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Biomass-based Sorbents for Oil spill Clean-up: A review

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ABSTRACT

The pervasive environmental and health impacts of oil spills, stemming from the extraction, transportation, and handling of crude oil, highlight an urgent need for sustainable remediation techniques. Traditional cleanup methods such as oil skimming, combustion, and synthetic sorbents are often limited by high costs, non-biodegradability, and potential environmental risks. As oil spills continue to rise with global oil consumption, sustainable, eco-friendly alternatives are essential. This review evaluates biomass-based sorbents, particularly agricultural fibres, as promising substitutes for synthetic materials. These natural sorbents exhibit high oil sorption capacities, are biodegradable, and possess hydrophobic properties that enable effective oil retention while repelling water. Their low cost, availability, and potential for reuse through carbonization also position them as economically viable and environmentally responsible solutions. Carbonized biomass sorbents produce biochar, a porous material applicable in wastewater treatment and soil conditioning, contributing to resource circularity and aligning with sustainability goals. Through an analysis of recent advancements, sorption efficiencies, and environmental impacts, this review assesses biomass-based sorbents' potential to reduce environmental degradation and enhance waste management, underscoring their role in supporting a circular economy approach for oil spill cleanup.

Keywords: *Biomass-based sorbents, Oil spill remediation, Carbonized biomass*

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1. INTRODUCTION

Crude oil has been the backbone of industrial economies and the primary energy source since the mid-20th century, with products that fuel industries, transportation, and households worldwide. Despite its essential role, oil extraction, transportation, and handling have raised significant environmental concerns due to oil spills. Oil spills release petroleum hydrocarbons into marine or terrestrial environments, often causing extensive harm. In marine ecosystems, for example, oil affects aquatic wildlife, impairing functions such as respiration and insulation, while its toxicity leads to developmental abnormalities, reduced growth rates, and compromised reproductive success in organisms exposed to contaminated water [1-2]. Field studies indicate that oil contamination in water can disrupt entire ecosystems by altering food webs, depleting oxygen levels, and reducing biodiversity [3]. These persistent pollutants can remain in sediments and biota for years, demonstrating the long-term ecological impacts of oil spills [4-5].

On land, oil spills degrade soil quality, affecting both flora and fauna and limiting the land's agricultural potential. In many cases, spills stem from activities like crude oil mining, transportation, and sabotage, which collectively contribute to widespread environmental damage. The negative effects of oil contamination are not restricted to the environment; human health is also at risk, particularly through exposure to polluted water or seafood in oil spill zones. Studies have shown an increase in respiratory issues, skin irritations, and even cancer in populations residing near oil spill sites [6]. The adverse effects of oil spills on human health and biodiversity, combined with the difficulty of removing oil residues, underscore the need for efficient, cost-effective, and sustainable remediation techniques.

Traditional oil spill clean-up methods, including oil skimming, combustion, and synthetic sorbents, are limited in terms of cost, effectiveness, and environmental impact. Synthetic materials like polypropylene are widely used due to their significant oil adsorption capacity, but they are costly and non-biodegradable, contributing to further environmental degradation [7-8]. As oil spills become increasingly common with the rise in global oil consumption, there is a pressing demand for sustainable alternatives that not only remediate affected areas but also minimize secondary environmental impacts. Natural biomass-based sorbents, such as agricultural fibres, are emerging as eco-friendly alternatives, combining high oil sorption capabilities with biodegradability and low cost [9]. The sustainable sorbent materials possess high oil sorption capacity, absorbing high amounts of crude oil per gram of fibre, and effectively retaining oil while repelling water due to hydrophobic properties [10-12]. Beyond oil sorption ability, sorbent materials are readily available and cost-effective, with the potential for reusability through carbonization, making them attractive options for large-scale application in oil spill remediation [13-14].

Carbonizing sorbent materials produces biochar, a material known for its high porosity and surface area, which can also serve as an adsorbent in wastewater treatment applications [15-17]. This approach enhances resource circularity by allowing the reuse of sorbent materials, reducing waste, and offering potential benefits for soil conditioning and carbon sequestration. The process also aligns with environmental sustainability and economic feasibility by converting waste into biochar. Such practices not only address environmental remediation but also adhere to resource conservation principles [18-19].

This review aims to evaluate the effectiveness of biomass-based sorbents in oil spill remediation. By analyzing recent advancements, sorption capacities, and the environmental impact of these natural fibres, this review seeks to establish the viability of biomass-based sorbents as sustainable alternatives to conventional synthetic materials. Specifically, the review addresses critical research questions, such as how biomass sorbents compare to synthetic sorbents in terms of sorption efficiency, environmental impact, and cost-effectiveness, and what role chemical or physical modifications play in enhancing their performance. It also investigates the long-term feasibility of integrating biomass sorbents into large-scale oil spill cleanup operations. Furthermore, this review contributes to the existing literature by identifying and addressing key gaps, such as the lack of extensive field trials and limited understanding of the environmental fate of biomass sorbents under marine conditions. Through insights into carbonization processes and the potential reuse of these sorbents, the review underscores the importance of natural materials in reducing environmental degradation, addressing waste management challenges, and supporting a circular economy approach in oil spill cleanup efforts.

2. NATURE OF OIL

Oil is a complex mixture of hydrocarbons, which are organic compounds made up of hydrogen and carbon atoms. Its nature varies depending on its source, which can include crude oil, refined petroleum products, or natural oils from plants and animals. Crude oil, the most common form, consists of various hydrocarbon molecules such as alkanes, cycloalkanes, and aromatic hydrocarbons. These molecules differ in size, structure, and properties, influencing characteristics like viscosity, density, volatility, and flammability. Additionally, oil can contain impurities such as sulfur, nitrogen, and heavy metals, which impact its environmental and health effects. Understanding these properties is crucial for managing oil effectively and mitigating the impacts of spills and pollution.

Oil plays a crucial role in various aspects of modern life, serving both practical and industrial purposes: Oil is a major source of energy, primarily used in transportation (as gasoline, diesel, and jet fuel) and electricity generation (through combustion in power plants). It serves as a feedstock for the production of numerous industrial products, including plastics, lubricants, solvents, asphalt, and synthetic fibres. Oil is used for heating homes and buildings, as well as in cooking and food preparation (e.g., vegetable oil, olive oil). Oil fuels the global transportation sector, powering cars, trucks, ships, aeroplanes, and trains, enabling the movement of people and goods across the world. It also serves as a raw material for the chemical industry, contributing to the production of fertilizers, pesticides, pharmaceuticals, cosmetics, and a wide range of other chemical products. The oil industry contributes significantly to national and global economies, providing employment, revenue, and investment opportunities. Oil-based products such as asphalt and bitumen are essential for building roads, highways, and infrastructure projects. Some medical products and pharmaceuticals are derived from oil-based compounds, including certain medications and medical devices.

While oil serves as a vital resource in numerous aspects of our daily lives, it's essential to acknowledge the significant environmental and economic repercussions associated with oil spillage. Despite its usefulness, the release of oil into our oceans, rivers, and land can have devastating consequences on ecosystems, wildlife, and communities.

3. OIL SPILLS

Oil spillage, defined as the release of liquid petroleum hydrocarbons into the environment due to human activity, presents significant ecological and health threats globally [20]. These releases are predominantly associated with crude oil mining and transport, including pipeline ruptures, tanker accidents, and spills at offshore drilling platforms or storage facilities. Oil spills occur not only in the production phase but also in various other stages, such as transportation, storage, and end-use scenarios, such as leaks at automobile workshops or PMS (premium motor spirit) outlets. These incidents highlight the ubiquity and complexity of oil-related pollution sources, complicating efforts to mitigate their effects on the environment and human health, Figure 1 shows the fate of oil spills in the marine environment.

The environmental consequences of oil spills are severe, as oil’s destructive characteristics lead to substantial ecosystem damage once it contaminates an area [21]. When oil comes in contact with soils, floors, or water bodies, its removal is notoriously difficult, often leaving persistent contamination that can extend far beyond the initial spill location [22]. Oil spill incidents are particularly impactful in aquatic environments; when spilled in water bodies, oil rapidly spreads across the surface, forming slicks or reaching shorelines, where it poses a direct threat to marine and coastal ecosystems. The rapid spread of oil on water prevents effective containment and clean-up, amplifying the likelihood of prolonged ecological harm, particularly to coastal marshes. These marshes are vulnerable because they are low-energy and anoxic environments, conditions that slow oil dispersal and decomposition, allowing them to persist within soils for decades [23].

