxic oil components, impacts on marine organisms, and limited effectiveness in cold water or with weathered oils (Olsen et al., 2013). As shown in Figure 3, dispersants are used in oil spill cleanup methods.

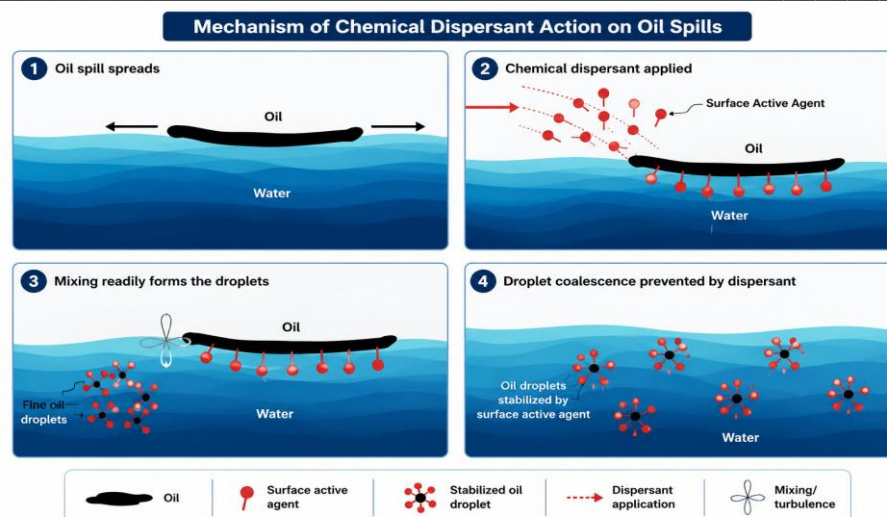


Figure 3. Dispersants as an oil spill clean-up technique (Reproduced from Adofo et al., 2022)

Solidifiers and gelling agents chemically convert liquid oil into semi-solid or solid materials that are easier to collect and remove from the water surface (Motta et al., 2018). These agents typically consist of polymeric materials that interact with oil molecules to form a gel-like matrix or solid mass (Shojaei et al., 2021). This solidification approach offers advantages in preventing oil spreading, reducing the volatilization of toxic components, and facilitating mechanical recovery (Sousa et al., 2019). Limitations of using solidifiers for oil spill response include high material costs and the need to use large quantities of product relative to the amount of oil being treated, which may make this approach economically impractical for large spills or emergency situations; decreased effectiveness due to weathered, thick, emulsified, or highly viscous oils, as these conditions hinder the complete penetration and reaction of the solidifier; and difficulty in handling and disposal of the resulting solidified oil-reagent mixture once formed, as this may require additional labor, equipment, or specialized waste management methods compared to other response options (Motta et al., 2018). These issues have been noted in reviews and experimental studies of solidification technology for oil spill response.

Surface active agents (SAA) are used in oil spill response to loosen and mobilize oil adhered to shorelines, enhancing its removal through mechanical reclamation or natural processes such as tidal action and wave action. Furthermore, these agents typically contain surfactants and solvents that reduce the interfacial tension of the oil substrate, facilitating oil removal from rocks, sand, or man-made structures (Bi et al., 2021). Application methods for SWAs range from low-pressure flushing to high-pressure hot water washing, with the choice of method depending on the type of substrate and the atmospheric conditions of the oil contamination, as highly weathered or viscous oil is more difficult to remove.

Despite their usefulness, concerns have been raised regarding the use of chemical washing regarding environmental impacts. Aggressive washing methods can dislodge sediment and potentially drive oil residues into deeper layers, where they can persist and increase the bioavailability of toxic components to interstitial tissues, which has long-term consequences for benthic fauna and habitat restoration (Zhao et al., 2024). These consequences highlight the need to balance oil removal efficiency with ecosystem protection when using surface cleaning products in sensitive coastal areas.

2.3. Biological remediation methods

Surface bioremediation utilizes natural microbial and plant processes to degrade petroleum hydrocarbons, offering cost-effective and environmentally compatible alternatives to purely physical or chemical remediation methods. These methods include bioremediation, which uses native or introduced microorganisms; phytoremediation, which uses plants to absorb contaminants; and natural attenuation, which relies on the environment's own processes to break down hydrocarbons over time

(Ghazali et al., 2023). Biological methods are particularly valuable for treating residual contaminants, diffuse contamination, and sensitive environments where mechanical intervention could cause unacceptable environmental damage (Ahmed and Ibrahim, 2019). However, biological approaches typically require long periods of time to achieve significant degradation, and their effectiveness is largely dependent on environmental conditions such as temperature, nutrient availability, oxygen levels, and salinity, which influence microbial activity and the bioavailability of contaminants (Zhang et al., 2024). The underlying mechanisms of bioremediation utilize the metabolic capabilities of complex microbial communities that convert petroleum hydrocarbons into less harmful compounds such as carbon dioxide and water through enzymatic reactions. Common strategies include bioaugmentation, biostimulation (improving the activity of indigenous microbes through the addition of nutrients), and controlled natural attenuation (Ajona and Vasanti et al., 2021). The rate and pathways of crude oil biodegradation vary significantly depending on oil composition and environmental conditions, and microbial responses can be modulated by factors such as salinity and other stressors that affect microbial growth and enzyme efficiency.

2.4. Thermal treatment technologies

Low-temperature thermal treatment and drying do not affect the oleophilic and hydrophobic properties of the sorbent. Its main effect is to remove some impurities from the surface, facilitating oil adsorption (El Gheriany et al., 2020). On the other hand, high-temperature thermal treatments, such as pyrolysis, lead to carbonization of the sorbent. Thus, the oil sorption capacity and oil-water selectivity are significantly improved (Jang et al., 2019). Thermal treatment technologies apply heat to volatilize, mobilize, or thermally decompose oil contaminants, achieving rapid volume reduction and effective destruction of many organic contaminants in contaminated soils and sediments (Vidonish et al., 2016). Primary thermal methods include in-situ combustion of surface oil slicks, thermal desorption of contaminated sediments or soils, and incineration of collected waste. Thermal methods also face significant limitations, including significant energy requirements and operating costs, the need for complex gas cleaning systems to control air emissions, and potential damage to soil properties or the environment as a whole due to prolonged or high-temperature heating (1, 4). Furthermore, in-situ and on-site combustion can generate air pollutants, including particulate matter and incomplete combustion products, raising air quality concerns and requiring careful emissions management, limiting their applicability in environmentally sensitive areas (Ding et al., 2019). Nowadays, various methods and technologies have been developed for the removal and collection of oil spills from the sea surface, which are mainly divided into three types as shown in Figure 4: (1) physical cleaning method, (2) chemical treatment method, (3) biological method.

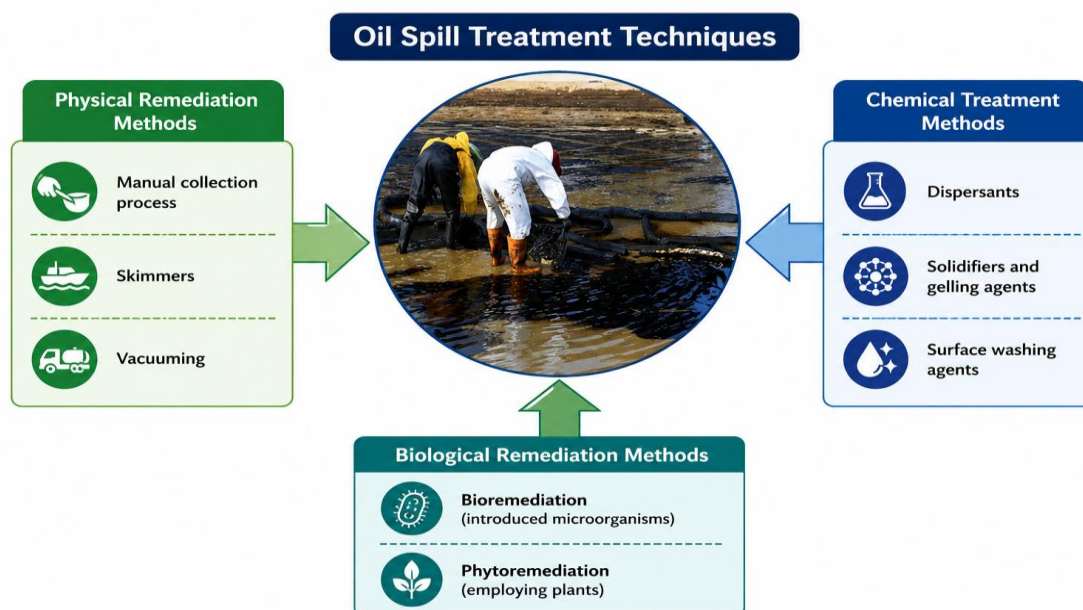


Figure 4. Three types of main techniques used for treating oil spills

According to the actual situation of the sea surface polluted by oil spills, these methods can be selected individually or in combination with each other. The chemical method involves in-situ burning, dispersion with dispersants, and solidification with solidifiers (Ding et al., 2019). In addition, in-situ burning (ISB) is an oil spill response method that involves the controlled burning of oil on the water surface, usually within the framework of fire-resistant booms that concentrate and contain the slick to maintain combustion (Niehaus et al., 2022). This method can quickly remove large volumes of oil with relatively limited equipment, and under favorable conditions, the combustion efficiency often exceeds 80-90%, according to some studies. removal efficiency approaches 90-98% (Mullin & Champ, 2003).

Successful operations require certain conditions, including a minimum oil slick thickness (typically around 2-3 mm), relatively calm weather, and a sufficient distance from populated areas. ISB is associated with smoke generation during combustion (Brandvik et al., 2021). Despite its effectiveness, ISB raises environmental concerns because combustion produces airborne emissions such as particulate matter and semi-sweet aromatic hydrocarbons (PAHs), while combustion residues can sink and contaminate marine sediments or impact aquatic organisms (Fingas et al., 2014).

