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Review

A sustainable approach to controlling oil spills

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A B S T R A C T

As a result of the huge economic and environmental destruction from oil spills, studies have been directed at improving and deploying natural sorbents which are not only the least expensive but also the safest means of spill control. This research reviews the limitations and environmental impact of existing cleanup methods. It also justifies the need for concerted research effort on oil spill control using natural and sustainable technology concepts. The article proposes future guidelines for the development of a sustainable cleanup technology. Finally, guidelines for the development of a new technology for the Middle East are proposed, which is the use of an abundant resource—date palm fibers—for such techniques.

1. Introduction

The attention of the world was drawn to the recent unprecedented oil spill in the Gulf of Mexico. On the 20th of April, 2010, the British Petroleum (BP) Deep water Horizon oil rig in the Gulf of Mexico blew up, killing 11 workers and injuring 17 others (Welch and Joyner, 2010). The spill lasted for about three months, released nearly 5 million barrels of crude oil to the Gulf of Mexico (Robertson and Krauss, 2010) which then affected and killed huge populations of marine animals and after 8 months after the incidence, soiled 320 miles (510 km) of beaches and shorelines (Bowermaster, 2010) and after additional 8 months (one and a half year later), a total of 491 miles (790 km) of shorelines were affected (Polson, 2011). The oil industry has recorded many of such huge spills in the past: the wrecking of the Torrey Canyon in 1967 (Bourne, 1979); the Santa Barbara channel platform blowout in 1969; the Gulf of Mexico drilling rig incidents in 1970 and 1971; the grounding of supertanker Amoco Cadiz in 1978; the disaster of the Piper Alpha platform in the North Sea; and operation Desert Storm that caused the release of a huge quantity of oil into the Arabian Gulf in 1991 (Bernard and Jakobson, 1972; Kapoor and Rawat, 1994). Others are the 1989 Exxon Valdez spill in Alaska; the 1999 Erika spill in France; the Prestige in Spain, 2002; and most recently the 2010 BP rig blowout in the Gulf of Mexico—the world worst oil spill on marine water ever (Robertson and Krauss, 2010).

Each year, an average of about 5 million tons of petroleum is transported across the seas around the world (Anisuddin et al., 2005) putting the marine lives and ecosystem in a dire risk. Hence, the impact of oil spill on the ecosystem is severe and cannot be overemphasized (Fig. 1 and Table 1). Spills affect marine life. Marine birds, especially diving birds, and shell fishes are the most vulnerable (Fig. 1a). However, the effect of chemical dispersants most commonly used to control the spills may even be more harmful and in some cases kill shell fishes. Oil spills also soil beaches (Fig. 1d) and shorelines (Fig. 1c) (Ladd and Smith, 1970).

As soon as oil spills on the sea surface, it undergoes various processes simultaneously, such as spreading, evaporation, emulsification, photo-oxidation, dispersion, sinking, resurfacing, tar ball formation, and biodegradation (Fig. 2) – all of which make clean up much difficult. Hence, the extent of the damage caused by the spill and the ease of cleanup depend on how quickly the cleanup response takes effect. The kinetics of these processes depends largely on sea conditions and the meteorological environment (Kapoor and Rawat, 1994).

In the wake of the current oil spill in the Gulf of Mexico, oil cleanup is still a major challenge due to the limitations and high cost of current cleanup practices. The common cleanup techniques that have been used include *in situ* burning of oil on water, mechanical tools (booms and skimmers), use of chemical dispersants, and synthetic sorbents (Table 1). In the cleanup effort in the