While the most visible and dramatic oil spill incidents occur in marine settings due to tanker or platform accidents, it is crucial to understand that these large-scale incidents represent less than 10% of total petroleum hydrocarbon discharges globally. Instead, up to 90% of hydrocarbons enter the environment through low-level, routine releases, including operational discharges and maintenance leaks [24]. This routine contamination underscores a steady influx of oil pollutants, with an estimated two million tonnes of oil released into marine environments annually. Notably, only about 18% of this oil pollution comes from refinery processes, offshore operations, and tanker activity, highlighting the pervasive nature of smaller, ongoing sources that contribute significantly to long-term environmental degradation.

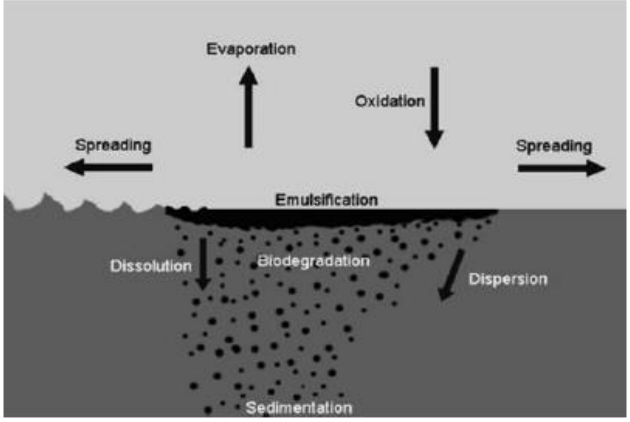

Figure 1. An illustration of the fate of oil spills in the marine environment [25]

In Nigeria, Africa's largest oil producer, oil spillage is both frequent and devastating due to pipeline vandalism, oil theft, and insufficient maintenance [26]. These spills pollute the air, soil, and water, where the volatile components of crude oil may evaporate or permeate into groundwater and surface water. This widespread pollution extends beyond environmental concerns, posing substantial health risks to communities through various exposure routes, including direct dermal contact with contaminated soil and water, ingestion of polluted food sources like crops and fish, or inhalation of vaporized toxins and particulate matter from fires [27]. Oil spills frequently result in fires, which release respirable particulate matter (PM) into the air, intensifying health hazards for nearby populations. Furthermore, these onshore spills disrupt critical livelihood resources by degrading agricultural land and fishing grounds, leading to indirect health and socioeconomic impacts, particularly in the Niger Delta region. While multiple studies document extensive soil and water contamination in this region, research has yet to provide causal evidence directly linking onshore spills to specific human health outcomes [28].

This extensive contamination in oil-producing regions like Nigeria's Niger Delta [29] illustrates the multifaceted nature of oil spills, encompassing both immediate environmental destruction and longer-term health and livelihood implications. Given the difficulty of effectively cleaning oil spills from affected ecosystems and the persistence of oil residues in anoxic soils and low-energy aquatic environments, it is evident that oil spillages present enduring environmental and public health challenges that require concerted global attention and action. Table 1 shows some past oil spill incidents in the world, their cost implications, and the most suitable technique used for remediation.

4. OIL SPILL CLEAN-UP

Oil spills present a formidable global challenge, creating extensive environmental damage and impacting ecosystems and human livelihoods. Clean-up efforts following spills are essential to mitigate their severe consequences on wildlife, local economies, and marine and terrestrial habitats. Effective oil spill remediation involves diverse strategies that vary widely in cost, environmental impact, and efficiency, with ongoing research aiming to optimize these approaches to address the limitations of existing methods [12].

Current remediation technologies include in situ burning, mechanical methods, chemical dispersants, and synthetic sorbents. In situ burning involves igniting spilled oil, ideally on the surface of the water, to quickly remove large volumes; however, it poses health risks and potential air pollution [30]. Mechanical tools, such as skimmers, leverage the adhesive nature of oil to physically separate it from the water surfaces. Skimmers vary by design, belt, brush, mop, and floating suction, all engineered to optimize oil recovery in different conditions. Nevertheless, their high operational costs and inefficiency at trace-level removal make them less ideal for large-scale or ongoing spills, especially in economically challenged regions [8]. The broad classifications of oil spill remediation are illustrated in Figure 2.

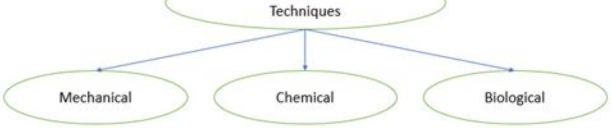

Figure 2. Broad classification of oil spill remediation

Table 1. Major oil spill incidents, their cost implication and remediation methods [30]

Incidence	Amount spilled	Length of affected areas	Cost implication	Environmental effect	Cleanup technique(s)
1967, Torrey Canyon off the English Channel	120,000 tons of crude oil	100 miles of coastlines	-	An estimated 25,000 birds died.	-Natural weathering. Dispersants were also used. Bombs were used to ignite a fire for in-situ combustion of remaining oil before it spread. Straws and gorse were used on many of the sandy beaches to soak oil. Floating booms were unsuccessful
1970, Liberian Registered Tanker at Chedabucto Bay, Nova Scotia	16,000 tons	190 miles of coastline	-	-	Skimmers successfully in sheltered waters. Dispersants could not penetrate thick layers of oil that formed as a result of low temperatures and wind. Sorbents such as peat moss proved to be a good sorbent; straw was used on some beaches. In-situ burning is used successfully on beaches and in solid slicks. Microbial degradation. On the shore, oil was removed mechanically and manually. Pressure-washing with hot water. Beaches sprayed with artificial fertilizers and bacterial cultures. Rubber powder and chalk-sinking agents were also not very successful.
2010, BP Gulf of Mexico	About 4.9 million barrels (208.5 million gallons)	Over 790 km of shorelines	$5.4 billion possible fines and $21 billion (if gross negligence) $20 billion for compensation and clean up (Welch and Joyner, 2010)	997 birds dead; 400 sea turtles dead; 47 Mammals including Dolphins dead	50% of the oil dispersed naturally; some oil was removed mechanically at sea; and some was dispersed with chemical dispersants; Booms and Skimmers; Dispersants; and Controlled burning.
1996, Sea Empress	Over 70,000 tonnes	100 km of coastline	$60 million of which $37 million was used for clean up	2200 birds killed. Seaweeds and, shellfishes were affected	50% of the oil dispersed naturally; some oil was removed mechanically at sea; and some was dispersed with chemical dispersants; Booms and Skimmers; Dispersants; and Controlled burning.
1990, the Gulf War in which 650 oil wells in Kuwait were set ablaze	1 million tonnes	-	-	20,000 sea birds were killed.	-

Chemical dispersants are another approach that has been extensively applied, particularly in cases of large offshore spills. Dispersants break down oil into smaller droplets, promoting natural biodegradation processes, yet they have been criticized for potential toxicity to marine life and limitations in certain environments [30]. Synthetic sorbents, often polymers, can be highly effective in absorbing oil; however, they tend to be costly and less biodegradable, posing challenges for eco-friendly disposal.

Despite these established methods, there are limitations in cost-effectiveness, efficiency, and environmental sustainability. Each approach comes with trade-offs, and there is a continuous need for novel solutions that balance economic feasibility and environmental safety. Some studies suggest that natural sorbents, including biomass-derived materials, show potential for being both low-cost and eco-friendly. However, further research and development are needed to verify their large-scale applicability and effectiveness, particularly in challenging field conditions [12], [30].

The impact on local communities and the environment is severe in countries like Nigeria, where oil spills are frequent due to pipeline vandalism, theft, and maintenance issues. Nigeria's Niger Delta region, an area rich in biodiversity, has endured decades of oil spills, leading to contaminated water sources, degraded farmlands, and compromised health among the local population. Conventional remediation methods face financial, logistical, and infrastructural hurdles, as the high costs associated with advanced technologies are often prohibitive [31]. Furthermore, environmental and socioeconomic conditions in regions like the Niger Delta necessitate affordable and adaptable solutions that can be implemented locally [29].

The search for more accessible oil spill cleanup solutions is critical in regions facing high spill frequency and limited resources. By exploring a wider range of cleanup options, including both established and experimental approaches, Nigeria and other similarly affected regions can work towards sustainable cleanup practices that align with local needs and resource availability. Evaluating each method's performance in real-world conditions, particularly those that are more cost-effective and sustainable, will be key in mitigating the ongoing impact of oil spills and fostering resilience against future incidents. In another study [32], treatment methods for oil spillage were classified into three major classes namely: biological treatment such as microbial remediation and enzymatic treatment; chemical treatment such as chemical coagulation and dispersion; and physical or mechanical treatment such as skimming, oil booms and adsorption. Figure 2 highlights these methods.

5. METHODS OF OIL CLEAN-UP

In most cases, two or more methods are combined to achieve an effective cleanup. Treating oil spills typically involves extensive methods, including Mechanical containment, chemical dispersions, in-situ burning and bioremediation. The methods and their examples as shown in Table 2.