Thermal desorption is another thermal treatment technology widely used for the cleanup of oil-contaminated materials. In this process, contaminated soils or sediments are heated to vaporize hydrocarbons, which are subsequently captured and treated or destroyed in secondary systems. Thermal desorption typically operates at temperatures between 200 and 600°C, lower than those used in incineration to limit the formation of combustion byproducts (Bykova et al., 2021). These systems are commonly used to treat oil-contaminated soils, sediments, and solid waste generated during cleanup operations, achieving high removal efficiencies for petroleum hydrocarbons. Advantages include efficient contaminant removal and the ability to reuse treated materials, while limitations include high energy costs, the need for exhaust gas treatment systems, and limited mobility for on-site deployment (Kim et al., 2020).

2.5. Sorbent-based cleanup methods

Sorbent-based cleanup methods utilize materials with a high affinity for petroleum hydrocarbons, enabling the removal of oil from contaminated water surfaces or coastal substrates through absorption or adsorption processes. Furthermore, these methods are widely used in oil spill response because they are simple to use, relatively inexpensive, and allow for oil recovery in both

marine and terrestrial environments. Sorbents can capture oil floating in water or present on solid surfaces, making them particularly useful in the later stages of spill response when residual contaminants remain (Motta et al., 2018).

Traditional sorbents are typically classified as natural organic, inorganic mineral, and synthetic polymeric materials. Natural organic sorbents include materials such as peat moss, straw, cotton fibers, and wood products, while inorganic mineral sorbents include clay, perlite, vermiculite, and other porous minerals. Synthetic sorbents, such as polypropylene fibers, polyurethane foams, and other polymeric materials, are widely used in commercial oil spill response products due to their high sorption capacity and hydrophobic characteristics (Gote et al., 2023). These materials function through a variety of mechanisms, including absorption, in which oil penetrates the internal porous structure of the material, and adsorption, in which oil adheres to the sorbent surface through intermolecular forces. The selection of suitable sorbents depends on several performance criteria, including oil sorption capacity, selectivity for oil over water, retention capacity, recoverability or reparability, and environmental compatibility (Adebajo et al., 2003). Sorbents with high selectivity and retention capacity are particularly valuable because they minimize secondary contamination and reduce material consumption during spill response operations.

For effective sorption, sorbent materials must have an appropriate critical surface tension, which promotes hydrophobic and oleophilic behavior, which can often be improved through physical or chemical surface modification methods. Furthermore, factors such as the porosity and porous structure of the sorbent, the viscosity and composition of the oil, and environmental conditions also influence the kinetics of oil sorption, all of which affect the overall sorption efficiency and oil removal rate (El Gheriany et al., 2020). Figure 5 shows a schematic representation of the oil absorption process.

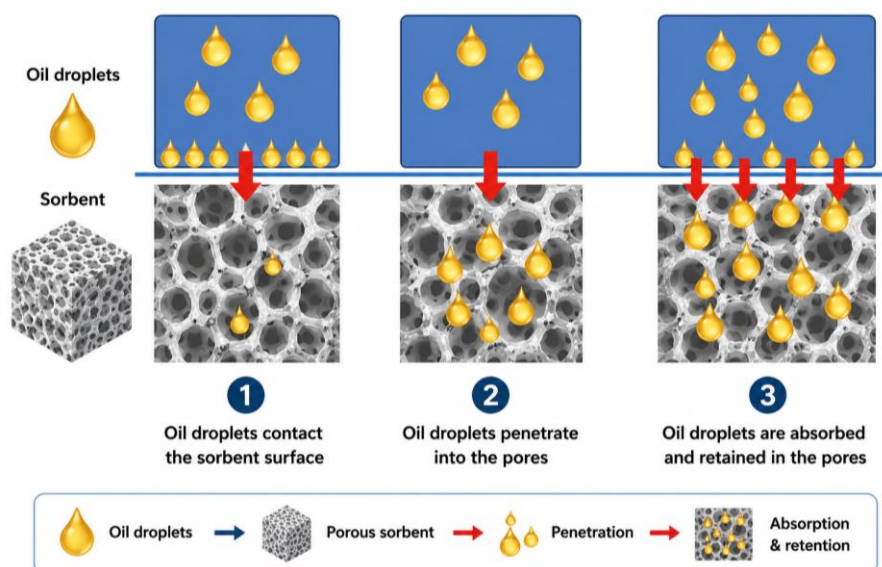


Figure 5. Schematic representation of the oil absorption process. (1) Oil droplets accumulate on the surface of the sorbents due to weak interaction forces; (2) Oil droplets penetrate into the intermolecular space of the sorbents under the action of capillary forces; (3) Both surface accumulation and intermolecular penetration exist (adapted from Ouyang et al., 2023)

Bioorganic sorbents are derived from plant-based materials such as agricultural waste, wood products, and natural fibers that are naturally oleophilic, allowing them to adsorb petroleum hydrocarbons from contaminated environments. Typical examples include peat moss, straw, sawdust, cotton fibers, and kenaf core fibers, which are widely used due to their biodegradability, low cost, and wide availability (Adebajo et al., 2003). These natural sorbents typically exhibit oil sorption capacities of approximately 3–15 times their own weight, depending on the physical

structure of the material, pore distribution, and the physicochemical properties of the oil. However, bioorganic sorbents also have a number of limitations, including lower sorption capacity compared to many synthetic sorbents, reduced buoyancy after saturation, and difficulties associated with recovery and disposal after use (Ouyang et al., 2023). To address these issues, recent research has focused on chemical modification, surface functionality, and structural engineering of natural fibers to improve their hydrophobicity, oil selectivity, and sorption capacity (El Gheriany et al., 2020).

Mineral-based sorbents consist of naturally occurring inorganic materials such as clay minerals, perlite, vermiculite, and zeolites, which remove oil primarily through surface adsorption and capillary interactions within porous structures (Gote et al., 2023). These materials offer several advantages, including high thermal stability, chemical inertness, and the ability to be regenerated through thermal treatment, enabling their potential reuse in some remediation applications. The typical sorption capacity of mineral sorbents ranges from approximately 2 to 10 times their own weight, depending largely on the particle size distribution, surface area, and pore structure. However, mineral sorbents also have disadvantages, such as relatively low oil sorption capacity, limited selectivity due to significant water absorption, and high material density, which can lead to sorbent sinking after saturation (Motta et al., 2018). Consequently, their use is often limited to onshore spills or included as components in composite sorbent materials designed to improve overall performance.

2.6. *Limitations of the conventional methods*

Traditional oil spill response methods face numerous limitations that limit their overall effectiveness and highlight the need for more advanced response technologies. Mechanical recovery systems, such as skimmers, booms, and pumps, often recover only 10-15% of the total amount of spilled oil under real-world conditions, primarily due to operational limitations and oil dispersion processes. Environmental factors also significantly impact cleanup effectiveness, as response operations can be delayed or suspended during adverse weather conditions, nighttime operations, or ice-covered waters, limiting rapid containment and restoration efforts (Fingas et al., 2016). Furthermore, the economic costs of large-scale oil spill response operations can reach hundreds of millions of dollars, particularly when long-term environmental remediation and ecosystem restoration are required. Traditional response methods can also cause secondary environmental impacts, including physical disturbance of sensitive habitats, toxicity of chemical dispersants, and incomplete removal of oil contaminants that persist in marine or coastal ecosystems (Dave & Ghaly, 2011).

Synthetic polymer sorbents are the most widely used industrial sorbent materials in oil spill response due to their high sorption capacity and strong oleophilic and hydrophobic properties. These sorbents are typically manufactured from polypropylene and polyurethane polymers and are available in a variety of configurations, such as loose fibers, pads, rods, and pillows, designed for a variety of spill containment and recovery scenarios (Adofo et al., 2022). Their oil sorption capacity typically ranges from approximately 10 to 70 times their own weight, and their hydrophobic characteristics minimize water absorption and improve oil selectivity. Polypropylene-based sorbents dominate the commercial market because they offer good performance at a relatively low cost, while polyurethane foams can offer even higher sorption capacities but are generally more expensive (Sharma et al., 2024). Despite their effectiveness, synthetic sorbents also have several drawbacks, including non-biodegradability, dependence on petroleum feedstocks, and difficulties associated with disposal or recycling after use, raising sustainability concerns (Ouyang et al., 2023). Traditional treatment methods can cause significant secondary environmental damage, which must be weighed against the benefits of treatment. Physical methods, including shoreline cleanup and sediment removal, can destroy habitat structure, disrupt ecological communities, and cause erosion (Sharma et al., 2024). Chemical dispersants and detergents can increase the bioavailability and toxicity of petroleum compounds to marine organisms. Bioremediation approaches, although generally environmentally friendly, can alter microbial community structure and introduce non-

native organisms into bioaugmentation applications (Ouyang et al., 2023). The decision-making process for selecting a remediation strategy should include a comprehensive environmental impact assessment and stakeholder consultation.

The operational effectiveness of traditional oil spill response methods is severely limited by environmental conditions, equipment limitations, and logistical challenges that impact response operations (Fingas et al., 2016). Mechanical recovery systems such as booms and skimmers often lose effectiveness in rough seas, with many skimmer systems becoming difficult or impossible to operate when sea levels exceed approximately 1–2 meters (Keramea et al., 2021). Furthermore, oil weathering processes, including evaporation, emulsification, dissolution, and viscosity increase, gradually alter the physical and chemical properties of spilled oil, reducing the effectiveness of mechanical recovery and chemical response strategies (Dave & Ghaly et al., 2011). Delays in response times due to equipment mobilization, regulatory permits, and limited site accessibility allow spilled oil to spread over large areas and be subject to weathering processes. This significantly complicates containment and recovery efforts. Analysis of historical oil spill incidents shows that cleanup effectiveness is influenced by numerous factors, including spill volume, geographic location, oil type, environmental conditions, and the availability of response resources and infrastructure (Sörengard et al., 2020). The economic costs of traditional oil spill response methods are significant and vary widely depending on the spill size, location, and response logistics, often reaching millions to billions of dollars for major incidents due to equipment deployment, personnel, materials, and monitoring requirements (Gnyazdovskaya, 2025). In addition to direct costs, indirect impacts such as damage to natural resources, economic losses, litigation, and long-term environmental monitoring further increase the overall financial burden. Cleanup operations also generate large volumes of contaminated waste, including oil-water mixtures, spent sorbents, and trash, requiring disposal methods such as incineration, landfill, or bioremediation, while the non-biodegradable nature of many synthetic sorbents highlights the need for biodegradable alternatives and waste minimization technologies (Keramea et al., 2021).