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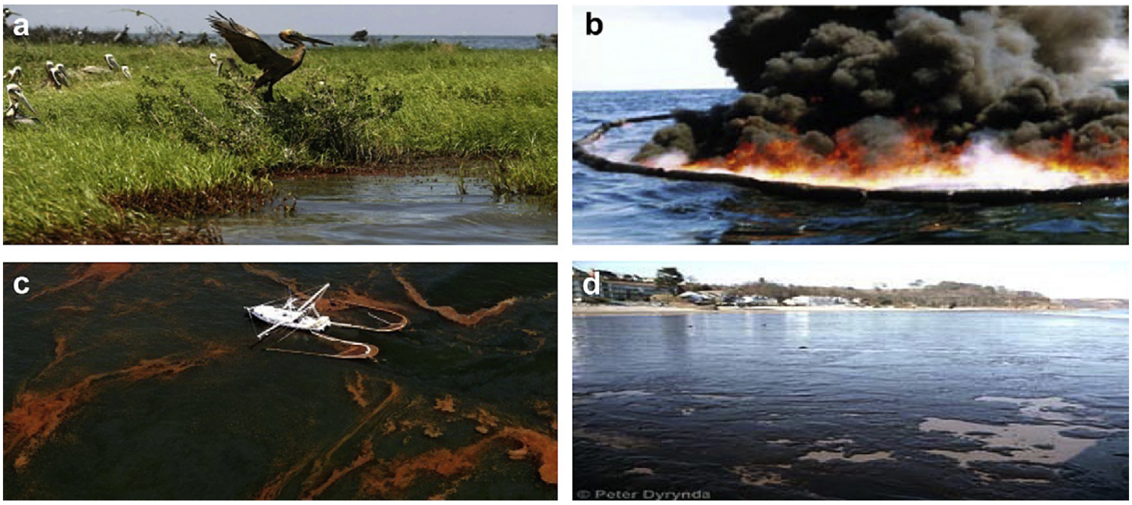


Fig.1. (a) An oil-stained pelican where hundreds of pelican nests exist (AP Photo/Gerald Herbert). (b) Fireproof boom used to contain *in-situ* burning (Office of Response and Restoration, National Ocean and Atmospheric Administration). (c) A shrimp boat (AP Photo/Eric Gay) and (John Moore/Getty Images). (d) A beach soiled with oil (photo care of Peter Dyrynda).

BP oil spill, BP and the U.S. government relied mainly on oil booms, mechanical skimmers, and oil dispersants—the same tools used more than 20 years ago to fight the *Exxon Valdez* spill in Alaska (Dabney, 2010). Also, the initial estimate of the cleanup is $12.5 billion (Weisenthal, 2010) which is about 80% higher than the total cost of the Exxon Valdez spill in 1989 (Table 1). The limitations of these techniques are obvious, ranging from inefficiency at high water tide, to high cost and environmental harmfulness. Much is yet to be understood about the effects of current spill cleanup techniques on the environment and ecosystem.

The use of natural sorbents to clean up oil spill in an eco-friendly and cost effective way is promising, and more attention should be paid to this prospect. The Literature shows that natural sorbents are very effective and, apparently, the most eco-friendly sorbent for oil spill cleanup. Adebajo et al. (2003), Karan et al. (2011) and others did a good review on the efficiency of natural sorbents for oil spill clean-up. Among these natural sorbents, straws and cotton proved to be the best natural sorbent materials known and tested with respect to certain criteria, which include sorption capacity and availability. In the past, the efficacy of cotton and straw has been thoroughly explored. However, other natural products which may be equally efficient or even more are given less attention. Moreover, the availability of cotton and straw may be challenging in some tropical regions of the world where weather and soil are not suitable for their cultivation. As a result, the use of those natural sorbents may not be economical in such locations. It is imperative, then, to study the applicability of other available natural products abundant in the region, particularly waste products, such as coconut shells, corn cobs, banana pith, and sugarcane bagasse. Other effective natural sorbents are human hair and animal skins or hair/fur. Most of these are dumped as waste. Instead of treating them as waste, they can be harnessed to complement other methods to clean up oil spills from small and large water bodies, depending on the level of their abundance. They can be gathered, collected, and processed in mat form and stored for future oil spill eventualities. Hair donations can come from salons, barber shops, and pet groomers. The hairs donated can then be processed into mat or cushion forms to be used by cleanup volunteers to protect shorelines and beaches. Example of the success story of this method is that reported by Dabney (2010) about a volunteer organization called “Matter of Trust” that successfully used hair mats from public donations for cleanup after the San Francisco Bay oil spill in 2007. However, not as much concern has been given to these alternative natural sorbents as has been given to cotton. This article therefore reviews current cleanup methods and also makes strong emphasis on the efficacy of natural sorbents for oil spill clean-up and the need to direct more research attention to other sustainable natural sorbents. Finally, a specific attention and research proposal and guidelines into the use of palm leaves as natural sorbents for oil spill cleanup are outlined because of their great abundance in the tropics.

2. Factors affecting oil spill control

There are many factors that might affect control of an oil spill. However, the most common and influential factors are outlined as follows:

2.1. Sea conditions

This is the most critical factor affecting spill control and it is described in terms of wave height and period. Wave heights of 1–2 ft and periods of 1–3S render most booms ineffective. Also, wave heights above 6 ft make control operations difficult for small vessels (Ladd and Smith, 1970). For example, cleanup efforts were restricted for two weeks following the *Amoco Cadiz* accident of 1978, as a result of the isolated location of the grounding and rough seas (Enzler, 2006).