5.1 Mechanical containment and recovery

It involves the use of booms spread over the surface of seas, estuaries and coastal waters to prevent the spread of oil slicks or to direct their movements [33]. This is among the primary methods used to address oil spills. This involves the use of booms to contain the oil and skimmers to remove it from the water's surface. Examples of mechanical containment and recovery methods for oil spill treatment include:

Boom Deployment: Booms are deployed to contain the spread of oil, while skimmers and vacuum trucks are employed to remove the oil from the water's surface. Mechanical methods are particularly effective in calm waters and can help prevent the oil from spreading further. Booms are floating barriers deployed around the perimeter of an oil spill to contain the oil and prevent its spread. Various types of booms, such as sorbent booms and inflatable booms, can be used depending on the specific conditions of the spill. Studies have shown that booms effectively contain oil, preventing it from spreading to sensitive areas and facilitating its recovery [34].

Table 2. Methods of Oil Spill Clean-up and their examples.

Mechanical containment	**Chemical dispersions**	**In-situ burning**	**Bioremediation**
Boom Deployment	Dispersant Application	Controlled Ignition	Biostimulation
Skimming	Remote Application Systems	Fire-Resistant Booms	Bioaugmentation
Sorbent Materials	Controlled Release	Ignition Techniques	Landfarming
Vacuum Trucks	-	--	Bioventing
Manual Cleanup	-	-	-

Skimming: Skimmers are specialized vessels or equipment that remove oil from the water's surface. These devices use various mechanisms, such as suction or absorption, to collect the oil, which is then transferred to storage tanks for disposal or recycling. Skimmers are highly effective in calm water conditions and have been widely used in oil spill response operations [35].

Sorbent Materials: Sorbents are particularly useful for small-scale spills or in situations where access is limited for larger vessels [36]. Sorbent materials, such as pads, booms, and loose materials like peat moss or hay, are used to absorb or adsorb oil from the water's surface. These materials act like sponges, capturing the oil and allowing for its removal from the environment. The effectiveness of various sorbents in recovering oil from water surfaces depends on their capacity to transform the oil from a liquid phase into a semi-solid or solid phase [25], [37].

Vacuum Trucks: Vacuum trucks equipped with suction hoses are used to remove oil from the water's surface, particularly in areas where access is limited for larger vessels. Vacuum trucks provide an efficient means of collecting oil and can be deployed quickly in response to spill incidents [38]. These trucks can efficiently collect oil and transport it to designated disposal facilities.

Manual Cleanup: In some cases, manual labour is employed to manually remove oil from shorelines or sensitive habitats. Workers may use shovels, rakes, and other tools to collect oil-contaminated debris, which is then disposed of properly.

5.2 Chemical dispersion

Chemical dispersion involves the application of dispersants to break up the oil into smaller droplets, enhancing microbial degradation. Dispersants contain surfactants that reduce the surface tension of the oil, facilitating its dispersion into the water column. However, the use of dispersants remains controversial due to potential environmental impacts and toxicity to marine life [39]. Chemical dispersants are applied to break up the oil into smaller droplets, enhancing microbial degradation. Examples of chemical dispersion methods in oil spill treatment include:

Dispersant Application: Chemical dispersants, such as Corexit, are applied directly to the oil spill either by spraying from aircraft or vessels or by injecting the dispersant underwater at the source of the spill. These dispersants contain surfactants that reduce the surface tension of the oil, breaking it into smaller droplets that can disperse throughout the water column. Dispersant application can significantly reduce the surface area coverage of oil slicks and enhance the rate of biodegradation [40].

Remote Application Systems: These systems allow for precise and targeted application of dispersants, minimizing environmental impacts. Remote-controlled or autonomous vehicles equipped with dispersant spraying systems are used to apply dispersants to oil spills in hard-to-reach or sensitive areas, such as near shorelines or in rough seas.

Controlled Release: Dispersants can also be released continuously or intermittently from vessels or platforms near the source of the spill, allowing for controlled dispersion of the oil over a larger area. This method helps to prevent the formation of large oil slicks and facilitates the dilution of the oil in the water column.

5.3 In-situ burning

Controlled burning of the oil on the water's surface, can be effective under certain conditions. It is another method used to address oil spills, particularly in situations where mechanical recovery is not feasible. Controlled burning of the oil on the water's surface can effectively reduce the volume of oil and minimize its impact on the environment. However, this method requires careful planning and consideration of air quality impacts. Examples of in-situ burning methods in oil spill treatment include:

Controlled Ignition: In-situ burning involves the controlled ignition of oil slicks on the water's surface, typically using specialized equipment such as fire-resistant booms or fire-resistant igniters towed behind vessels. The burning process consumes the oil, reducing its volume and minimizing its environmental impact. Controlled ignition effectively reduces the volume of oil and minimizes environmental damage, particularly in offshore environments.

Fire-Resistant Booms: Fire-resistant booms play a critical role in ensuring the safety and effectiveness of in-situ burning operations [41]. Fire-resistant booms are deployed to contain the oil slick and facilitate controlled burning. These booms are designed to withstand high temperatures and prevent the fire from spreading beyond the desired area.

Ignition Techniques: Various ignition techniques, such as aerial ignition using helicopters or fixed-wing aircraft, can be employed to ignite the oil slick safely and efficiently. Ignition timing and placement are critical factors in ensuring the success of in-situ burning operations. In-situ burning is typically used in situations where mechanical recovery or other methods are not feasible, such as in remote or inaccessible locations or rough sea conditions.

5.4 Bioremediation

Bioremediation involves the stimulation of naturally occurring microorganisms to degrade the oil, either through the addition of nutrients or the manipulation of environmental conditions. Microorganisms such as bacteria and fungi play a crucial role in breaking down hydrocarbons present in oil, ultimately reducing their toxicity and environmental impact (Premnath et al., 2021). Examples of bioremediation methods in oil spill treatment include:

Biostimulation: Biostimulation involves the addition of nutrients, such as nitrogen and phosphorus, to the environment to stimulate the growth of indigenous microorganisms capable of degrading oil. These nutrients enhance the metabolic activity of microorganisms, accelerating the biodegradation process.

Bioaugmentation: Bio-augmentation involves the introduction of specialized microbial cultures or enzymes to the oil-contaminated environment to enhance the biodegradation of oil. These introduced microorganisms or enzymes may have specific capabilities to degrade hydrocarbons efficiently.

Landfarming: Land farming, also known as bio-piling, involves the spreading of contaminated soil or sediment in a controlled environment and stimulating the growth of indigenous microorganisms to degrade the oil. This method is often used for onshore oil spill remediation. Studies have shown that land farming promotes the degradation of various hydrocarbons by indigenous microbial communities [26].

Bioventing: Bioventing is a technique used to enhance the aerobic biodegradation of oil vapours in the soil by supplying oxygen to Indigenous microorganisms. This method is particularly effective for treating subsurface oil contamination. Research has demonstrated the effectiveness of bio-venting in treating subsurface oil contamination at spill sites and petroleum storage facilities [42]. Bioremediation methods harness the natural abilities of microorganisms to degrade oil and can be applied in both marine and terrestrial environments to mitigate the environmental impact of oil spills.

5.5 Factors Affecting Methods of Oil Spill

Oil spills pose significant environmental threats, demanding effective mitigation strategies. Various factors influence the selection and efficacy of treatment methods, ranging from the type of oil spilled to environmental conditions and technological capabilities. Concurrently, the exploration of alternative sorbent materials, such as ginger fibre, introduces another dimension to oil spill remediation efforts, with considerations extending from suction capacity determination to reutilization potential. Factors Influencing Oil Spill Treatment Methods:

Oil Type: Different types of oil possess distinct physical and chemical properties, impacting their behaviour in aquatic environments and responses to treatment methods. For instance, heavy oils tend to linger longer, requiring specialized approaches for containment and removal [34].

Environmental Conditions: Factors like temperature, water currents, and weather conditions significantly affect oil spill behaviour and treatment effectiveness. Cold temperatures can increase oil viscosity, complicating cleanup efforts, while strong currents may disperse oil over larger areas, necessitating rapid response strategies [40].

Proximity to Sensitive Ecosystems: Oil spills occurring near sensitive ecosystems, such as coral reefs or mangrove forests, present unique challenges due to the heightened risk of ecological damage. Treatment methods must prioritize minimizing environmental impact while effectively containing and removing spilled oil [43].

Resource Availability and Technology: The availability of resources, including equipment, manpower, and funding, influences the choice and implementation of oil spill treatment methods. Advanced technologies, such as unmanned aerial vehicles (UAVs) and satellite monitoring, enhance response capabilities but may not be readily accessible in all regions [38].