3. Materials

3.1. *Materials development and challenges of oil sorbents in oil spill cleanup*

This section comprehensively reviews the existing literature on materials engineering, focusing on both fundamental theories and state-of-the-art advances. It explores the complex interplay between material properties, processing methods, and peak performance, highlighting the ongoing challenges in achieving optimal material performance for a variety of applications (Vidonish et al., 2016). Despite significant progress, the development of new materials often faces significant hurdles, particularly in areas requiring advanced performance characteristics such as those required for clean energy, efficient transportation, and sustainable infrastructure (Hastings et al., 2024). For example, tailoring the microstructure of high-entropy alloys to optimize their mechanical function remains a critical challenge, despite their promising advances in metallurgical design beyond traditional single-base element strategies (Oketola et al., 2025). However, addressing issues such as microstructural homogeneity, long-term environmental stability, and the development of cost-effective manufacturing processes for these complex materials remains an active area of research (Poulia & Karantzalis, 2025). Furthermore, the vast compositional space inherent in multicomponent systems such as high-entropy alloys presents significant challenges for efficient materials design and discovery (Muradj & Chen, 2023). This complexity requires innovative approaches to predict and control phase evolution, mechanical properties, and other critical behavioral characteristics (Rost et al., 2024). Moreover, scientific understanding of phase formation, phase stability, and microstructures at different time and temperature scales in these complex systems remains a significant hurdle for the materials science community (Kumar et al., 2022). Recent advances in computational materials science, particularly through atomistic modeling and data-driven methods, offer promising avenues to overcome these challenges. problems by revealing

the complex interaction between chemical and structural complexities and their impact on material performance (Wang et al., 2024).

3.2. Overview of oil spill problem and sorbent solutions

Oil spills pose a serious environmental problem, causing widespread environmental damage that depends largely on the chemical composition of the oil, the characteristics of the affected environment, and the effectiveness of the recovery strategies employed during response operations. In marine ecosystems, spilled oil can undergo weathering processes such as emulsification and dispersion, forming stable oil-water emulsions, significantly complicating recovery and cleanup efforts. To address these issues, sorbent materials are widely used in oil spill response, as they can extract petroleum hydrocarbons through absorption within their porous structure or adsorption on their surfaces (Muvel et al., 2025). Due to their ease of use, cost-effectiveness, and ability to remove oil residues from water and solid surfaces, sorbents have become an important component of modern oil spill response technologies.

Absorbents are materials that retain liquids within their structure and swell significantly (more than 50%) when saturated. They must be at least 70% insoluble in the absorbed liquid. Oil-absorbing materials such as sponges, foams, nanoparticles, and aerogels can be tuned to have both hydrophobic and oleophilic wettability while exhibiting a porous structure. This can be advantageous for oil spill response in large-scale environmental and disaster situations, as these materials can readily absorb oil (Hose et al., 2023).

Adsorbents are materials that trap oil on their surface without significant swelling. These include meshes, textiles, and clays, which are often inexpensive and easy to produce. These materials can effectively absorb oil from larger spills. They adsorb adherent oil to the surface of the material, which can be useful for combating specific types of oil spills. Although sorbents provide a rapid response to oil spills, their effectiveness may vary depending on the type of oil and environmental conditions, highlighting the need for ongoing research and development of sorbent technologies (Ismaylova et al., 2023).

3.3. Categories of oil sorbent materials

Oil sorbent materials are generally divided into synthetic and natural categories, each with different properties, advantages, and limitations in oil spill response applications. Synthetic sorbents typically consist of polymer-based materials such as polypropylene and polyurethane that are specifically designed to exhibit high oil sorption capacity, hydrophobicity, and recyclability, making them widely used in commercial oil spill response operations. However, growing environmental concerns about the non-biodegradability and oil-derived nature of synthetic sorbents have stimulated research into more sustainable alternatives (Adebajo et al., 2003).

Natural sorbents derived from renewable biomass resources, including agricultural waste and plant fibers, offer advantages such as biodegradability, low cost, environmental compatibility, and high availability. In particular, lignocellulosic materials have attracted considerable attention as environmentally friendly alternatives because their porous structure and surface chemistry allow for efficient oil sorption. Plant fibers are considered promising bio-based sorbents due to their natural hydrophobic and oleophilic properties, which can be further enhanced through physical or chemical surface modification. Recent advances in biomass-based sorbents have explored nanostructured modifications and advanced materials science approaches, enabling researchers to exploit the hierarchical architecture of natural biomass using nanotechnology to enhance sorption efficiency (Ajao and Yakubu, 2022). For example, modified sphagnum moss-based adsorbents demonstrated efficient oil-water separation due to their inherent porous structure and enhanced oil-water separation properties. These advances highlight the potential of sustainable bio-based sorbents to meet the growing demand for environmentally responsible technologies for oil spill response and oil-water remediation. The methods for modifying biomass materials are shown in Figure 6.

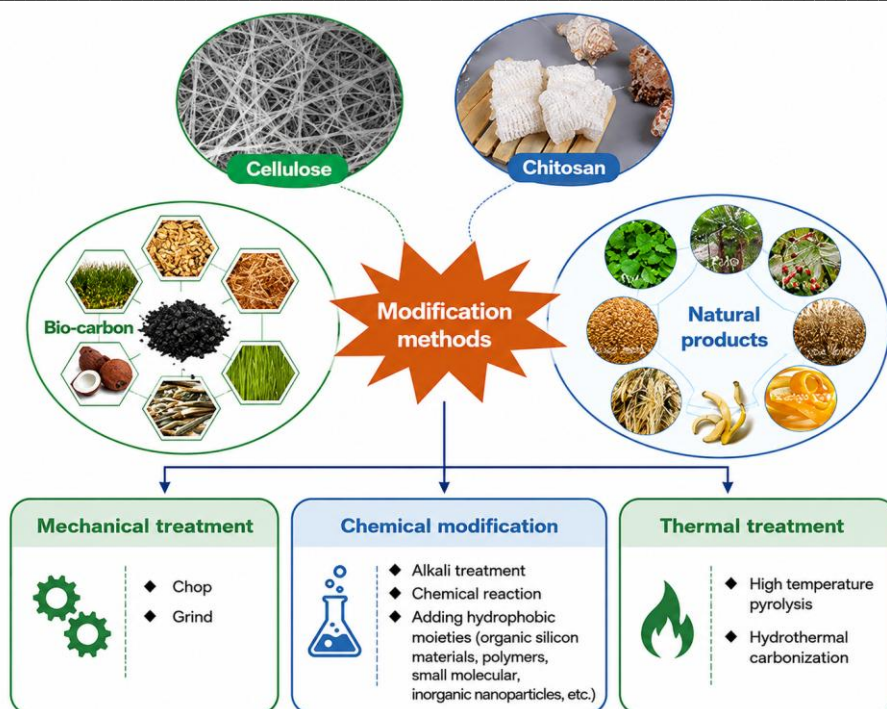


Figure 6. Modification methods for biomass materials (Zamparas et al., 2020)

Recent advances in biomass-based materials for oil spill response have focused on nanoscale modifications that enhance sorption capacity and selectivity. These materials utilize the hierarchical structure of natural biomass in combination with nanotechnology to improve surface roughness, porosity, and wettability, thereby enabling efficient oil-water separation. In particular, hydrophobic biobased adsorbents derived from modified sphagnum moss have shown promising results. Sphagnum moss has a naturally porous structure and multiple functional groups that can be chemically modified to significantly enhance hydrophobicity and oil affinity, increasing adsorption efficiency and selectivity (Riyal et al., 2024). Recent studies have shown that such modified biomass materials can provide high oil storage capacity and reusability, making them effective candidates for environmental remediation. Furthermore, current research on bio-based sorbents emphasizes sustainable modification methods, resource circularity, and waste valorization strategies where used. Sorbents can be regenerated, reused, or converted into value-added products after oil extraction (Wang et al., 2025).

Synthetic sorbents include various polymer-based materials designed for oil absorption and adsorption. These materials have been extensively studied for their performance characteristics and reuse potential. Several new synthetic sorbents in the form of foams, sponges, fibers, meshes, nanoparticles, etc. have been developed to achieve high absorption capacity, oil/water selectivity, and reusability for the effective separation and collection of oil from aqueous surfaces (Gui et al., 2013). Recently, much attention has been paid to synthetic polymers such as polypropylene (PP), polystyrene (PS), and polyurethane (PU) since they are viable sorbent materials among others. They have good oil sorption capacity (Sarbatly, 2016; Zhang et al., 2018). They are substantiated by properties such as lower density, high porosity, large surface area, and excellent mechanical strength. Polymers offer several advantages in that they can be easily processed, molded, and functionalized compared to other materials (Guo et al., 2017). However, certain drawbacks, such as poor resilience, low oil retention, and poor oil recovery, still limit their effectiveness in oil spill cleanup. Consequently, it has become necessary to modify these polymeric materials to increase their hydrophobicity and oleophilicity to improve their performance in oil/water separation (Zhou et al., 2013).

Surface wettability. The rate of oil and water absorption plays a critical role in the oil/water separation process, as only the oil component should be absorbed while minimizing or removing water. Sorption. This behavior is influenced by the wettability of the sorbent surfaces by both water and oil (Xue et al., 2014). It is typically assessed by measuring the contact angle for liquids of different polarities. The WCA of $133 \pm 3^\circ$ confirmed the hydrophobic nature of Foam 1. Accurately determining the WCA for Foam 2 is more challenging due to the roughness and inhomogeneity of the surface (Chen et al., 2019). These factors significantly influence the measured value, which was estimated as $71 \pm 3^\circ$ in Figure 7.

One research strategy has been to modify the surface of synthetic polymer sorbents by using certain low-surface-energy materials to increase their surface roughness and transform them into more hydrophobic and oleophilic materials to achieve higher oil absorption capacity (Lu et al., 2016). Generally, if the water contact angle (WCA) is below 90° , a solid surface is considered hydrophilic, and if the WCA is greater than 90° , it is considered hydrophobic. Highly hydrophobic surfaces made from low-surface-energy materials can achieve WCAs of up to $\approx 120^\circ$ (Chen et al., 2019). Some materials with highly rough surfaces can achieve static water absorption angles greater than 150° and dynamic water absorption angles less than 10° due to the presence of air pockets under liquid droplets and are called superhydrophobic surfaces. Several reports have been published illustrating the superior performance of superhydrophobic materials in oil-water separation systems due to their superantiwetting and self-cleaning properties (Chen et al., 2022). Over the past couple of decades, significant effort has been devoted to researching methods for producing and synthesizing durable superhydrophobic materials for effective oil-water separation during global oil spill response.