2.2. Wind velocity and direction

These are the most important factors controlling slick movement over open water. In oceans, wind spreads oil more than currents or waves, with a velocity between 3 and 10% of that of the wind. Hence, within minutes of a spill, oil spreads to cover hundreds of square yards and within an hour, it covers hundreds of square miles (Bernard and Jakobson, 1972). This makes early confinement necessary to limit the spread of an oil spill; reduce the area of contamination; prevent oil from entering drains, sewers, or water courses; and of course, make cleanup operations easier (Agius et al., 1975; Lehr, 1974). Hence, local wind data are useful in predicting slick movement and in planning spill control actions (Ladd and Smith, 1970).

Table 1
Some major oil spills and corresponding effects and cleanup techniques.

Incidence	Amount spilled	Length of affected areas	Cost implication	Environmental effect	Cleanup technique(s)
1967, Torrey Canyon off the English Channel (Bourne, 1979; Boyes and Elliott, 2010; Enzler, 2006)	120,000 tons of crude	100 miles of coast lines	–	An estimated 25,000 of birds died.	-Natural weathering. - Dispersants were also used. - Bombs were used to ignite 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
1970, Liberian Registered Tanker at Chedabucto Bay, Nova Scotia	16,000 tones	190 miles of coast line	–	–	- Floating booms were unsuccessful. - Skimmers successfully in sheltered waters. - Dispersants could not penetrate thick layers of oil that formed as a result of low temperatures and weathering; -Sorbents such as peat moss proved to be a good sorbent; straw was used on some beaches. - *In-situ* burning-used successfully on beaches and on isolated slicks
1978, Amoco Cadiz off the coast of Brittany, France (Bourne, 1979; Boyes and Elliott, 2010; Enzler, 2006)	230,000 tones of light crude	300 km of coast line Beaches of 76 Breton communities polluted	$282 million of which $85 million for fine	Killed over 3450 sea birds. fisheries, oysters and sea weed beds were also greatly affected	- Microbial degradation - On the shore, oil 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 but not very successful
1989, Exxon Valdez in Prince Williams Sound Alaska (Cleveland et al., 2010; Cutler et al., 2010; Enzler, 2006; ITOPF, 2010)	10.9 million gallons	1900 km of coast line	$7 billion for fines, penalties and claims of which over $2.1 billion used for clean up	Casualties include 250,000 sea birds, 2800 sea otters, 250 bald eagles and 22 killer whales.	- Booms - Dispersant unsuccessful because much of the oil turned to mousse - *In-situ* burning was successful but could not continue because of change in oil state as a result of the storm - Sorbents were used where mechanical means were less practical. However, sorbents were labor intensive and generated additional solid waste. - Warm water flushing of the beach used but the consequences were not favorable. - Bioremediation enhancement agents were very effective in cleaning over 70 miles of shorelines.
1990, Gulf war in which 650 oil wells in Kuwait set ablaze (Enzler, 2006)	1 million tones		–	20,000 sea birds killed.	–
1996, Sea Empress (Boyes and Elliott, 2010)	Over 70,000 tones	100 km of coast line	$60 million of which $37 million was used for clean up	2200 birds killed. Sea weeds and, shell fishes were affected	50% of oil dispersed naturally; some oil removed mechanically at sea; and some were dispersed with chemical dispersants
2010, BP Gulf of Mexico (Cleveland et al., 2010)	About 4.9 million barrels (208.5 million gallons)	Over 790 km of shorelines (Polson, 2011)	$5.4 billion possible fines and $21 billion (if gross negligence) (Robertson and Krauss, 2010). $20 billion for compensation and clean up (Welch and Joyner, 2010)	997 birds dead; 400 sea turtles dead; 47 Mammals Including Dolphins dead[a]	- Booms and Skimmers. - Dispersants. - Controlled burning.

[a] Tentative figures as of June 16, 2010. It is too early to come up with a definite figure as more data and investigations are still on.