6. SORBENT MATERIALS FOR OIL CLEAN-UP

6.1 Mechanism of sorption

Sorption is a common term used for both absorption and adsorption processes [44]. Mechanism of Sorption for Oil Spill Cleanup, the process by which substances are adsorbed or absorbed onto a surface, plays a crucial role in oil spill cleanup. Understanding the mechanisms of sorption is essential for developing effective strategies to remove oil from contaminated environments and mitigate environmental damage.

Adsorption Mechanism: Adsorption refers to the adherence of oil molecules onto the surface of a sorbent material as illustrated in Figure 3. This process occurs due to the attractive forces between the oil molecules and the surface of the sorbent material [45]. The surface of the sorbent material plays a critical role in adsorption, as it provides sites for oil molecules to adhere. Materials with a high surface area and specific surface chemistry are more effective in adsorbing oil molecules [46]. Hydrophobic materials are particularly effective in adsorbing oil molecules due to their strong affinity for non-polar substances. The hydrophobic nature of the sorbent material promotes the adsorption of oil while repelling water [47]. Adsorption is a rapid process, as oil molecules can quickly adhere to the surface of the sorbent material upon contact. However, the capacity of the sorbent material to adsorb oil may become saturated over time, limiting its effectiveness [7].

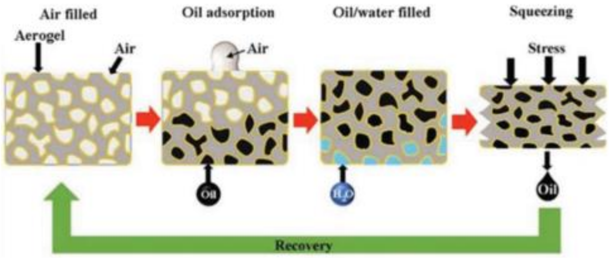

Figure 3. Adsorption mechanism of oil to fill pore space of graphene structures [48]

Absorption Mechanism: Absorption involves the penetration of oil molecules into the pores or structure of the sorbent material (Figure 4). Unlike adsorption, which occurs on the surface of the material, absorption occurs within the bulk of the material [49]. The pore structure of the sorbent material significantly influences its absorption capacity. Materials with well-defined pores provide ample space for oil molecules to infiltrate, increasing the overall absorption capacity [50]. Absorption is a slower process compared to adsorption, as it involves the diffusion of oil molecules into the interior of the sorbent material. However, absorption can result in higher oil retention capacity, as oil molecules are securely trapped within the structure of the material [51].

Surface Interaction: The surface interaction mechanism is a fundamental aspect of the sorption process for oil spill cleanup, influencing the adhesion and retention of oil molecules onto the sorbent material's surface. Understanding this mechanism is crucial for optimizing sorbent materials and enhancing their effectiveness in mitigating the environmental impact of oil spills. The effectiveness of sorption depends on the interaction between the oil molecules and the surface of the sorbent material. Hydrophobic materials exhibit a strong affinity for non-polar oil molecules, facilitating their adhesion and retention [14]. Surface chemistry plays a critical role in determining the sorption capacity and selectivity of the sorbent material. Functional groups present on the surface of the material may interact with specific components of the oil, influencing adsorption kinetics and sorption [52]. The surface roughness and topography of the sorbent material also influence surface interactions. Materials with a rough surface texture may provide more sites for oil molecules to adhere to, enhancing sorption performance [53]. Furthermore, electrostatic interactions between the oil molecules and the surface of the sorbent material may contribute to sorption behaviour. Materials with polar functional groups may exhibit electrostatic interactions with polar components of the oil, influencing sorption kinetics and oil retention [54]. Understanding and optimizing surface interactions is essential for developing sorbent materials with enhanced oil sorption capabilities. By tailoring the surface chemistry, texture, and topography of sorbent materials, researchers can improve their effectiveness in oil spill cleanup operations.

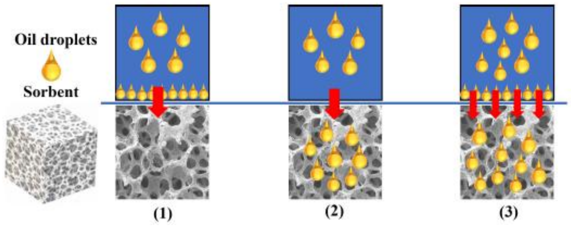

Figure 4. Schematic diagram of oil absorption process. (1) oil droplets accumulate on the surface of sorbents via weak interaction forces; (2) oil droplets penetrate the intermolecular of sorbents under the capillary forces; (3) both surface accumulation and intermolecular penetration exist [55]

Pore Structure: The pore structure of sorbent materials refers to the arrangement, size, and distribution of pores within the material. Materials with a high surface area and well-defined pore structure provide more sites for oil molecules to adhere or penetrate, thereby enhancing sorption performance [56]. The size of pores within the sorbent material affects the accessibility of oil molecules to the sorption sites. Materials with a range of pore sizes, including micro-, meso--, and macro-pores, can accommodate oil molecules of varying sizes, maximizing sorption capacity [54]. The distribution of pores within the sorbent material influences the diffusion of oil molecules into the material's structure. Materials with a homogeneous pore distribution facilitate uniform oil uptake and retention, ensuring efficient sorption throughout the material [57]. The interconnectedness of pores within the sorbent material is critical for facilitating the transport of oil molecules into the material's interior. Materials with interconnected pores allow for unhindered diffusion of oil molecules, enhancing sorption kinetics and overall efficiency [54]. Tailoring the pore structure of sorbent materials through methods such as templating, carbonization, or chemical modification enables the optimization of sorption performance for specific oil spill cleanup applications [58].

Chemical Composition: The chemical composition of sorbent materials plays a significant role in the sorption process for oil spill cleanup, influencing sorption behaviour, selectivity, and efficiency. Understanding the chemical composition mechanism is essential for designing sorbent materials with tailored properties to effectively mitigate the environmental impact of oil spills. The presence of functional groups on the surface of sorbent materials governs their interaction with oil molecules. Functional groups such as hydroxyl (-OH), carboxyl (-COOH), and amine (-NH_2) groups can form hydrogen bonds or undergo other chemical interactions with oil molecules, influencing sorption kinetics and selectivity [59]. The polarity of functional groups on the sorbent material's surface affects their affinity for polar or non-polar components of the oil. Materials with polar functional groups may exhibit stronger interactions with polar oil components, while materials with non-polar functional groups may preferentially adsorb non-polar oil molecules [60]. The abundance and distribution of functional groups on the sorbent material's surface influence sorption capacity and efficiency. Materials with a higher density of functional groups may offer more sites for oil molecule interaction, enhancing sorption performance [61]. Chemical modification of sorbent materials through processes such as grafting, impregnation, or surface coating allows for the incorporation of specific functional groups to tailor sorption properties. This enables the design of sorbent materials with enhanced affinity for target oil components and improved overall sorption performance [62]. The stability of chemical bonds between the sorbent material and oil molecules impacts sorption durability and reusability. Materials with strong, reversible bonds can undergo multiple sorption-desorption cycles without significant degradation, prolonging their effective lifespan for oil spill cleanup [60]. By understanding and manipulating the chemical composition of sorbent materials, researchers can develop tailored solutions for oil spill cleanup that effectively target specific oil components while minimizing environmental impact.

6.2 Isotherm for sorption process

Isotherms for sorption processes serve as fundamental tools in understanding the interaction between adsorbate molecules and solid surfaces. These isotherms depict the relationship between the amount of adsorbate molecules adsorbed onto a solid adsorbent and the concentration of the adsorbate in the gas or liquid phase, under conditions of constant temperature. One of the seminal works in this field is the Langmuir isotherm, proposed by Irving Langmuir in 1916. The Langmuir model assumes monolayer adsorption on a homogenous surface with no interaction between adsorbate molecules once a monolayer is formed. However, the Langmuir model has its limitations, particularly in situations where adsorption occurs in multiple layers or on heterogeneous surfaces. To address these shortcomings, alternative models have been developed. Among these is the Freundlich isotherm, introduced by Herbert Freundlich in 1906. The Freundlich model accounts for heterogeneous surface adsorption and permits multilayer adsorption, making it more suitable for describing a broader range of adsorption phenomena. Another significant advancement in isotherm modelling is the BET (Brunauer, Emmett, and Teller) theory, established in 1938 by Stephen Brunauer, Paul Hugh Emmett, and Edward Teller. The BET isotherm extends the Langmuir model by incorporating the formation of multilayer adsorption on a heterogeneous surface, considering different adsorption energies for each layer. The choice of the isotherm model depends on various factors, including the specific characteristics of the adsorbate and adsorbent, as well as the experimental conditions. Researchers often employ multiple isotherm models and compare their fits to experimental data to determine the most appropriate model for a particular adsorption system. In recent years, advancements in experimental techniques and computational methods have led to the development of more sophisticated isotherm models. These models aim to capture complex adsorption phenomena, such as cooperative adsorption, surface heterogeneity, and non-ideal behaviour. Such advancements have enhanced our understanding of sorption processes in diverse applications, including environmental remediation, gas separation, and purification.