Figure 7. Wettability of foams by water and crude oil. Water and crude oil were colored for better visibility (derived from Hailan et al., 2025)

One of the drawbacks of using hydrophobic, highly porous polymeric materials for oil spill cleanup is the tendency of highly viscous oil to become trapped within the material's pores due to its low surface tension, which reduces regeneration and the potential for reuse of the material, which continues to absorb the oil. Therefore, modification of polymeric materials to enhance their adsorption capacity, surface self-cleaning, and regeneration properties should be carefully studied. Furthermore, the problems associated with reduced thermal stability of polymeric materials at high temperatures and low energy conversion efficiency must be overcome (Jose et al., 2023).

Bio-based sorbents for marine oil spill cleanup have been developed through modification methods, circular approaches, and waste valorization. These developments are aimed at creating closed-loop systems in which sorbent materials can be regenerated and reused or converted into

value-added products after oil recovery (Cardoso et al., 2025). Modified polyurethane foams have been developed as reusable materials for the mechanical cleanup of marine oil spills. These materials are undergoing experimental characterization and field testing to validate their effectiveness under real-world conditions. The aspect of reusability addresses both the economic and environmental concerns associated with single-use sorbents (Niehaus et al., 2022). Recent advances in porous polymeric materials have shown significant advances in oil absorption applications. These materials are engineered with a specific pore structure of polymeric materials to optimize oil absorption capacity and selectivity (Rial et al., 2024). Development focuses on controlling porosity, surface chemistry, and mechanical properties to enhance performance. Furthermore, hydrophobic polyoxometalate-MOF-808 metalloorganic composites represent a new class of synthetic sorbents for oil absorption (Li et al., 2022). These advanced materials combine the structural advantages of metal-organic frameworks with hydrophobic modifications to achieve selective oil absorption while repelling water.

3.4. *Ecofriendly biobased sorbents*

An important trend in the current literature is the shift from purely synthetic sorbents (e.g., polypropylene, polyethylene) to bioderived, biodegradable materials that support circular economy principles. Biomass-based sorbents are attractive due to their low cost, natural abundance, and environmental compatibility (Silvani et al., 2017). A comprehensive analysis of biomass-derived materials for oil spill cleanup highlights agricultural waste, plant fibers, and biochar as promising candidates for sustainable remediation strategies. These materials often exhibit high porosity and sorption capacity due to their intrinsic structural features and can be further enhanced through chemical or physical treatments to tailor their surface properties and hydrophobicity (Zhang et al., 2025). Agricultural waste and natural fibers such as rice husks, corn cob residues, wheat straw, and plant-based fibers have been identified as oil sorbents due to their high lignocellulose content and porous architecture. When carbonized, these residues form biospheres with significantly increased surface area and stability, making them effective at removing oils from both water and contaminated soils. Economic analysis of such biomass conversion suggests that increasing resource value not only provides environmental benefits but also increases the value of otherwise low-value waste (Zhang et al., 2019).

Recent studies of modified biomass sorbents show that treating natural sorbent materials with surface modifiers or functionalizing agents can significantly enhance their oil sorption performance. Surface treatment methods such as oxidation, alkali treatment, and silanization are widely used to modify the physicochemical properties of lignocellulosic materials, improving their hydrophobicity and oleophilicity (Silvani et al., 2017). For example, sphagnum moss treated with hydrogen peroxide, alkaline solutions, and silane-based modifiers has been reported to achieve a water contact angle of approximately 157°, indicating superhydrophobic behavior. This modification significantly enhances oil sorption capacity, with reported adsorption values exceeding 20 g of oil per g of sorbent, which is substantially higher than many untreated natural sorbents (Hubbe et al., 2013). These improvements are primarily attributed to changes in surface roughness and the introduction of hydrophobic functional groups, which reduce the affinity for water while promoting oil absorption. Despite these promising results, future research should focus on optimizing surface performance methods that remain durable, non-toxic, and compatible with large-scale industrial processes. Particular attention should be paid to the balance between hydrophobicity and biodegradability to ensure that modified materials do not become persistent secondary pollutants in the environment (Xue et al., 2014). Furthermore, the integration of waste valorization strategies, in which agricultural or forestry waste is converted into highly effective sorbents, represents an important path toward sustainable and circular environmental restoration technologies.

3.5. *Nanotechnology and nanoenhanced sorbents*

Nanomaterials offer significant potential for overcoming the limitations of traditional oil sorbents due to their extremely high surface-to-volume ratios, tunable surface chemistry, and enhanced mechanical strength. These properties enable nanoscale materials to exhibit enhanced sorption capacity, increased selectivity for hydrophobic compounds, and improved recovery properties compared to traditional materials (Bharadwaj et al., 2024).

In particular, nanocomposite sorbents—materials formed by integrating polymers with nanostructures such as carbon nanotubes (CNTs), graphene derivatives, and magnetic nanoparticles—have demonstrated significant improvements in the efficiency and stability of oil sorption (Benkhaya et al., 2024). Carbon-based nanocomposites, including graphene foams, CNT sponges, and mesoporous carbon fibers, have been extensively studied due to their inherent hydrophobicity, high specific surface area, and strong oleophilic interactions with hydrocarbons. These materials often exhibit exceptional oil sorption capacity, as well as structural robustness, which allows multiple reuse without significant performance loss (Kim et al., 2025). Recent developments include polyacrylonitrile (PAN)-based nanocomposite fibers that incorporate CNTs or graphene oxide to enhance porosity, hydrophobicity, and mechanical stability (Yan & Wang, 2023; Momenzadeh, 2024; Lu et al., 2024). These sorbents have shown oil absorption values of approximately 15 g/g with good performance under repeated reuse, indicating their potential for multiple applications.

3.6. Magnetic nanoparticles and smart recovery

The introduction of magnetic components (Fe_3O_4) into oil sorbents enables easy mechanical extraction from water, eliminating the need for sorption degreasing or manual collection. Functionalized magnetic nanoparticles embedded in polymer or biomass matrices have been shown to provide nearly complete oil removal in laboratory settings. However, concerns remain regarding nanoparticle aggregation, potential ecotoxicity, and post-use environmental impacts. As shown in Figure 8, environmentally friendly and hydrophobic foams were developed by uniformly distributing natural rubber (NR) over the CNF surface [145]. The resulting composite foam exhibited excellent sorption capacity and rate (more than 50 g/g in 3 s), as well as excellent reusability of various organic solvents and oils. By fully exploiting the synergistic effect of cellulose and chitosan, Hardian et al. fabricated an oil- and solvent-resistant nanofiltration membrane with excellent separation efficiency and chemical stability (Lorevice et al., 2020). Two kinds of modified CNFs were used to create a hydrophilic and underwater oleophobic cellulose sponge, which exhibits high separation efficiency (99%) by gravity alone (Hardian et al., 2022). The phase separation process is illustrated in Figure 8.

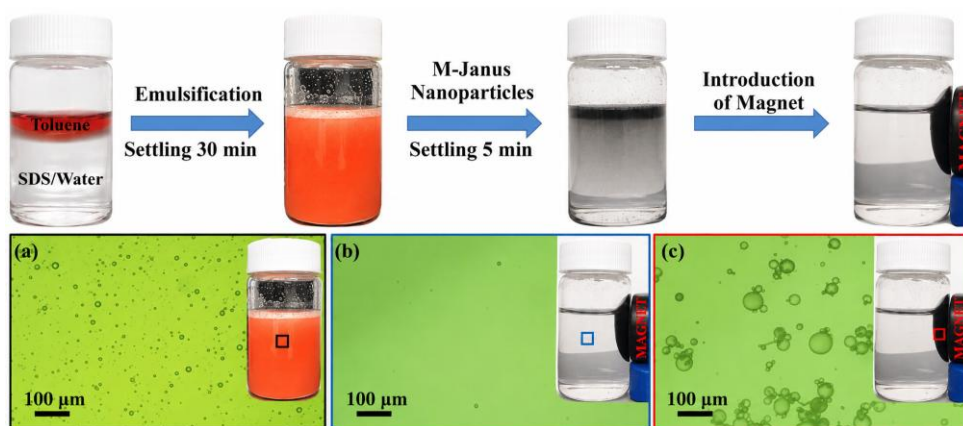


Figure 8. Phase separation process of SDS-stabilized toluene-water emulsions with the addition of M-Janus nanoparticles in an external magnetic field (top row) and micrographs of SDS-stabilized toluene emulsion droplets in water (bottom row). (a) Stable small toluene droplets before phase separation. (b) Pure water phase after phase separation and (c) toluene droplets labeled with M-Janus nanoparticles after phase separation (Reproduced from (He et al., 2019)

Furthermore, environmental impacts and safety considerations remain important concerns, particularly for sorbents that incorporate nanomaterials or functional surface coatings. Although these materials can significantly enhance adsorption capacity, hydrophobicity, or selectivity, their long-term environmental effects are not yet fully understood. Therefore, comprehensive environmental risk assessments and toxicological studies are needed to evaluate potential impacts on aquatic ecosystems and ensure that remediation technologies do not introduce new environmental hazards (Adebajo et al., 2003). Finally, performance under real environmental conditions remains poorly understood. Many laboratory studies rely on oil models and simplified experimental setups that do not fully reproduce the complexity of real spill scenarios. In the natural environment, spilled oil may undergo weathering processes, form stable emulsions, and interact with seawater, sediments, and biological materials. These factors can significantly affect sorbent performance. Thus, further research is needed to evaluate the effectiveness of sorbents when dealing with weathered crude oil, oil-in-water emulsions, and dynamic marine conditions such as waves, salinity, and temperature fluctuations (Cardoso et al., 2025). Addressing these challenges will be crucial for translating promising laboratory-scale sorbent technologies into practical and environmentally friendly solutions for large-scale oil spill response projects.