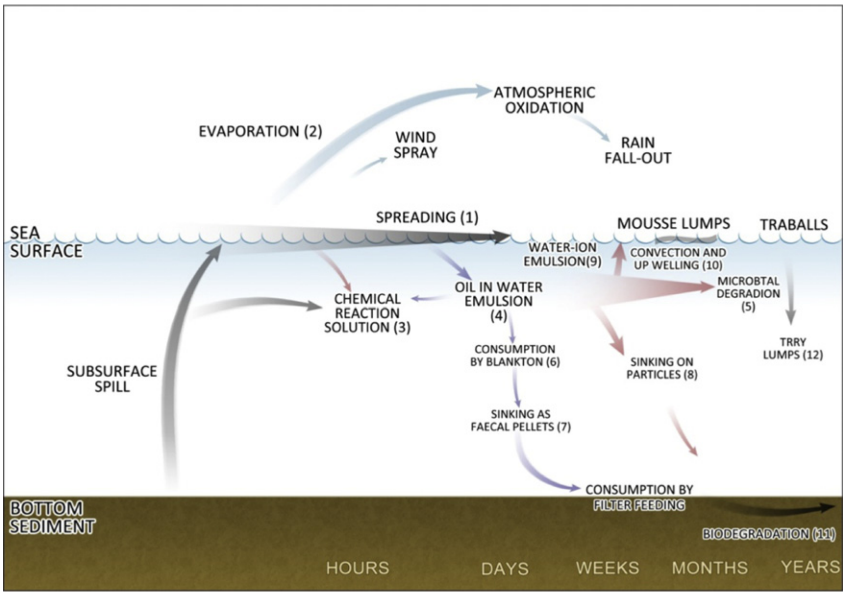


Fig. 2. Physical, chemical and biological processes changing properties of oil slicks (redrawn from Kapoor and Rawat, 1994).

2.3. *Current and tides*

Sea current velocity of one knot or more tends to build up hydraulic forces against floating booms, causing oil to flow and escape under the boom (Bernard and Jakobson, 1972; Ladd and Smith, 1970). Similarly, large tidal ranges complicate shoreline protection and cleanup.

2.4. *Temperature and atmospheric conditions*

High temperature causes more evaporation of lighter fractions of oil and increases the tendency of heavier fractions to persist on water surfaces, which in turn can reduce the effectiveness of chemical dispersant on the highly viscous and thicker crude and also make the oil unable to sustain combustion (Husseien et al., 2009; Ladd and Smith, 1970; Satish, 2003; U.S. Department of Agriculture, 2008). Also, rain, snow, or fog may make accessibility to the spill area difficult.

3. Methods for containment and removal of spills

The various cleanup methods in practice include *in-situ* burning, mechanical methods (removal by physical means using skimmers, vacuum units, and booms), chemical methods (use of chemical dispersants), and sorbents (mineral products, agricultural products, and synthetic products).

There is no simple procedure which can be recommended for all spills. Spilled oil will behave differently depending on the type of oil, the surface on which it spills, the soil and subsoil conditions, and the prevailing weather conditions. Hence, the choice of cleaning method must take into account these factors. In most cases, two or more methods are combined to achieve an effective cleanup (Agius et al., 1975). The different cleanup techniques are discussed as follows:

3.1. *In-situ burning of oil slick*

This technique involves burning a thick oil slick on the water surface (Fig. 1b). It helps to reduce the amount of oil on the water's surface and, hence reduces the hazards of the oil slick on the ecosystem and the environment. It can remove 600–1800 barrels (100–300 tons) of oil per hour (Allen, 1988). Ignition of an oil spill is done using a device such as a Helitorch, a sort of flamethrower suspended beneath a helicopter; or a diesel-soaked rag dropped from the helicopter (ITOPF, 2010). A fireproof U-shaped boom (a mechanical device for spill control) is used to contain/hold a large and very thick oil slick in place, after which the oil is carefully set ablaze and monitored. This technique has been used in many large spills and its use is generally subject to the approval of governmental agencies. The first recorded burn was in northern Canada in 1958, where a long boom was used to successfully control an oil spill during *in-situ* burning on the Mackenzie River. After this operation, many burns were used in Canada without any form of documentation. Similarly, several successful burns in Sweden and Finland resulted in the use of burning on many occasions in those and surrounding countries. In Britain, extensive efforts to ignite the *Torrey Canyon* spill and the vessel itself resulted in mixed results. Consequently, burning was not tried again in Britain for some time (Fingas, 1998). In the mid-1980s, Elastec/American Marine (2010) designed the first commercial fire boom that is capable of containing burning oil at 2000 °F. This was the first (practical and successful) boom that allowed *in situ* burning of oil spills on water. The burns in which it was used included a test burn off the coast of Spitsbergen, Norway (1988); spillage from the *Exxon Valdez* (1989); involvement with experimental burns off Newfoundland, Canada (1993); and the Southampton test burn in the United Kingdom (1996).