7. MATERIALS USED FOR OIL SORPTION

Materials for oil sorption in spill cleanup operations include a diverse array of substances, each suited to specific types and stages of spills. Sorbents, which absorb or adsorb oil from water, represent a primary category of materials. Polypropylene-based sorbents, such as pads and booms, are frequently employed due to their high oil sorption capacity and buoyancy, facilitating efficient recovery from water surfaces [63]. Biological agents like oleophilic bacteria and enzymes provide an eco-friendly alternative, accelerating oil degradation; research by Bharali et al. [64] underscores the role of microbial consortia in breaking down hydrocarbons, thereby enhancing bioremediation in oil-contaminated areas.

Chemical dispersants also play a key role, breaking oil slicks into smaller droplets that disperse more easily and biodegrade faster. However, the application of dispersants must be carefully evaluated for ecological impacts, as noted in studies by Merlin et al. [65]. Beyond traditional sorbents, innovative materials like graphene-based nanomaterials are being investigated for their superior oil sorption and reusability. For instance, Chowdhury et al. [66] demonstrated the high capacity and reuse potential of graphene-based aerogels, pointing to their promise in advanced oil spill technologies.

Natural sorbents like hay, straw, and peat moss have long been used for oil absorption, although they typically offer lower efficiency compared to synthetic options. Al-Jammal & Juzsakova [67] discuss the practicality of using natural sorbents in spill cleanup, emphasizing their biodegradability and ease of access. Meanwhile, magnetic nanoparticles present a novel approach, enabling targeted recovery of oil through magnetic separation. Research by Qiao et al. [68] highlights the effectiveness of magnetic nanocomposites in selectively removing oil, providing a sustainable and efficient cleanup option.

Sorbents are broadly categorized into seven classes: bio-sorbents, activated carbons, biochars, polymers and resins, clays and minerals, nanoparticles, and composites [32]. Among these, bio-sorbents are most commonly used for their availability and ease of preparation, whereas activated carbon, clays, and minerals see less frequent application. Typical examples of bio-sorbent materials include rice straw, wood fibre, sawdust, cotton, kapok, luffa, kenaf, coconut husk, and bagasse, among others [25]. Numerous studies have investigated the oil sorption potential of these materials, focusing on properties such as hydrophobicity or oleophilicity, high uptake capacity, buoyancy, durability, reusability, biodegradability, and oil recovery [8]. Since it may be difficult to find a single material with all these qualities, compromises are often necessary in selecting the most appropriate sorbent.

A comprehensive oil spill response considers the optimal use of these materials and technologies, carefully assessing factors like the type of oil spilled, spill size, and environmental conditions to maximize efficiency and minimize ecological impact. Sorbents are most often used to remove final traces of oil, or in areas that cannot be reached by skimmers. Once sorbents have been used to recover oil, they must be removed from the water and properly disposed of on land or cleaned for reuse. Any oil that is removed from sorbent materials must also be properly disposed of or recycled. Sorbent materials for oil spills present urgent environmental challenges, necessitating effective cleanup strategies. Sorbent materials play a crucial role in mitigating the impact of oil spills by adsorbing and removing oil from contaminated surfaces. A diverse range of sorbents, including natural, synthetic, and composite materials, have been investigated for their efficacy in oil spill cleanup applications [69].

Natural organic: Natural sorbents, such as peat moss, sawdust, and cotton, offer advantages in terms of biodegradability and cost-effectiveness [60]. They are relatively inexpensive and usually readily available. Organic sorbents can soak up from 3 to 15 times their weight in oil, but they do present some disadvantages. Some organic sorbents tend to soak up water as well as oil, causing them to sink. Many organic sorbents are loose Application of sorbents. Photo courtesy of US Coast Guard particles, such as sawdust, and are difficult to collect after they are spread on the water. Adding flotation devices, such as empty drums attached to sorbent bales of hay, can help to overcome the sinking problem, and wrapping loose particles in the mesh will aid in the collection. These materials have demonstrated promising performance in absorbing and retaining oil from aqueous environments, making them suitable candidates for oil spill remediation efforts [47].

Natural inorganic sorbents: Include clay, perlite, vermiculite, glass, wool, sand, and volcanic ash. They can absorb from 4 to 20 times their weight in oil. Inorganic substances, like organic substances, are inexpensive and readily available in large quantities.

Synthetic sorbents: Synthetic sorbents, such as polypropylene and polyurethane foam, possess high oil absorption capacities and can be engineered to target specific types of oil and environmental conditions [60]. Most synthetic sorbents can absorb as much as 70 times their weight in oil, and some types can be cleaned and reused several times. Synthetic sorbents that cannot be cleaned after they are used can present difficulties because they must be stored temporarily until they can be disposed of properly. However, concerns regarding the environmental impact and long-term persistence of synthetic sorbents have prompted researchers to explore alternative materials with reduced ecological footprint [70].

Composite sorbents: Combining natural and synthetic components, aims to harness the benefits of both material types while mitigating their respective drawbacks [71]. These hybrid sorbents offer improved oil absorption capacities and environmental sustainability, making them attractive options for oil spill cleanup operations [36].

The following characteristics must be considered when choosing sorbents for cleaning up spills:

- **Rate of absorption**—The rate of absorption varies with the thickness of the oil. Light oils are soaked up more quickly than heavy ones.
- **Oil retention**—The weight of recovered oil can cause a sorbent structure to sag and deform. When it is lifted out of the water, it can release oil that is trapped in its pores. During the recovery of absorbent materials, lighter, less viscous oil is lost through the pores more easily than heavier, more viscous oil.
- **Ease of application**—Sorbents may be applied to spills manually or mechanically, using blowers or fans. Many natural organic sorbents that exist as loose materials, such as clay and vermiculite, are dusty, difficult to apply in windy conditions, and potentially hazardous if inhaled.

7.1 Factors affecting materials for sorption

The performance of materials used for remediation in hydrocarbon-contaminated environments is significantly influenced by their surface area, pore structure, and functional group chemistry. These factors play critical roles in enhancing the material's effectiveness in tasks such as adsorption, separation, and oil spill cleanup. Various studies have highlighted the importance of these characteristics.

In the context of petroleum hydrocarbon contamination, biochar has been demonstrated to possess a high surface area, which provides more active sites for the adsorption of pollutants. The extensive surface area of biochar-based materials allows them to adsorb larger quantities of hydrocarbons, thus improving their efficiency in soil and water remediation. Wei et al., [72] noted that the performance of biochar-based sorbents is closely related to their specific surface area and microporous structure, which enable greater interaction with petroleum contaminants. Similarly, the surface area of nanocellulose composites has been identified as a key factor for improving their oil sorption capabilities. In their review, Muhammad et al., [73] emphasized that enhancing the surface area of biomass-based aerogels can lead to better oil spill cleanup performance due to increased exposure to the contaminant molecules.

The pore structure of these materials is equally critical, as it dictates the accessibility and diffusion of hydrocarbons within the material. Pore size distribution and the volume of pores in biochar-based materials and cellulose-derived aerogels are crucial in determining their efficiency. Materials with a high proportion of mesopores and macropores provide better access for larger hydrocarbon molecules, while micropores are effective for smaller molecules. This structure facilitates a combination of adsorption and capillary action, which is essential for the removal of oils and other organic contaminants from affected water or soil. Studies by Soares et al., [74] highlighted that the pore structure of nanocellulose-based sorbent composites greatly impacts their sorption properties, with optimal pore sizes improving the rate of contaminant uptake. Likewise, the pore architecture in cellulose aerogels, as reviewed by Zhai et al., [75], allows for efficient separation of oil from water, with the ability to trap oil molecules while repelling water, showcasing the importance of tailoring pore size distribution in materials for oil spill remediation.

Functional group chemistry also plays a pivotal role in the performance of these materials. The presence of functional groups such as hydroxyl, carboxyl, and phenolic groups can significantly influence the adsorption of hydrophobic pollutants. These groups can enhance the interaction between the sorbent material and the oil molecules, increasing the overall efficiency of the cleanup process. Functionalization of biochar, for example, can introduce additional chemical sites that increase its affinity for hydrophobic substances, improving its performance in oil spill scenarios. In their study, Zamparas et al., [76] emphasized that natural-based modified materials, including biochar, with tailored functional groups, show promising results for oil spill cleanup by enhancing the hydrophobicity and adsorption capacity of the materials. Similarly, the modification of cellulose aerogels with functional groups like carboxyl and amine has been shown to increase their affinity for oil, as discussed by Chhajed et al., [77], further confirming the role of chemical modifications in improving performance.