4. Conclusion

The increasing frequency and environmental impact of oil spills has increased the need for effective, sustainable, and environmentally responsible cleanup technologies. This review highlights significant advances in sorbent materials for oil spill cleanup, ranging from traditional synthetic sorbents to new nanostructured materials. Biomass-based sorbents derived from agricultural waste and natural fibers are attracting increasing attention due to their abundance, low cost, biodegradability, and compatibility with circular economy principles. Through processes such as carbonization, surface functionalization, and chemical modification, these materials can achieve enhanced hydrophobicity, porosity, and oil sorption capacity, making them a viable alternative to traditional polymer sorbents.

Meanwhile, recent advances in nanotechnology have led to the emergence of advanced sorbent systems, including carbon-based nanocomposites, electrospun polymer nanofibers, and magnetically responsive materials. These technologies offer superior adsorption capacities, fast sorption kinetics, and improved recovery capabilities. For example, nanocomposites incorporating graphene, carbon nanotubes, or magnetic nanoparticles have demonstrated promising results in laboratory studies, enabling efficient oil capture and simplified sorbent recovery. However, despite these technological advances, a number of significant challenges remain. The scalability and economic feasibility of producing nanostructured sorbents on an industrial scale is still limited, and the long-term environmental and toxicological impacts of nanomaterials require further research.

Therefore, future research should prioritize the development of cost-effective, environmentally friendly sorbents that combine high performance with safe degradation and the possibility of large-scale production. Integrating biomass value-added strategies with advanced materials science technologies may offer a promising path to sustainable oil spill remediation. Ultimately, bridging the gap between laboratory innovation and practical field application will be essential for developing robust solutions capable of addressing large-scale environmental pollution challenges.

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6. Author Contributions

Conceptualization, N.M. and N.B.; methodology, N.M., N.B., and Zh.M.; formal analysis, N.M., Zh.M., and M.S.; investigation, M.S.; data curation, M.S. and K.S.; writing—original draft preparation, N.M. and N.B.; writing - review and editing, N.M., N.B., Zh.M., and K.S.; visualization,

Zh.M. and K.S.; supervision, N.B.; project administration, N.M. All authors have read and agreed to the published version of the manuscript.

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10. References

1. Abhinav, D., & Pradipta, C. (2021). A review on physical remediation techniques for treatment of marine oil spills. *Journal of Environmental Management*, 288, 112428. <https://doi.org/10.1016/j.jenvman.2021.112428>
2. Abu, T. O., Zubairu, A., Achepa, O. V., Olansile, G. K., Adewoye, T. L., & Hambali, H. U. (2025). Biomass-derived oil sorbents, their low density, biodegradability, and high oil adsorption potential: biomass-based sorbents for oil spill cleanup - a review. *Malaysian Journal of Catalysis*, 9(1), 1–15. <https://doi.org/10.11113/mjcat.v9n1.1928>
3. Adebajo, M. O., Frost, R. L., Klopogge, J. T., Carmody, O., & Kokot, S. (2003). Porous materials for oil spill cleanup: a review of synthesis and absorbing properties. *Journal of Porous Materials*, 10(3), 159–170. <https://doi.org/10.1023/A:10274841170659>
4. Adofu, Y. K., Nyankson, E., & Agyei-Tuffour, B. (2022). Dispersants as an oil spill clean-up technique in the marine environment: a review. *Heliyon*, 8(8), e10226. <https://doi.org/10.1016/j.heliyon.2022.e10226>
5. Ahmed, F. I., & Ibrahim, S. A. (2019). Bioremediation of soil and water contaminated with petroleum hydrocarbons: A review of remediation techniques. *Environmental Technology & Innovation*, 15, 100526. <https://doi.org/10.1016/j.eti.2019.100526>
6. Ajao, O., & Yakubu, M. (2022). Sustainable hydrophobic bio-based adsorbents from modified sphagnum moss for oil–water separation. *Scientific Reports*, 12, 14628. <https://doi.org/10.1038/s41598-022-18888-311>
7. Ajona, M., & Vasanthi, P. (2021). Bioremediation of petroleum-contaminated soils – a review. *Materials Today: Proceedings*, 45(7), 7117–7122. <https://doi.org/10.1016/j.matpr.2021.01.949>

8. Akhtar, M. S. (2024). Innovative adsorbents for pollutant removal: Exploring the latest advancements and sustainable prospects. *Molecules*, 29(18), 4317. <https://doi.org/10.3390/molecules2918431715>
9. Askari, E., Alipour, V., & Rahmanian, O. (2025). Synthesis and application of adsorbent pads for removal of oil pollutants from water. *Heliyon*, 11(4), e42885. <https://doi.org/10.1016/j.heliyon.2025.e42885>
10. Assumma, V., Bottero, M., De Angelis, E., Lourenço, J. M., Monaco, R., & Soares, A. J. (2021). A decision support system for territorial resilience assessment and planning: an application to the Douro Valley (Portugal). *Science of the Total Environment*, 756, 143806. <https://doi.org/10.1016/j.scitotenv.2020.143806>
11. Benkhaya, S., El Harfi, A., & El Idrissi, N. (2024). Recycled PET–lignocellulose/carbon nanotube–graphene nanosheet nanocomposite as an efficient extractor for oil spill remediation. *Processes*, 12(11), 2437. <https://doi.org/10.3390/pr1211243718>
12. Bharadwaj, R., Kumar, A., & Singh, R. (2024). Nano-welded carbon nanotube sponges for efficient oil spill remediation. *Journal of Cleaner Production*, 467, 142841. <https://doi.org/10.1016/j.jclepro.2024.14284118>
13. Bi, H., An, C., Owens, E., Lee, K., Chen, Z., Mulligan, C., Taylor, E., & Boufadel, M. (2021). A framework for the evaluation and selection of shoreline surface washing agents in oil spill response. *Journal of Environmental Management*, 287, 112346. <https://doi.org/10.1016/j.jenvman.2021.11234619>
14. Brandvik, P. J., et al. (2021). Offshore field experiments with in-situ burning of oil: emissions and burn efficiency. *Environmental Research*, 203, 112419. <https://doi.org/10.1016/j.envres.2021.11241921>
15. Bykova, M. V., Alekseenko, A. V., Pashkevich, M. A., & Drebenstedt, C. (2021). Thermal desorption treatment of petroleum hydrocarbon-contaminated soils of tundra, taiga, and forest steppe landscapes. *Environmental Geochemistry and Health*, 43(6), 2331–2346. <https://doi.org/10.1007/s10653-020-00802-021>
16. Cardoso, C. K. M., Moreira, Í. T. A., de Souza Queiroz, A. F., de Oliveira, O. M. C., & de Carvalho Lima Lobato, A. K. (2025). Bio-based sorbents for marine oil spill response: advances in modification, circularity, and waste valorization. *Resources*, 14(9), 140. <https://doi.org/10.3390/resources1409014022>
17. Chang, S. E., Stone, J., Demes, K., & Piscitelli, M. (2014). Consequences of oil spills: a review and framework for informing planning. *Ecology and Society*, 19(2), Article 28. <https://doi.org/10.5751/ES-06873-1902281>
18. Chen, B., Zhang R., Fu, H., Xu, J., Jing, Y., Xu, G., Wang, B., & Hou, X. (2022). Efficient oil–water separation coating with robust superhydrophobicity and high transparency. *Scientific Reports*, 12, 2187. <https://doi.org/10.1038/s41598-022-06220-923>
19. Chen, C., Weng, D., Mahmood, A., Chen, S., & Wang, J. (2019). Separation mechanism and construction of surfaces with special wettability for oil/water separation. *ACS Applied Materials & Interfaces*, 11(12), 11006–11027. <https://doi.org/10.1021/acsami.9b0129324>
20. Chen, J., Ni, Y., Gou, Y., Zhu, T., Sun, L., Chen, Z., Huang, J., Yang, D., & Lai, Y. (2024). Hydrophobic organogel sorbent and its coated porous substrates for efficient oil/water emulsion separation and effective spilled oil remediation. *Journal of Hazardous Materials*, 461, 132674. <https://doi.org/10.1016/j.jhazmat.2023.1326744>
21. Chen, X., Bi, H., Yue, R., Chen, Z., & An, C. (2022). Effects of oil characteristics on the performance of shoreline response operations: A review. *Frontiers in Environmental Science*, 10, 1033909. <https://doi.org/10.3389/fenvs.2022.103390925>
22. D’Andrea, M. A., & Reddy, G. K. (2013). Health consequences among subjects involved in Gulf oil spill clean-up activities. *The American Journal of Medicine*, 126(11), 966–974. <https://doi.org/10.1016/j.amjmed.2013.05.01426>