In-situ burning is effective if the following conditions are in place: i) the oil slick is sufficiently wide so that a good volume of oil is burnt off at a time; ii) the oil is very thick to sustain combustion; iii) the water is calm; and iv) the slick location is distant from sensitive facilities. However, because of sea weather conditions discussed above (Sea current, wind and temperature), all of these conditions rarely exist for a long time and for this reason *in-situ* burning is limited by the following limitations in next section. However, a strong advantage of *in-situ* combustion over conventional spill clean-up techniques is in ice or cold water application where mechanical booms and chemical dispersants have limited efficiency whereas all conditions favoring combustion tend to persist for a long time since ice strongly influences weathering. The more the ice concentration on sea surface, the less the weathering by evaporation, and the more the ices limit oil spreading keeping the oil slick thick enough for burning (Buist et al., 2011; Fritt-Rasmussen and Brandvik, 2011). This is true because atmospheric and sea condition in ice water is expected to be characterized by low or no tidal currents and low temperature all of which are in favor of combustion.

3.1.1. Limitations of in-situ burning

In-situ burning is normally done as early as possible, before evaporation and natural dispersion occur. In reality, there are a number of problems that limit the viability of this technique (summarized in Table 2). These include the following:

3.1.1.1. Ignition of the oil. The loss of lighter fractions of the oil through evaporation makes ignition difficult. This makes it necessary for *in-situ* combustion to be carried out as soon as possible following spillage, before significant evaporation takes place. Also, the formation of an oil-in-water emulsion and dispersion of the oil slick into scattered, smaller slicks complicate ignition and proper burning. The “prime rule” of *in-situ* burning is that oil will ignite if it is at least 2–3 mm thick. For most crude oil this only occurs for a few hours after the spill event. Oil on the open sea rapidly spreads to equilibrium thicknesses. For light crude oils, the equilibrium thickness is about 0.01–0.1 mm, and for heavy crudes and heavy oils this is about 0.05–0.5 mm. These are far too thin to ignite. After ignition, oil will continue to burn down to slicks of about 1–2 mm thick. For very thin slicks, most of the heat is lost to the water and combustion is not sustained (Fingas, 1998). Hence, the layer of oil on the sea surface needs to be at least 2–3 mm thick to counter the cooling effect of the wind and sea.

3.1.1.2. Maintaining combustion of the slick. Complete removal may not be achievable because of the prevailing conditions in the sea: the cooling effect of wind, and wave action, which may rise high and extinguish the fire even if booms are used to contain the slick.

3.1.1.3. Generation of large quantities of smoke. Large amounts of smoke from oil slick burning can result in oil rain. For example, in 1983, a fire occurred on board a vessel in South Africa and clouds of black smoke resulted in an oily rain falling on farms up to 80 km inland. The subsequent contamination affected sheep and wheat in South Africa (ITOPF, 2010). A similar incident occurred in Spain in 1992, where a black cloud of smoke resulting from a cargo fire on board the *Aegean Sea* caused soot deposition on buildings and city structures (ITOPF, 2010).

3.1.1.4. Viscous residue. The formation and possible sinking of extremely viscous and dense residues can damage the sea bed and its inhabitants. The viscous residue may also be transported to shorelines and beaches by ocean tides or currents.

3.1.1.5. Safety concerns. Airborne irritants and possibility of secondary fire are sources of concern when combustion has to be carried out close to residential areas (Fritt-Rasmussen and Brandvik, 2011). Carbon monoxide, sulfur dioxide, and polycyclic aromatic hydrocarbons (PAH) are common toxic compounds emitted while burning oil on water.

3.2. Mechanical techniques

Mechanical methods involve the use of booms spread over surface of seas, estuaries and coastal waters to prevent the spread of oil slicks or to direct their movements (Muttin, 2008). Booms are combined to make “V” shaped barriers, which concentrate the oil for pickup by skimmer barges and boats (Bernard and Jakobson, 1972; Lehr, 1974). The advantage of booms and skimmers over other commonly used methods such as chemical dispersants and *in-situ* combustion is the absence of adverse environmental effects (Castro et al., 2010). Broje and Keller (2007) studied the dependence of recovery efficiency of skimmers on several factors such as oil slick viscosity, thickness, and oil slick temperature where high slick viscosity and thickness increase skimmer recovery efficiency. Low temperature tends to increase oil thickness and viscosity thereby enhancing recovery. High rotational speed of skimmer drum also improves oil recovery. Finally, the sorption capacity of the material on the surface area has a great impact on oil recoverability.