7.2 Utilization used for sorbents

After the initial absorption of oil using biomass as a sorbent, exploring reutilization methods becomes crucial in tackling the problem of oil spills across various applications. One promising approach is the carbonization of the used sorbent material [78]. Wong *et al*., [79] have demonstrated the effectiveness of carbonization in transforming organic waste materials into activated carbon, which possesses enhanced adsorption properties. The carbonization process involves heating the used sorbent material to high temperatures in the absence of oxygen, resulting in the decomposition of organic components and the formation of a carbon-rich structure. This transformation enhances the surface area and porosity of the material, thereby increasing its capacity to adsorb oil and other hydrocarbons. Research by Shaer *et al*., [80] has shown that carbonized sorbents derived from natural fibres exhibit superior adsorption capacities compared to their non-carbonized counterparts. The carbonization process can help address concerns regarding the disposal of used sorbent materials. Instead of ending up in landfills or incinerators, which can contribute to environmental pollution, the carbonized sorbents can be repurposed for various applications. For instance, activated carbon derived from carbonized ginger fibre sorbents can be utilized in wastewater treatment, air purification, and even as a component in rechargeable batteries [81]. In addition to its environmental benefits, the reutilization of used sorbents through carbonization offers economic advantages by providing a cost-effective alternative to traditional disposal methods. By transforming waste materials into valuable resources, this approach aligns with the principles of the circular economy, where resources are kept in use for as long as possible.

7.4 Different methods of conversion of used sorbents

Pyrolysis involves heating the sorbent material, such as ginger fibre, in the absence of oxygen to thermally decompose the absorbed oil. This process typically occurs at temperatures ranging from 300 to 800 °C [82]. During pyrolysis, the organic components of the absorbed oil break down into smaller molecules, producing gases, liquids, and char residues [83]. Vamvuka (2011) investigated the pyrolysis of oil-saturated sorbents, including plant-based materials, to recover energy and valuable products. Their study highlighted the potential of pyrolysis for oil recovery and sorbent regeneration.

Biomass includes the by-products and residues of farm products and agricultural processing industries, such as husks, cobs, leaves, straw, stalks, barks, grains, and weeds [85]. These materials have long remained the primary energy source for household usage in many underdeveloped and developing countries [86]. It is the only renewable energy source that can be utilized to make biofuel [87], and one of the techniques to achieve this in modern times is thermal conversion through retort carbonization. Carbonization is a slow pyrolysis process in which biomass is converted into a highly carbonaceous, charcoal-like material referred to as *biochar* [88]. Typically, it involves heating the biomass in the absence or insufficiency of oxygen, and reaction conditions can be tailored to maximize the production of the char. The characteristic feature that distinguishes carbonization from other, dry thermochemical conversion techniques is the heating time- it is significantly longer. However, this long duration results in a high yield of char with better porous properties. An overview of other characteristic features is highlighted in Table 3.

Table 3. Typical Reaction Conditions and Product Yields in wt% from Different Types of (Dry) Thermochemical Conversion Processes (Bridgwater, 2012; Nachenius et al., 2013)

Properties	**Thermochemical Conversion Process Type**			
	Fast Pyrolisis	**Carbonization**	**Gasification**	**Torrefaction**
Temperature	~500°C	>400°C	600-1800°C	<300°C
Heating rate	Fast, up to 100°C	<80 °C/min	-	-
Reaction time	Few seconds	Hours ~days	-	<2h
Pressure	Atmospheric (and vacuum)	Atmospheric (or elevated up to 1MPa)	Oxygen-limited (air or steam/oxygen)	Oxygen-free
Medium	Oxygen-free	Oxygen-free or Oxygen-limited	Oxygen-limited (air or steam/oxygen)	Oxygen-free
Liquids (Bio-oil)	75%	30%	5%	5%
Noncondensable gases	13%	35%	85%	15%
Char/Solids	12%	35%	10%	80%

Gasification involves subjecting the sorbent material to high temperatures and controlled amounts of oxygen or steam to produce a combustible gas mixture known as syngas. This process occurs at temperatures above 700 °C [89]. Ali *et al*., [90] explored gasification as a method for treating oil-contaminated sorbents, demonstrating its potential for energy recovery and sorbent regeneration. Gasification offers a pathway for utilizing the energy content of the oil while simultaneously regenerating the sorbent material by converting the absorbed oil into syngas [91].

Hydrothermal treatment utilizes water at elevated temperatures and pressures to chemically decompose the absorbed oil and regenerate the sorbent material. This process typically occurs at temperatures above 200 °C and pressures above atmospheric pressure [92]. Zamparas *et al*., [69] Investigated the hydrothermal treatment of oil-contaminated sorbents, highlighting their effectiveness in removing oil and recovering the sorbent's adsorption capacity. Hydrothermal treatment offers a sustainable approach to sorbent regeneration by utilizing water as a medium for oil removal and sorbent recovery [93].

Catalytic Conversion: Catalytic conversion involves the use of catalysts to enhance thermochemical processes such as pyrolysis or gasification for more efficient oil recovery and sorbent regeneration [94]. Claydon, [95] explored the catalytic pyrolysis of oil-saturated sorbents, indicating improved oil recovery and sorbent reusability compared to non-catalytic methods. By facilitating the decomposition of absorbed oil at lower temperatures and promoting the formation of valuable products, catalytic conversion enhances the overall efficiency of sorbent regeneration processes [7].

7.5 Biomass-based and synthetic sorbents

The synthesis and application of advanced materials for oil-water separation and spill cleanup have seen significant progress, offering solutions to critical environmental challenges. The reviewed studies present innovative approaches leveraging diverse mechanisms, material properties, and fabrication techniques to enhance oil absorption, separation efficiency, durability, and scalability, as well as address the viscosity challenges of crude oil. These advancements collectively contribute to the broader objectives of environmental sustainability and pollution control. Table 4 shows a list of both biomass-based and synthetic sorbents with their respective features.

In Lu et al., [96], the superhydrophilic Cu-HHTP@Cu foam and its superhydrophobic counterpart, PDMS@Cu-HHTP@Cu foam, demonstrated excellent oil/water separation efficiency and durability. Notably, the hierarchical structure and photothermal conversion properties of the modified foam enabled rapid reduction of crude oil viscosity under simulated sunlight, thereby facilitating effective cleanup. This multifunctionality addresses key challenges such as handling high-viscosity oils and achieving long-term performance. Additionally, the material's stability under acidic, alkaline, and saline conditions reinforces its practical applicability in diverse environmental settings, highlighting its potential for real-world implementation.

The work by Fu et al., [97] introduced SNC-g-P(MA-co-PMMA), a high-oil-absorbing resin prepared via grafting spherical nanocrystalline cellulose with methacrylic acid and methyl methacrylate. The porous structure and large specific surface area enhanced oil absorbency, while thermal stability allowed usage in high-temperature environments. These features, combined with the cost-effectiveness of cellulose as a raw material and the simplicity of the manufacturing process, make this resin a promising candidate for large-scale production and deployment in oil pollution mitigation.

Table 4. Comparison of Oil Absorption Capacities and Performance Metrics

Material	**Type**	**Oil Absorption Capacity (g/g)**	**Key Features**	**Ref**
Superhydrophobic Fe3O4/PAN/PBA Nanofibrous Aerogel (NFA)	Synthetic	54.4–97.1	Ultra-high absorption for oils and solvents; photothermal and magnetothermal effects for crude oil recovery (6.67 x 10^3 kg/m^3·h).	[101]
Recycled PET with PEG and HDIT	Synthetic	~22	Sustainable use of PET waste; effective oil-water separation with high flux (~726.7 L/m^2·h under gravity). >97% (oil-water emulsion)	[102]
Electrospun nanofibrous membranes based on fluorine-free polyimide.	Synthetic	35–60	Hydrophobic with water contact angle of 114° and oil contact angle of ~0°. Rapid sorption with equilibrium reached in minutes for crude oil. High flux (1991 L/m^2/h for dodecane, 1508 L/m^2/h for n-hexane, 206 L/m^2/h for crude oil).	[99]
Carbonized sponge (P-Fe_3O_4@CMS)	Synthetic	45.3–88.5	Superhydrophobic and magnetically responsive. Self-heating ability with high compressibility. Pump-assisted continuous oil recovery with a high flux of 785 kg/m^2/h.	[100]
PVA/CNC Membranes	Biomass-based	17.01–113.76	High absorption is influenced by oil viscosity, with exceptional reusability and separation efficiency (>99%).	[103]
SNC Resin	Biomass-based	8.5	High thermal stability, with effective network volume and surface area for enhanced absorption.	[97]
LPUF Foam	Biomass-based	13.2–53.0	High hydrophobicity (WCA = 151.3°) and mechanical performance, with flame retardancy for safe oil absorption.	[98]

Cui et al., [98] presented a lignin-based polyurethane foam modified with aluminium 12-hydroxy stearate (Al HSA) and expanded graphite (EG). The resulting composite demonstrated exceptional oil sorption capacity and hydrophobicity, alongside enhanced mechanical resilience and flame retardancy. The biomimetic microstructure and the inclusion of organogelator components facilitated efficient oil retention and recyclability, even after repeated use. The combination of high porosity and robust physical properties suggests that this material is suitable for continuous oil/water separation and provides a sustainable approach to remediating oil spills and organic solvent pollution.