23. Dave, D., & Ghaly, A. E. (2011). Remediation technologies for marine oil spills: a critical review and comparative analysis. *American Journal of Environmental Sciences*, 7(5), 423–440. <https://doi.org/10.3844/ajessp.2011.423.4402728>
24. Dehmani, Y., Ba Mohammed, B., Oukhrib, R., Dehbi, A., Lamhasni, T., Brahmi, Y., El-Kordy, A., Franco, D. S. P., Georgin, J., Lima, E. C., Alrashdi, A. A., Tijani, N., & Abouarnadasse, S. (2024). Adsorption of various inorganic and organic pollutants by natural and synthetic zeolites: a critical review. *Arabian Journal of Chemistry*, 17(1), 105474. <https://doi.org/10.1016/j.arabjc.2023.105474>
25. Duarte, H., Aliano-González, M. J., Romano, A., & Medronho, B. (2024). Advancements in detection and mitigation strategies for petroleum-derived contaminants in aquatic environments: a comprehensive review. *Sensors (Basel)*, 24(11), 3284. <https://doi.org/10.3390/s241132841>
26. Ekunke, O. V., Odor, G. E., Sani, S. M., Ojeilua, C. H., Attairu, M. L., Ahmed, M. A., & Elabor, I. (2025). A review of modern technologies and best practices for oil spill containment and response. *World Journal of Advanced Research and Reviews*, 25(3), 2117–2128. <https://doi.org/10.30574/wjarr.2025.25.3.09336>
27. El Gheriany, I. A., El Saqa, F. A., Amer, A. A. E. R., & Hussein, M. (2020). Oil spill sorption capacity of raw and thermally modified orange peel waste. *Alexandria Engineering Journal*, 59(2), 925–932. <https://doi.org/10.1016/j.aej.2020.03.0249>
28. Elgarahy, A., Eloffy, M. G., Ak, P., Zirari, M., Ali, M., Alkhatib, L., Alqahtani, M., & Al-Wakeel, K. (2025). Sustainable biopolymer-based materials for oil spill remediation: artificial intelligence integration and technoeconomic insights – a review. *International Journal of Biological Macromolecules*, 332, 148310. <https://doi.org/10.1016/j.ijbiomac.2025.14831015>
29. Falciglia, P. P., Lumia, L., Giustra, M. G., Gagliano, E., Roccaro, P., Vagliasindi, F. G. A., & Di Bella, G. (2020). Remediation of petrol hydrocarbon-contaminated marine sediments by thermal desorption. *Chemosphere*, 260, 127576. <https://doi.org/10.1016/j.chemosphere.2020.127576>
30. Farahani, M. D., & Zheng, Y. (2022). The formulation, development and application of oil dispersants. *Journal of Marine Science and Engineering*, 10(3), 425. <https://doi.org/10.3390/jmse100304251231>
31. Fernandes, J. C., Agrawal, N. R., Aljirafi, F. O., Bothun, G. D., McCormick, A. V., John, V. T., & Raghavan, S. R. (2019). *Langmuir*, 35(50), 16630–16639. <https://doi.org/10.1021/acs.langmuir.9b0218412>
32. Fingas, M. (2011). Oil spill dispersants: a technical summary. In M. Fingas (Ed.), *Oil spill science and technology: Prevention, response, and cleanup* (pp. 435–582). Elsevier, Gulf Professional Publishing. <https://doi.org/10.1016/B978-1-85617-943-0.10015-23>
33. Fingas, M. (2014). In-situ burning of oil spills: a historical perspective. *Journal of Hazardous Materials*, 279, 9–15. <https://doi.org/10.1016/j.jhazmat.2014.06.04632>
34. Fingas, M. (2016). *Oil Spill Science and Technology* (2nd ed.). Gulf Professional Publishing. <https://doi.org/10.1016/C2014-0-04066-42>
35. Fodrie, F. J., & Heck, K. L. (2011). Response of coastal fishes to the Gulf of Mexico oil disaster. *PLoS ONE*, 6(7), e21609. <https://doi.org/10.1371/journal.pone.002160926>
36. Gao, P., Zhang, Y., & Zhao, L. (2024). Synthetic zeolites derived from fly ash as effective mineral sorbents for diesel fuel spill remediation. *Clays and Clay Minerals*, 64(5), 552–559. <https://doi.org/10.1346/CCMN.2016.06403529>
37. Ge, J., Shi, L., Wang, Y. C., Zhao, H. Y., Yao, H. B., Zhu, Y. B., Zhang, Y., Zhu, H. W., Wu, H. A., & Yu, S. H. (2016). A superhydrophobic magnetic cellulose aerogel for oil absorption. *Angewandte Chemie International Edition*, 55(25), 7081–7085. <https://doi.org/10.1002/anie.20160194633>
38. Ge, J., Shi, L.-A., Wang, Y.-C., Zhao, H.-Y., Yao, H.-B., Zhu, Y.-B., Zhang, Y., Zhu, H.-W., Wu, H.-A., & Yu, S.-H. (2017). Joule-heated graphene-wrapped sponge enables fast clean-up of

- viscous crude-oil spill. *Chemical Engineering Journal*, 308, 696–703. <https://doi.org/10.1016/j.cej.2016.09.10234>
39. Ghazali, F. M., Rahman, R. N. Z. R. A., Salleh, A. B., Basri, M., & Noor, M. J. M. (2023). New insights into the bioremediation of petroleum contaminants: a systematic review. *Chemosphere*, 333, 138391. <https://doi.org/10.1016/j.chemosphere.2023.13839135>
40. Ghobashy, M. M., & Gayed, H. M. (2024). Thermal conversion of irradiated LLDPE waste into sustainable spongelike compounds: a novel approach for efficient tracelevel oil–water removal. *Scientific Reports*, 14, Article 4833. <https://doi.org/10.1038/s4159802455401136>
41. Gniazdowska, J. (2025). The potential of waste-derived sorbents for absorbing oil spills: implications for cleanup cost and waste management. *Materials*, 18(16), 3752. <https://doi.org/10.3390/ma1816375237>
42. Googol, F., & Rahmati, A. (2024). Synthesis of dicholesteryl organogelator as a green sorbent nanomaterial for oil spill remediation. *Scientific Reports*, 14, 21111. <https://doi.org/10.1038/s4159802472077938>
43. Gote, M. G., Dhila, H. H., & Muley, S. R. (2023). Advanced synthetic and bio-based sorbents for oil spill clean-up: a review of novel trends. *Nature Environment and Pollution Technology*, 22(1), 39–61. <https://doi.org/10.46488/nept.2023.v22i01.0048>
44. Gui, X., Wei, J., Wang, K., Cao, A., Zhu, H., Jia, Y., Shu, Q., & Wu, D. (2013). Carbon nanotube sponges as excellent absorbents for oil spill cleanup. *ACS Applied Materials & Interfaces*, 5(12), 5845–5850. <https://doi.org/10.1021/am401256740>
45. Guo, F., Wen, Q., Peng, Y., & Guo, Z. (2017). Multifunctional hollow superhydrophobic SiO₂ microspheres with robust and self-cleaning and separation of oil/water emulsion properties. *Journal of Colloid and Interface Science*, 494, 54–63. <https://doi.org/10.1016/j.jcis.2017.01.07041>
46. Hailan, S. M., Krupa, I., & McKay, G. (2025). Removal of oil spills from aqueous systems by polymer sorbents. *International Journal of Environmental Science and Technology*, 22, 3833–3854. <https://doi.org/10.1007/s1376202405959036>
47. Hailan, S. M., Nógellová, Z., Popelka, A., Ilčíková, M., Mrlík, M., Minářík, A., Mikulka, F., McKay, G., & Krupa, I. (2025). Utilization of polyethylene waste for designing foamy oil sorbents. *Emergent Materials*, 8, 3075–3087. <https://doi.org/10.1007/s42247-025-01024-9424>
48. Hardian, R., Alammari, A., Holtzl, T., & Szekely, G. (2022). Fabrication of sustainable organic solvent nanofiltration membranes using cellulose–chitosan biopolymer blends. *Journal of Membrane Science*, 658, 120743. <https://doi.org/10.1016/j.memsci.2022.12074342>
49. Hastings, J. R., Lee, M., & Patel, S. (2024). Advanced materials for sustainable energy, transportation, and infrastructure systems. *Progress in Materials Science*, 142, 101212. <https://doi.org/10.1016/j.pmatsci.2024.10121243>
50. He, X., Liang, C., Liu, Q., & Xu, Z. (2019). Magnetically responsive Janus nanoparticles synthesized using cellulosic materials for enhanced phase separation in oily wastewaters and water-in-crude oil emulsions. *Chemical Engineering Journal*, 378, 122045. <https://doi.org/10.1016/j.cej.2019.12204542>
51. Hoang, A. T., Nguyen, X. P., Duong, X. Q., & Huynh, T. T. (2021). Sorbentbased devices for the removal of spilled oil from water: a review. *Environmental Science and Pollution Research*, 28(23), 28876–28910. <https://doi.org/10.1007/s1135602113775z16>
52. Hubbe, M. A., Rojas, O. J., Fingas, M., & Gupta, B. S. (2013). Cellulosic substrates for removal of pollutants from aqueous systems: a review. *Bioresource Technology*, 160, 206–221. <https://doi.org/10.1016/j.biortech.2013.01.09644>
53. Huynh, T. B., Groth, C. P., Ramachandran, G., Banerjee, S., Stenzel, M., Blair, A., Sandler, D. P., Engel, L. S., Kwok, R. K., & Stewart, P. A. (2022). Estimates of inhalation exposures among land workers during the Deepwater Horizon oil spill clean-up operations. *Annals of Work Exposures and Health*, 66, i124–i139. <https://doi.org/10.1093/annweh/wxab0287>