3.2.1. Limitations of mechanical techniques

Oil spill clean-up by mechanical technique is expensive, and requires large number of personnel and equipment (Broje and Keller, 2007). Some mechanical limitations of booms generally include attrition under harsh sea conditions and escape of oil underneath the boom at slick velocity in excess of one knot (Allen and Ferek, 1993). An important structural limitation is boom drainage failure which occurs when the effective boom draft is lower than the oil slick thickness resulting in escape of some oil below the barrier (Goodman et al., 1996; Castro et al., 2010). Other structural limitations of booms are droplet entrainment failure and critical accumulation failure. For further discussion on these failure mechanisms, the reader is referred to Chebbi (2009). Booms and skimmers are also expensive to operate when they have to be deployed far offshore. Furthermore, poor efficiency results can result in higher cost of spill clean-up (Brown et al., 1997). In summary, booms are only effective in calm water conditions with little wind or currents such as coastal waters, estuaries and port basins. However, their structural designs also have a great impact on their performance efficiency (Muttin, 2008; Castro et al., 2010).

3.3. Bioremediation

Biodegradation is a process by which small organisms like bacteria, yeasts, and fungi break up complex compounds into smaller compounds for their food. This process occurs naturally. Its application in oil spill cleanup involves the artificial introduction of biological agents such as fertilizers and nutrients to native microorganisms in the contaminated site so they proliferate (bio-stimulation) or the introduction of non-native microorganisms (bio-augmentation) to speed up the natural process of biodegradation so as to protect shorelines, wetlands, and other marshy areas affected by spills from further damage. This process is known as *bioremediation*. Proof of its effectiveness as an oil spill cleanup technology was developed on the shoreline of the Delaware Bay in 1994 (U.S. Environmental Protection Agency [EPA], 2000).

3.3.1. Limitations of bioremediation

Bioremediation is ineffective in removing oil spills that consist of large coherent masses or for sunken oil spills (Smith, 1983). Bioremediation is also limited by abiotic environmental factors such as a low level of nutrients including phosphate and fixed forms of nitrogen, very low temperatures, and insufficient oxygen (Atlas and Cerniglia, 1995).

3.4. Dispersants

Dispersants are able to treat larger areas compared with other methods. Dispersants consist of different surfactants (surface active, “soap-like” molecules). Surfactants are partially soluble in both oil and water. When sprayed on an oil slick, surfactants reduce

Table 2
Comparison of spillage control techniques.

Method	Material	Sorption capacity (where *x* means gram of crude per gram of sorbent)	Limitations	Area of application	Environment friendliness	Cost
Sinking materials (Choi, 1996; Cleveland et al., 2010; Hussein et al., 2008; Jarre et al., 1979; Louisiana State University Agricultural Center)	Granular or powdered	Ineffective	Retention capacity not certain. May release some fraction while traveling down sea bed, non-biodegradable	Banned in many countries.	Very harmful. Contaminate sea beds and fishes	Expensive
Sorbents (Sorption) (Adebajo et al., 2003)	Mineral Synthetic Organic	Sorbs up to 80*x* Sorbs up to 100*x* Sorption capacity up to 80*x*	Same as sinking materials Not Biodegradable or degrade very slowly No effective means of spreading and recovery.	Offshore, shorelines.	Friendly Unfriendly Eco-friendly	Expensive Expensive Very Cheap
Bio-remediation (Atlas and Cerniglia, 1995; McLeod and McLeod, 1974)	Biological substances and agents	Very efficient	Limited to biotic environment only. Also ineffective in spill with large coherent mass.	Shorelines, marshes and wetlands	Friendly	Cheap
Dispersants (Bly et al., 2007; Daling and Indrebo, 1996; Lewis et al., 2010; Saito et al., 2003; ITOPF, 2010)	Chemical substances	Very efficient with helicopter spray. Can treat large sea areas	Little effect on very viscous oil. Effective for viscosity <2000 cSt. Ineffective in calm water.	Good in calm, harsh and very deep water body to allow for sufficient dilution before reaching bed	Harmful to aquatic flora and fauna.	Expensive
In-situ Burning (Adebajo et al., 2003; Elastec/American Marine, 2010; Fritt-Rasmussen and Brandvik, 2011)	Bombs, explosives, fire resistance booms, sometimes liquid fuel	Efficient-remove large quantities of oil very quickly Also effective before weathering	Effective in: waves height <3 ft. Minimum slick thickness 2–3 mm. <30% Evaporites loss. Emulsion < 25% water content. Inability to sustain/maintain complete combustion of slick. Viscous and dense residue of combustion damage sea bed and shorelines and beaches. It's a source of secondary fire.	Water body and on land	Harmful near residential areas and near flammable structures. Toxic compounds like carbon monoxide, sulfur dioxide, and PAHs emitted during combustion of oil on water cause air borne diseases.	Cheapest
Booms & skimmers (Broje and Keller, 2007; Chebbi, 2009; Schatzberg and Nagy, 1971)	Mechanical tools	Efficient	Structural failure, time consuming, expensive, oil slick escape at slick velocity up to 1 knot, sediments and plants debris block skimmer pumps	Used only on water. Effective only in calm sea	Friendly	Expensive