The electrospun fluorine-free polyimide nanofibrous membranes developed by Alharthi and Abdulhamid, [99] further contribute to advancements in oil spill cleanup technology. These membranes exhibited high adsorption capacities, rapid sorption kinetics, and impressive flux rates for various oils. Their hydrophobic nature and recyclability, coupled with stability at high temperatures, underline their effectiveness in real-world applications. The scalability of these membranes through industrial electrospinning also positions them as viable candidates for addressing large-scale oil and chemical spillages.

Liu et al., [100] tackled the challenge of high-viscosity crude oil by introducing a multifunctional, superhydrophobic, and magnetically responsive carbonized sponge. The sponge's electro-thermal and photo-thermal conversion capabilities enabled significant viscosity reduction, enhancing oil absorption speed and recovery efficiency. The pump-assisted continuous oil recovery system showcased the sponge's adaptability for energy-efficient, all-weather operation. Its straightforward fabrication process and 24/7 functionality underscore its practical value in addressing oil spill remediation challenges under varying environmental conditions.

While synthetic materials may excel in certain attributes, biomass-derived materials like PVA/CNC membranes with 113.76 g/g absorption capacity offer sustainable and competitive performance. Collectively, these studies underscore the transformative potential of engineered materials in oil spill cleanup and water-oil separation technologies. They highlight key innovations, including the integration of photothermal conversion for viscosity reduction, incorporation of cost-effective and biodegradable raw materials, enhancement of mechanical and thermal properties, and scalability for industrial applications. However, future research should address specific challenges, such as further optimizing material performance under extreme environmental conditions, reducing manufacturing costs for widespread adoption, and evaluating the long-term environmental impacts of these materials. By building on these advances, researchers can continue to refine and expand the applicability of these promising solutions to global environmental challenges.

4. CONCLUSION

Oil spill cleanup remains a critical environmental and ecological challenge with profound implications for marine ecosystems and coastal regions. This review has evaluated various oil spill remediation methods, including mechanical containment and recovery, chemical dispersion, in-situ burning, bioremediation, and sorption. Among these, sorption stands out as a particularly promising approach, especially when employing biomass-derived sorbent materials due to their sustainability, cost-effectiveness, and environmentally friendly properties.Biomass sorbents offer significant advantages over synthetic alternatives, such as biodegradability, renewability, and the potential for chemical modification to enhance sorption efficiency. Their adaptability enables the optimization of surface area, pore structure, and functional group composition, resulting in superior oil retention capacity, stability, and reusability. Despite these benefits, challenges related to their mechanical strength, stability under marine conditions, and scalability must be addressed to maximize their potential.

To advance the application of biomass sorbents for oil spill cleanup, future research should focus on:

- **Enhancing Material Performance**: Developing biomass sorbents with improved surface area, pore structure, and functional groups to boost sorption efficiency and oil affinity while maintaining hydrophobicity and water resistance.

- **Improving Mechanical Stability**: Investigating treatments or hybrid designs that integrate biomass with synthetic or inorganic materials to enhance mechanical strength and durability in harsh marine environments.

- **Assessing Environmental Impact**: Conducting studies on the long-term effects of biomass sorbents on marine ecosystems, including degradation byproducts and potential secondary contamination, while leveraging life cycle assessments to evaluate their environmental footprint.

- **Scalability and Cost Efficiency**: Exploring cost-effective, high-yield production methods to make biomass sorbents viable for large-scale applications, alongside assessing their economic feasibility compared to conventional methods.

- **Field Testing and Real-World Applications**: Performing field trials in diverse marine environments to validate laboratory findings, addressing variables such as wave action, temperature fluctuations, and oil composition to understand their practical performance.

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REFERENCES

[1] M. L. Bender, M. Frantzen, L. Camus, S. Le Floch, J. Palerud, and J. Nahrgang, (2018) 468–477.

[2] J. Short, (2003) 509–517.

[3] L. N. Dornberger, “Using Ecosystem-Based Modeling to Describe an Oil Spill and Assess the Long-Term Effects,” University of South Florida, 2018.

[4] R. Al-Ruzouq, (2020) 3338. doi: 10.3390/rs12203338.

[5] A. Bejarano, E. Levine, and A. Mearns, (2013) 185. doi: 10.1007/s10661-013-3332-y.

[6] B. Laffon, E. Pásaro, and V. Valdiglesias, (2016) 105–128. doi: 10.1080/10937404.2016.1168730.

[7] S. Hammouda, Z. Chen, C. An, and K. Lee, (2021) 127630. doi: 10.1016/j.jclepro.2021.127630.

[8] N. A. binti Nordin, “Oil Spill Cleanup using Raw Kapok as the Sorbent Material,” Universiti Teknologi PETRONAS, 2013.

[9] R. Gautam, A. Mudhoo, G. Lofrano, and M. Chattopadhyaya, (2013).

[10] H. Cheng, (2020) 101253. doi: 10.1016/j.progpolymsci.2020.101253.

[11] O. M. Lawal and N. C. Nwokem, (2017) 973–975.

[12] H. J. Perera, A. Goyal, S. M. Alhassan, and H. Banu, (2022) 5310. doi: 10.3390/polym14235310.

[13] Z. Raji, A. Karim, A. Karam, and S. Khalloufi, (2023) 74–91. doi: 10.1016/j.tifs.2023.05.004.

[14] Y. Wang, Z. Guo, and W. Liu, (2021) 4895–4928.

[15] S. M. Abegunde, K. S. Idowu, O. M. Adejuwon, and T. Adeyemi-Adejolu, (2020) 100001. doi: https://doi.org/10.1016/j.resenv.2020.100001.

[16] L. M. Macdonald, M. Williams, D. Oliver, and R. Kookana, (2015) 142–147.

[17] V. Singh, S. Jinka, K. Hake, S. Parameswaran, R. Kendall, and S. Ramkumar, (2014) 11954–11961. doi: 10.1021/ie5019436.

[18] S. E. Allan, B. W. Smith, and K. A. Anderson, (2012) 2033–2039. doi: 10.1021/es202942q.

[19] M. Husseien, A. Amer, A. El- Maghraby, and N. Taha, (2008).

[20] H. O. Nwabueze, P. N. Chiaha, B. C. Ezekannagha, and O. E. Okoani, (2016) 53–59.

[21] J. O. Nwadiogbu, V. I. E. Ajiwe, and P. A. C. Okoye, (2016) 56–63. doi: 10.1016/j.jtusci.2015.03.014.

[22] N. Duc, (2018) 201. doi: 10.15625/2525-2518/54/2A/11931.

[23] S. C. Pennings, B. D. McCall, and L. Hooper-Bui, (2014) 789–795. doi: 10.1093/biosci/biu118.

[24] N. K. Shah, Z. Li, and M. G. Ierapetritou, (2011) 1161–1170. doi: 10.1021/ie1010004.

[25] R. Asadpour, N. Sapari, and Z. Harith, (2013) 46–57.

[26] M. O. Mafiana, M. D. Bashiru, F. Erhunmwunsee, C. G. Dirisu, and S.-W. Li, (2021) 4073–4094. doi: 10.1007/s11356-020-11533-1.

[27] J. E. Johnston, E. Lim, and H. Roh, (2019) 187–199. doi: 10.1016/j.scitotenv.2018.11.483.

[28] R. Olawoyin, S. A. Oyewole, and R. L. Grayson, (2010) 120–130.

[29] A. D. Ogbu, W. Ozowe, and A. H. Ikevuje, (2024) 208–227. doi: 10.30574/gscarr.2024.20.1.0262.

[30] A. A. Al-Majed, A. R. Adebayo, and M. E. Hossain, (2012) 213–227.

[31] M. M. Nuhu, E. R. Rene, and A. Ishaq, (2017) 21793. doi: 10.1002/tqem.21793.