54. Ismayilova, R. A., Aliyev, E. N., & Geraybeyli, S. A. (2023). Innovative technologies for oil spill response by adsorption separation of oil and water: A review. *Caspian Hydrometeorological Studies*, 7(2), Article 25003. <https://doi.org/10.25514/chs.2023.2.2500345>
55. Jang, E., Choi, S. W., & Lee, K. B. (2019). Effect of carbonization temperature on the physical properties and CO₂ adsorption behavior of petroleum coke-derived porous carbon. *Fuel*, 248, 85–92. <https://doi.org/10.1016/j.fuel.2019.03.05120>
56. José, M. H., Canejo, J. P., & Godinho, M. H. (2023). Oil/water mixtures and emulsions separation methods - an overview. *Materials*, 16(6), 2503. <https://doi.org/10.3390/ma160625032245>
57. Juraij, K., Sagitha, P., & Sujith, A. (2025). Electrospun nanofibrous membranes based sorbents for oil/water separation: blends, composites, functionalized, and smart membranes. *Journal of Environmental Chemical Engineering*, 116262. <https://doi.org/10.1016/j.jece.2025.11626246>
58. Keramea, P., Spanoudaki, K., Zodiatis, G., Gikas, G., & Sylaios, G. (2021). Oil spill modeling: a critical review on current trends, perspectives, and challenges. *Journal of Marine Science and Engineering*, 9(2), 181. <https://doi.org/10.3390/jmse90201812837>
59. Keramea, P., Zodiatis, G., & Sylaios, G. (2026). Analysis of major global oil spill incidents: part 1-environmental and ecological impacts. *Journal of Marine Science and Engineering*, 14(2), 153. <https://doi.org/10.3390/jmse1402015331>
60. Khalil, M., El-Boghdady, I., & Reda, E. (2022). Oil-recovery performance of a sponge-covered drum skimmer. *Alexandria Engineering Journal*, 61, 12653–12660. <https://doi.org/10.1016/j.aej.2022.06.01125>
61. Kim, J., Lee, H., & Park, S. (2025). Electrospun PVC/graphene composite nanosponges for oil spill cleanup. *Fibers and Polymers*, 26, 1061–1073. <https://doi.org/10.1007/s12221-024-00820-018>
62. Kim, Y. (2020). Removal of petroleum hydrocarbons from contaminated soils using thermal desorption. *Applied Biological Chemistry*, 63, 69. <https://doi.org/10.1186/s13765-020-00569-z39>
63. Kumar, R., Singh, P., & Gupta, A. (2022). Phase stability and microstructure evolution in complex alloy systems: A review. *Journal of Materials Science*, 57(18), 8754–8775. <https://doi.org/10.1007/s10853-022-07123-547>
64. Lee, K., & Neff, J. M. (2018). Oil spill cleanup techniques and response strategies: a review. *Marine Pollution Bulletin*, 129(1), 35–47. <https://doi.org/10.1016/j.marpolbul.2018.02.01125>
65. Li, A., Huber, T., Barker, D., Nazmi, A. R., & Najaf Zadeh, H. (2024). An overview of cellulose aerogels and foams for oil sorption: preparation, modification, and potential of 3D printing. *Carbohydrate Polymers*, 343, 122432. <https://doi.org/10.1016/j.carbpol.2024.12243248>
66. Li, C., Zhang, Q., Wang, X., Li, X., & Wu, T. (2022). Hydrophobic polyoxometalate–MOF-808 composites for selective oil adsorption. *Chemical Engineering Journal*, 450, 138427. <https://doi.org/10.1016/j.cej.2022.13842749>
67. Liang, J., Zhou, Y., Wu, Q., Zhu, Z., Lin, K., He, J., Hong, H., & Luo, Y. (2024). Superhydrophobic foam combined with biomass-derived TENG based on upcycled coconut husk for efficient oil-water separation. *RSC Advances*, 14, 13005–13015. <https://doi.org/10.1039/D4RA01841A50>
68. Liu, Y., Yin, Z., & Cai, H. (2025). Enhanced global oil spill dataset from 1967 to 2023 based on textform incident information. *Scientific Data*, 12, 1394. <https://doi.org/10.1038/s4159702505601936>
69. Lorevice, M. V., Mendonça, E. O., Orra, N. M., Borges, A. C., & Gouveia, R. F. (2020). Porous cellulose nanofibril–natural rubber latex composite foams for oil and organic solvent absorption. *ACS Applied Nano Materials*, 3(11), 10954–10965. <https://doi.org/10.1021/acsanm.0c02203>
70. Lu, S., Xu, X., & Wang, Y. (2016). Facile fabrication of superhydrophobic meshes with different water adhesion and their influence on oil/water separation. *RSC Advances*, 6(93), 90824–90830. <https://doi.org/10.1039/C6RA15123A23>

71. Lu, T., Zhang, Q., Yang, J., Xin, Y., Zhang, Z., Hu, J., Qin, Q., & Yang, H. (2024). Preparation of PAN/graphene oxide composite nanofiber membrane for oil-containing wastewater treatment. *Carbon Letters*, 34, 109–122. <https://doi.org/10.1007/s42823-023-00637-651>
72. Momenzadeh, Z., Ashjari, M., Nemati Laya, E., & Paki, M. (2024). Highly efficient and reusable polyacrylonitrile-based nanocomposite sorbents for oil spill removal. *Advanced Composite Materials*. <https://doi.org/10.1080/09243046.2024.238741351>
73. Mooraj, S., & Chen, L. (2023). Exploring the compositional space of high-entropy alloys using computational design approaches. *Computational Materials Science*, 215, 111788. <https://doi.org/10.1016/j.commatsci.2023.11178852>
74. Motta, F. L., Stoyanov, S. R., & Soares, J. B. P. (2018). Application of solidifiers for oil spill containment: a review. *Chemosphere*, 194, 837–846. <https://doi.org/10.1016/j.chemosphere.2017.11.10319>
75. Mullin, J. V., & Champ, M. A. (2003). Introduction/overview to in-situ burning of oil spills. *Spill Science & Technology Bulletin*, 8(4), 323–330. [https://doi.org/10.1016/S1353-2561\(03\)00076-832](https://doi.org/10.1016/S1353-2561(03)00076-832)
76. Muvel, H., Jindal, M. K., Tewari, P. K., & Anand, V. (2025). Minimizing oil pollution: a review of current status and its treatment options. *RSC Sustainability*, 3(9), 3681–3723. <https://doi.org/10.1039/D5SU00403A45>
77. Niehaus, D., Hofmann, S., Kumar, S. B., Hoffmann, M., Cisneros-Aguirre, J., & Schlüter, M. (2022). Experimental characterisation and field experience of a reusable, modified polyurethane foam for the mechanical clean-up of oil spills on the sea surface. *Journal of Marine Science and Engineering*, 10(10), 1369. <https://doi.org/10.3390/jmse10101369>
78. Niehaus, D., Hofmann, S., Kumar, S. B., Hoffmann, M., Cisneros-Aguirre, J., & Schlüter, M. (2022). Experimental characterisation and field experience of a reusable, modified polyurethane foam for the mechanical clean-up of oil spills on the sea surface. *Journal of Marine Science and Engineering*, 10, 1369. <https://doi.org/10.3390/jmse10101369>
79. Odoom, D., Agyepong, L., Dick-Sago, C., & Mensah, E. O. (2024). Unveiling the social media landscape: exploring factors influencing usage patterns among tertiary education students in Ghana. *Education and Information Technologies*, 30, 3861–3883. <https://doi.org/10.1007/s1063902412944016>
80. Oketola, F., Johnson, T., & Adeyemi, O. (2025). Microstructure control and mechanical performance of high-entropy alloys: challenges and opportunities. *Materials Today Advances*, 16, 100356. <https://doi.org/10.1016/j.mtadv.2025.100356>
81. Olsen, G. H., Klok, C., Hendriks, A. J., Geraudie, P., De Hoop, L., De Laender, F., Farmen, E., Grøsvik, B. E., Hansen, B. H., Hjorth, M., Jansen, C. R., Nordtug, T., Ravagnan, E., Viaene, K., & Carroll, J. (2013). Toxicity data for modeling impacts of oil components in an Arctic ecosystem. *Marine Environmental Research*, 90, 9–17. <https://doi.org/10.1016/j.marenvres.2013.05.00753>
82. Ouyang, D., Lei, X., & Zheng, H. (2023). Recent advances in biomass-based materials for oil spill cleanup. *Nanomaterials*, 13(3), 620. <https://doi.org/10.3390/nano130306201013>
83. Philippine Coast Guard. (2024). Report on the sinking of MT Terranova and oil spill response operations in Manila Bay. <https://www.coastguard.gov.ph/17>
84. Pi, P. (2024). A review of various dimensional superwetting materials for oil-water separation. *Nanoscale*. <https://doi.org/10.1039/D4NR01473A46>
85. Poulia, A., & Karantzalis, A. (2025). Processing challenges and environmental stability of multicomponent alloys for advanced structural applications. *Metals*, 15(2), 204. <https://doi.org/10.3390/met1502020452>
86. Prince, R. C. (2015). Oil spill dispersants: boon or bane? *Environmental Science & Technology*, 49(11), 6376–6384. <https://doi.org/10.1021/es504808r26>

87. Ragoonaden, S. (2021). Environmental impact of the MV Wakashio oil spill on the coastal ecosystems of Mauritius. *Regional Studies in Marine Science*, 48, 102008. <https://doi.org/10.1016/j.rsma.2021.10200817>
88. Riser-Roberts, E. (2020). Treatment of petroleum-contaminated soils. (n.d.). USDA Forest Service. <https://www.fs.usda.gov/td/pubs/htmlpubs/htm02712801/section07.htm56>
89. Riyal, I., Sharma, H., & Dwivedi, C. (2024). Arising hydrophobic wettable materials for oil spill clean-up: A review. *Groundwater for Sustainable Development*, 26, 101274. <https://doi.org/10.1016/j.gsd.2024.10127440>
90. Rost, C. M., Pickering, E. J., & Miracle, D. B. (2024). High-entropy alloys: From fundamentals to advanced structural materials. *Nature Reviews Materials*, 9, 215–232. <https://doi.org/10.1038/s41578-023-00564-747>
91. Saleem, J., Riaz, M. A., & McKay, G. (2018). Oil sorbents from plastic wastes and polymers: a review. *Journal of Hazardous Materials*, 341, 424–437. <https://doi.org/10.1016/j.jhazmat.2017.07.07248>
92. Sarbatly, R., Krishnaiah, D., & Kamin, Z. (2016). A review of polymer nanofibres by electrospinning and their application in oil–water separation for cleaning up marine oil spills. *Marine Pollution Bulletin*, 106(1–2), 8–16. <https://doi.org/10.1016/j.marpolbul.2016.03.0374857>
93. Sharma, K., Gupta, S., & Verma, R. (2024). Structure–processing–property relationships in advanced engineering materials. *Materials Science and Engineering: A*, 882, 145527. <https://doi.org/10.1016/j.msea.2024.14552713>
94. Sharma, K., Shah, G., Singh, H., Bhatt, U., Singhal, K., & Soni, V. (2024). Advancements in natural remediation management techniques for oil spills: challenges, innovations, and future directions. *Environmental Pollution and Management*, 1, 128–146. <https://doi.org/10.1016/j.epm.2024.08.00338>
95. Shojaei, N., Aminsharei, F., & Abbastabar Ahangar, H. (2021). Application of hydrophobic polymers as solidifiers for oil spill cleanup. *International Journal of Environmental Science and Technology*, 18, 1419–1424. <https://doi.org/10.1007/s13762-020-02882-y54>
96. Silvani, L., Vrchotova, B., Kastanek, P., Demnerova, K., & Petrangeli Papini, M. (2017). Characterizing biochar as alternative sorbent for oil spill remediation. *Scientific Reports*, 7, 43912. <https://doi.org/10.1038/srep4391258>
97. Sivashunmugam, S. (2021). Biocarbons as emerging and sustainable hydrophobic/oleophilic sorbent materials for oil/water separation. *Sustainable Materials and Technologies*, e00268. <https://doi.org/10.1016/j.susmat.2021.e0026850>
98. Soares, M. O., Teixeira, C. E. P., Bezerra, L. E. A., Paiva, S. V., Tavares, T. C. L., & Garcia, T. M. (2020). Oil spill in South Atlantic (Brazil): environmental and governmental disaster. *Marine Policy*, 115, 103879. <https://doi.org/10.1016/j.marpol.2020.10387955>
99. Söregård, M., Lindh, A. S., & Ahrens, L. (2020). Thermal desorption as a high removal remediation technique for soils contaminated with per- and polyfluoroalkyl substances (PFASs). *PLoS One*, 15(6), e0234476. <https://doi.org/10.1371/journal.pone.023447637>
100. Sousa, A. L., Matos, H. A., & Guerreiro, L. P. (2019). Preventing and removing wax deposition inside vertical wells: a review. *Journal of Petroleum Exploration and Production Technology*, 9, 2091–2107. <https://doi.org/10.1007/s13202-019-0609-x54>
101. Vidonish, J. E., Zygourakis, K., Masiello, C. A., Sabadell, G., & Alvarez, P. J. J. (2016). Thermal treatment of hydrocarbon-impacted soils: a review of technology innovation for sustainable remediation. *Engineering*, 2(4), 426–437. <https://doi.org/10.1016/j.eng.2016.04.0054356>
102. Vu, K. A., & Mulligan, C. N. (2023). An overview on the treatment of oil pollutants in soil using synthetic and biological surfactant foam and nanoparticles. *International Journal of Molecular Sciences*, 24, 1916. <https://doi.org/10.3390/ijms2403191631>
103. Wang, Y. (2024). Data-driven materials design and atomistic simulations for complex alloys. *npj Computational Materials*, 10, 64. <https://doi.org/10.1038/s41524-024-01120-347>