the interfacial tension between the oil and water (Daling and Indrebo, 1996; Lewis et al., 2010). This enhances dispersion and increases the natural dilution and biodegradation process of oil in water. Surfactants are generally applied by spray equipment followed by agitation to mix the chemical with the oil for maximum effectiveness (Ladd and Smith, 1970). Wind therefore plays an important role in the mixing. Daling and Indrebo (1996) published the results of an extensive laboratory and field test that investigated the effectiveness of dispersant spraying techniques and the need to understand the weathering process of an oil slick before spraying. The results showed that a 15 m^3 oil slick treated with helicopter spray disappeared 10 min after spraying while the same volume of slick treated with boat spray disappeared after 0.5–1 h. This is because the helicopter was equipped with remote sensing equipment and other gadgets to monitor the distribution of the slick and also to identify the thick/very viscous part that requires a higher dispersant dosage rate (Daling and Indrebo, 1996). Lewis et al. (2010) also studied the length of time dispersants effectively sprayed on an oil slick in calm water will to be effective. Their studies became important considering the low effectiveness of chemical dispersant in calm water where there is no sufficient energy to break the oil and water whose interfacial energy has been greatly reduced by dispersant. However, ecological considerations, experience, and technological developments in the handling of oil spills have pushed chemical dispersants very much out of the picture (McLeod and McLeod, 1974). Dispersants have not been used extensively in the United States because of difficulties with application, disagreement among scientists about their effectiveness, and concerns about the toxicity of the dispersed mixtures (EPA, 2000). Also, in the United Kingdom, the use of dispersants is a regulated activity (Bly et al., 2007). Research into fish health after the *Exxon Valdez* spill of 1989 showed that PAHs affected the developing hearts of Pacific herring and pink salmon embryos. This could affect the fisheries food industry and, hence, have a health impact on people including respiratory, nervous system, liver, kidney, and blood disorders (U.S. Department of Agriculture, 2008). Dispersants are most widely used but their use should be restricted to sufficiently deep water where proper agitation will result in rapid dilution in the upper column of the water body and the toxic effect will be minimal at the sea bed (Ladd and Smith, 1970).

Allen and Ferek (1993) did a cost comparison using representative mechanical, dispersant, and burning systems for the recovery/elimination of approximately 8000–10,000 barrels (1272–1590 m^3) of oil in a 12-h period: mechanical, $100–$150 per barrel of oil; dispersants, $50–$100 per barrel; and *in-situ* burning, $20–$50 per barrel.

3.4.1. Limitations of dispersants

Dispersants are expensive and contain toxic compounds harmful to aquatic fauna and flora. Furthermore, they are ineffective in calm water where is no sufficient mixing energy needed to mix dispersants with oil and to also aid immediate dispersion of the oil. They are also more effective in thicker oil slicks than thinner ones because the dispersants are easily lost in thinner slicks (Lewis et al., 2010). Also, thicker slicks subjected to weathering action will become more viscous and thereby reduce the effectiveness of the dispersants, though the effect is less severe than dispersant loss in thick slick (Lewis et al., 2010).

3.5. Sorbents

Sorbents are products or materials that are oleophilic and hydrophobic, i.e., they have a high capacity to sorb oil and repel water. There are three classes of sorbents—*synthetic organic*, inorganic *mineral*, and *agricultural (organic) products* (Bernard and Jakobson, 1972; Sun et al., 2002; Teas et al., 2001). The sorbent material is broadcast over a slick and allowed to sorb oil. The oil-soaked material is then collected and, depending upon the sorbent, the sorbent will be squeezed to remove oil and then re-broadcasted, or the oil-laden material will be disposed of safely (Lehr, 1974). The efficiency of a sorbent depends on its recyclability, wettability, density, geometry, sorption capacity and sorption rate. These properties determine the time required to spread and harvest the sorbents (Bernard and Jakobson, 1972). A common requirement for all sorbents is that they must be spread on the spill before the oil viscosity increases (due to evaporation of volatile components) to the point that sorption is no longer possible. The advantage of sorbents is their insensitivity to sea conditions (Lehr, 1974). Sorbents have been recorded to be one of the most effective and cheapest methods of cleaning oil spills on shorelines whose contamination has always had the highest economic and environmental impact because of the difficulty in cleaning oil spilled on them (Carmody et al., 2007).