[32] E. C. Emenike, (2022) 103330. doi: 10.1016/j.jwpe.2022.103330.

[33] A. Dhaka and P. Chattopadhyay, (2021) 112428.

[34] J. Michel and M. Fingas, (2016) 159–201. doi: 10.1142/9789814699983_0007.

[35] M. Naseri, J. Barabady, T. Nowakowski, M. Młyńczak, A. Jodejko-Pietruczuk, and S. Werbińska-Wojciechowska, (2015) 6017–614.

[36] A. T. Hoang, X. P. Nguyen, X. Q. Duong, and T. T. Huynh, (2021) 28876–28910.

[37] M. A. Abdullah, A. U. Rahmah, and Z. Man, (2010) 683–691. doi: 10.1016/j.jhazmat.2009.12.085.

[38] P. Li, Q. Cai, W. Lin, B. Chen, and B. Zhang, (2016) 6–27.

[39] D. Dimitrakiev, Y. Dachev, and D. Milev, (2020) 710–712.

[40] Y. K. Adofo, E. Nyankson, and B. Agyei-Tuffour, (2022) e10153.

[41] M. Fingas, (2011) 737–903. doi: 10.1016/B978-1-85617-943-0.10023-1.

[42] B. Macaulay and D. Rees, (2014) 9–37.

[43] I. B. Ivshina, (2015) 1201–1219.

[44] C. Karan, R. Rengasamy, and D. Das, (2011).

[45] N. Bhardwaj and A. N. Bhaskarwar, (2018) 1758–1771. doi: 10.1016/j.envpol.2018.09.141.

[46] E. K. Sam, J. Liu, and X. Lv, (2021) 2353–2364.

[47] J. Ge, H. Zhao, H. Zhu, J. Huang, L. Shi, and S. Yu, (2016) 10459–10490.

[48] P. L. Yap, M. J. Nine, K. Hassan, T. T. Tung, D. N. H. Tran, and D. Losic, (2021) 2007356. doi: 10.1002/adfm.202007356.

[49] J. Zhang, G. Lu, and Z. You, (2020) 108340.

[50] L. Jiang and Z. Fan, (2014) 1922–1945. doi: 10.1039/C3NR04555B.

[51] Y. Lu, Y. Zhu, F. Yang, Z. Xu, and Q. Liu, (2021) 2004082.

[52] D. Angelova, I. Uzunov, S. Uzunova, A. Gigova, and L. Minchev, (2011) 306–311.

[53] A. T. Hoang, S. Nižetić, X. Q. Duong, L. Rowinski, and X. P. Nguyen, (2021) 130274.

[54] N. Babanejad, K. Mfoafo, E. Zhang, Y. Omidi, R. Razeghifard, and H. Omidian, (2022) 463546.

[55] D. Ouyang, X. Lei, and H. Zheng, (2023) 620.

[56] J. Dai and H. Zhang, (2021) 2005334. doi: 10.1002/smll.202005334.

[57] S. Dutta et al, (2017) 522–545.

[58] L. M. T. M. Oliveira, J. Saleem, A. Bazargan, J. L. D. S. Duarte, G. McKay, and L. Meili, (2020) 124842. doi: 10.1016/j.jhazmat.2020.124842.

[59] J. Li et al.,(2022) 118789.

[60] Q.-W. Zhang, L.-G. Lin, and W.-C. Ye, (2018) 20. doi: 10.1186/s13020-018-0177-x.

[61] F. Ding and M. Gao, (2021) 102377. doi: 10.1016/j.cis.2021.102377.

[62] A. Pintor, V. Vilar, C. Botelho, and R. Boaventura, (2016). doi: 10.1016/j.cej.2016.03.121.

[63] C. S. Quek, N. Ngadi, and M. A. Ahmad Zaini, (2020) 507–512.

[64] P. Bharali et al., (2022) 13, doi: 10.1007/s13205-021-03068-0.

[65] F. Merlin et al., (2021) 37. doi: 10.1186/s40068-021-00241-5.

[66] S. Chowdhury, S. Pan, R. Balasubramanian, and P. Das, (2019) 43–68. doi: 10.1007/978-3-319-75484-0_3.

[67] A. S. I. Al-Jammali, (2022) 47–63. doi: 10.52716/jprs.v12i2.657.

[68] K. Qiao et al., (2019) doi: 10.1016/j.jtice.2019.01.029.

[69] M. Zamparas, D. Tzivras, V. Dracopoulos, and T. Ioannides, (2020) 4522.

[70] H. Kim, G. Zhang, T. Chung, and C. Nam, (2021). doi: 10.1002/adsu.202100211.

[71] T.-C. Tang et al., (2020) 332–350. doi: 10.1038/s41578-020-00265-w.

[72] Z. Wei et al., (2024) 350–372. doi: 10.1016/j.jes.2023.04.008.

[73] S. Muhammad et al., (2024) 100249, doi: 10.1016/j.giant.2024.100249.

[74] A. P. S. Soares, Maria F. V. Marques, and M. G. Mothé, (2024) 4539–4553. doi: 10.1007/s13399-022-02660-5.

[75] Y. Zhai, X. Yuan, C. C. Weber, R. J. Varley, and L. C. Henderson, (2024) 113716. doi: 10.1016/j.jece.2024.113716.

[76] M. Zamparas, D. Tzivras, V. Dracopoulos, and T. Ioannides, (2020) 4522. doi: 10.3390/molecules25194522.

[77] M. Chhajed, C. Verma, and P. K. Maji, (2024) 116024. doi: 10.1016/j.marpolbul.2024.116024.

[78] A. I. Osman, A. M. Elgarahy, N. Mehta, A. H. Al-Muhtaseb, A. S. Al-Fatesh, and D. W. Rooney, (2022) 12433–12447.

[79] W. Syie Luing, N. Ngadi, I. Inuwa, and O. Hassan, (2018) 361–375.

[80] C. Shaer, L. Oppenheimer, A. Lin, and H. Ishida, (2021) 3775. doi: 10.3390/polym13213775.

[81] Z. Sun et al., (2021) 1–12. doi: 10.1007/s42114-021-00352-8.

[82] I. M. Maafa, (2021) 225.

[83] M. Sekar, V. K. Ponnusamy, A. Pugazhendhi, S. Nižetić, and T. Praveenkumar, (2022) 114046.

[84] D. Vamvuka, (2011) 835–862.

[85] A. Adeniyi et al., (2022). doi: 10.1007/s10098-022-02415-w.

[86] S. K. Sansaniwal, K. Pal, M. A. Rosen, and S. K. Tyagi, (2017) 363–384.

[87] Y.-K. Park et al., (2019) 1706–1718. doi: 10.1016/j.apenergy.2019.05.088.

[88] F. Ronsse, R. W. Nachenius, and W. Prins, (2015) 293–324. doi: 10.1016/B978-0-444-63289-0.00011-9.

[89] Y. A. Situmorang, Z. Zhao, A. Yoshida, A. Abudula, and G. Guan, (2020) 109486.

[90] I. Ali, M. Asim, and T. A. Khan, (2012) 170–183 doi:https://doi.org/10.1016/j.jenvman.2012.08.028

[91] B. Wang, R. Gupta, L. Bei, Q. Wan, and L. Sun, (2023) 26676–26706.

[92] T. R. Sarker, F. Pattnaik, S. Nanda, A. K. Dalai, V. Meda, and S. Naik, (2021) 131372.

[93] A. V. Baskar et al., (2022) 153555.

[94] Y. Wu et al., (2022) 462–481.

[95] R. Claydon, “Advanced assessment of in-situ thermal Enhanced Oil Recovery (EOR) to promote coproduction of both catalytically-upgraded oil and hydrogen gas,” University of Birmingham, 2021.

[96] J. Lu, X. He, B. Li, S. Meng, and Z. Li, (2025) 128483. doi: 10.1016/j.seppur.2024.128483.

[97] E. Fu, L. He, J. Chao, and X. Dai, (2025) 140622, doi: 10.1016/j.molstruc.2024.140622.

[98] S. Cui et al., (2025) 130177. doi: 10.1016/j.seppur.2024.130177.

[99] S. N. Alharthi and M. A. Abdulhamid, (2025) 129189. doi: 10.1016/j.seppur.2024.129189.

[100] T. Liu et al., (2025) 128516. doi: 10.1016/j.seppur.2024.128516.

[101] X. Zeng et al., (2025) 128460. doi: 10.1016/j.seppur.2024.128460.

[102] Y. Gao, H. Xing, and Y. Zhang, (2025) 128721. doi: 10.1016/j.seppur.2024.128721.

[103] J. Bang et al., (2025) 129278. doi: 10.1016/j.seppur.2024.129278.