104. Wang, Y., Zhang, X., Li, J., Chen, H., Liu, Q., & Zhao, L. (2025). Sustainable hydrophobic bio-based adsorbent from modified sphagnum moss for efficient oil–water separation. *Scientific Reports*, 15, 96059. <https://doi.org/10.1038/s41598-025-96059-740>
105. Wu, D., Fang, L., Qin, Y., Wu, W., Mao, C., & Zhu, H. (2014). Oil sorbents with high sorption capacity, oil/water selectivity and reusability for oil spill cleanup. *Marine Pollution Bulletin*, 84(1–2), 263–267. <https://doi.org/10.1016/j.marpolbul.2014.05.00533>
106. Wu, Z.-Y., Li, C., Liang, H.-W., Zhang, Y.-N., Wang, X., Chen, J.-F., & Yu, S.-H. (2014). Carbon nanofiber aerogels for emergent cleanup of oil spillage and chemical leakage under harsh conditions. *Scientific Reports*, 4, 4079. <https://doi.org/10.1038/srep0407959>
107. Xue, Z., Cao, Y., Liu, N., Feng, L., & Jiang, L. (2014). Special wettable materials for oil/water separation. *Journal of Materials Chemistry A*, 2(7), 2445–2460. <https://doi.org/10.1039/C3TA13397D2444>
108. Yan, X., & Wang, Y. (2023). Janus polyacrylonitrile/carbon nanotube nanofiber membranes for oil/water separation. *ACS Applied Nano Materials*, 6(6), 4511–4521. <https://doi.org/10.1021/acsanm.3c0000651>
109. Yang, Y., Guo, Z., & Liu, W. (2022). Special superwetting materials from bioinspired to intelligent surface for on-demand oil/water separation: a comprehensive review. *Small*, 18(48), 2204624. <https://doi.org/10.1002/sml.20220462446>
110. Zamparas, M., Tzivras, D., Dracopoulos, V., & Ioannides, T. (2020). Application of sorbents for oil spill cleanup focusing on natural-based modified materials: a review. *Molecules*, 25(19), 4522. <https://doi.org/10.3390/molecules251945223>
111. Zekri, A. Y., & Chaalal, O. (2005). Effect of temperature on biodegradation of crude oil. *Energy Sources*, 27, 233–244. <https://doi.org/10.1080/009083104904509713>
112. Zhang, D., Wang, G., Zhi, S., Xu, K., Zhu, L., Li, W., & Zeng, Z. (2018). Superhydrophilicity and underwater superoleophobicity TiO₂/Al₂O₃ composite membrane with ultra-low oil adhesion for highly efficient oil-in-water emulsions separation. *Applied Surface Science*, 458, 157–165. <https://doi.org/10.1016/j.apsusc.2018.07.05257>
113. Zhang, H., Tazhibayeva, S., & Yang, J. (2025). Development of biochar adsorbents based on walnut shell with magnetic modification for efficient crude oil removal from water. *Scientific Reports*, 15, 38174. <https://doi.org/10.1038/s41598-025-22084-158>
114. Zhang, M., Chen, Q., & Gong, Z. (2024). Microbial remediation of petroleum-contaminated soil focused on the mechanism and microbial response: a review. *Environmental Science and Pollution Research International*, 31, 33325–33346. <https://doi.org/10.1007/s11356-024-33474-914>
115. Zhang, W., Cao, F., & Zhang, Y. (2019). Sorption and removal of crude oil spills from seawater using peat-derived biochar: an optimization study. *Journal of Environmental Management*, 250, 109465. <https://doi.org/10.1016/j.jenvman.2019.10946544>
116. Zhao, Y., Sun, Y., Sun, H., Zuo, F., Kuang, S., Zhang, S., & Wang, F. (2024). Surfactant-based chemical washing to remediate oil-contaminated soil: the state of knowledge. *Toxics*, 12(9), 648. <https://doi.org/10.3390/toxics1209064835>
117. Zhong, L., Wu, J., Wen, Y., Yang, B., Grifoll, M., Hu, Y., & Zheng, P. (2023). Analysis of factors affecting the effectiveness of oil spill clean-up: a bayesian network approach. *Sustainability*, 15, 4965. <https://doi.org/10.3390/su150649655>
118. Zhou, X., Zhang, Z., Xu, X., Guo, F., Zhu, X., Men, X., & Ge, B. (2013). Robust and durable superhydrophobic cotton fabrics for oil/water separation. *ACS Applied Materials & Interfaces*, 5(15), 7208–7214. <https://doi.org/10.1021/am401534641>
119. Zodiatis, G., Coppini, G., Perivoliotis, L., Lardner, R., Alves, T., Pinardi, N., Liubartseva, S., De Dominicis, M., Bourma, E., & Sepp Neves, A. A. (2017). Numerical modeling of oil pollution in the Eastern Mediterranean Sea. In A. Carpenter & A. G. Kostianoy (Eds.), *Oil pollution in the Mediterranean Sea: Part I: The international context* (The Handbook of

Мұнай төгінділерін тазалауға арналған жетілдірілген сорбенттер: материалдар, әдістер және болашақ перспективалар

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Аңдатпа. Мұнай төгінділері қоршаған орта үшін үлкен мәселе болып табылады. Олар жануарларға, өсімдіктерге және тіпті экономикаға зиян келтіреді. Мұхитта мұнай өндіруге қызығушылық артқан сайын, апаттардың орын алу қаупі де жоғарылайды. Сондықтан төгілген мұнайды тез әрі тиімді тазарту әдістерін табу қажет. Осындай әдістердің бірі – мұнайды сіңіре алатын арнайы материалдарды пайдалану. Бұл материалдар қолдануға оңай, көп мөлшерде мұнайды сіңіре алады және салыстырмалы түрде арзан. Сонымен қатар, олар әртүрлі орта жағдайларында тиімді жұмыс істейді. Мақалада мұндай арнайы материалдарды – мұнай сорбенттерін әзірлеу саласындағы жетістіктер қарастырылады. Онда материалдардың түрлері, оларды дайындау тәсілдері және олардың тиімділігі сипатталады. Бұл материалдардың кейбірі табиғи болса, басқалары жасанды жолмен өндіріледі. Олардың қасиеттерін жақсарту үшін ғалымдар әртүрлі әдістерді қолданады, мысалы, беттік қасиеттерін өзгерту немесе өлшемдерін кішірейту. Қуантатыны, мұндай жетілдірілген материалдар судан мұнайды өте тиімді түрде жоя алады. Дегенмен, оларды одан әрі жетілдіру үшін қосымша зерттеулер қажет. Бұл әртүрлі компоненттерден тұратын гибриді материалдарды жасау, экологиялық таза өндіру әдістерін табу және олардың ұзақ қызмет етуін қамтамасыз ету сияқты бағыттарды қамтиды. Мұнай төгінділерін экологиялық тұрғыдан қауіпсіз әрі тиімді тазалайтын материалдарды әзірлеу аса маңызды. Қоршаған ортаны қорғау үшін бұл бағыттағы зерттеулерді жалғастыру қажет.

Түйін сөздер: мұнай төгінділерін жою; мұнай сорбенттері; табиғи және синтетикалық сорбенттер; гибриді сорбенттік материалдар; тұрақты тазарту технологиялары; мұнай-су эмульсиялары.

Современные сорбенты для ликвидации разливов нефти: материалы, методы и перспективы развития

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Аннотация. Разливы нефти представляют собой серьёзную проблему для окружающей среды. Они наносят вред животным, растениям и даже экономике. По мере роста интереса к добыче нефти в океане увеличивается риск возникновения аварий. Поэтому необходимо находить способы быстрого и эффективного устранения разливов нефти. Одним из таких способов является использование специальных материалов, способных поглощать нефть. Эти материалы просты в применении, способны поглощать большие объёмы нефти и являются относительно недорогими. Кроме того, они эффективно работают в различных условиях окружающей среды. В данной статье рассматриваются достижения в области разработки таких специальных материалов, нефтяных сорбентов. Описываются типы материалов, способы их получения и их эффективность. Некоторые из этих материалов имеют природное происхождение, другие создаются искусственно. Для улучшения их свойств учёные

применяют различные методы, например, изменение поверхностных характеристик или уменьшение размеров. Радует то, что такие усовершенствованные материалы способны очень эффективно удалять нефть из воды. Однако для их дальнейшего совершенствования необходимы дополнительные исследования. Это включает создание гибридных материалов, состоящих из различных компонентов, поиск экологически безопасных способов их производства и обеспечение их долговечности. Разработка материалов, способных эффективно и экологически безопасно очищать разливы нефти, имеет важное значение. Для защиты окружающей среды необходимо продолжать исследования в данном направлении.

Ключевые слова: ликвидация разливов нефти; нефтяные сорбенты; природные и синтетические сорбенты; гибридные сорбентные материалы; устойчивые технологии очистки; нефтеводные эмульсии.