3.5.1. Inorganic mineral sorbents

These are also known as sinking sorbents, and they are highly dense, fine-grained mineral materials—natural or processed—used to sink floating oil. Examples include stearate-treated chalk and silicone-treated pulverized fly ash, zeolites, graphite, activated carbon, organoclay, silica (sand), and silica gel.

It is sometimes difficult to determine which class of sorbentsdo activated carbon belongs because it is of either botanical origin (e.g., wood, coconut shells, fruit seeds and stones), mineral origin (e.g., coal, lignite, peat, petroleum coke), or polymeric material origin (rubber tires, plastics) (Alaya et al., 2000). Activated carbon can have any of these three types of origin.

Carmody et al. (2007) carried out experimental studies on effectiveness of organoclays to sorb diesel, hydraulic and engine oil. Results showed that they are hydrophobic, they have high sorption and retention capacity. However, their results also showed that they are not degradable, they are expensive, and also showed low re-usability. Activated carbon is a commonly used sorbent in sugar refining, chemical and pharmaceutical industries, water and wastewater treatment, and in point-of-use and point-of-entry home water filtration system (Diya'uddeen et al., 2008; Kim et al., 2001; Namita et al., 2006; Ng et al., 2003). Activated carbons (particularly those of agriculture origin) are cheap and readily available from many companies. They owe their distinguished properties to an extensive surface area, high degree of surface reactivity and favorable pore size distribution. It has good sorption capacity. However, granular organoclay can be seven times more effective than activated carbon (Adebajo et al., 2003). Hence, organoclays can be used to improve the sorption efficiency of activated carbon (Alther, 2001). Beall (2003) used activated carbon enhanced with organoclay to clean hydrocarbon spill in water. Activated carbon is widely used in oil spill cleanup. Many commercial sorbents incorporate activated carbon in the sorbent pads to facilitate cleanup. For example, one common type consists of two sheets of cotton with activated carbon sandwiched between them. The activated carbon separates and holds toxic parts of the oil such as the polycyclic aromatic hydrocarbons, protecting spill cleanup workers (Teeter, 2010). Arbatan et al. (2011) studied the oil sorption capacity of calcium carbonate powder treated with fatty acid to change the wettability of the carbonate powder from water wet to oil wet. Results showed that the treated calcium carbonate powder to be very hydrophobic and selectively absorbed diesel and crude oil out of oil–water mixture. Although, Calcium carbonate is a natural material and not known to be harmful, however, the recoverability and re-usability of the calcium carbonate sorbent after its saturation with oil were not discussed by the authors.

A study of exfoliated graphite (Inagaki et al., 2011; Toyoda et al., 2002) indicates their high heavy oil sorption capacity compared to polypropylene mats, perlite, cotton, milkweed, and kenaf. Perlites have also proven to have a sorption capacity less than, but comparable to, most synthetic sorbents for oil spill cleanup (Teas et al., 2001).

3.5.1.1. Limitations of mineral sorbents. Mineral sorbents are generally disliked as they have numerous shortcomings, such as contamination of sea beds and harmful effects to aquatic habitats. They also tend to release some of the sorbed oil while sinking because of the low retention capacity of some of the solids (Ladd and Smith, 1970; McLeod and McLeod, 1974; Schatzberg and Nagy, 1971; U.S. Department of Agriculture, 2008). Other disadvantages of activated carbon include fire risk, pore clogging, and problems with regeneration. Another limitation of mineral sorbents (apart from those of agriculture origin) is that they are very expensive and are not commonly used. Also, because they are highly dense (Ornitz and Champ, 2002), transportation to required site requires much effort. Table 3 compares the applications and limitations of different sorbents for oil spill cleanup.

3.5.2. Synthetic organic products

The most widely used sorbents are synthetic sorbents made from high molecular weight polymers, such as polyurethane and polypropylene. They are available under various trade names. They have good hydrophobic and oleophilic properties and high sorption capacity. For example, ultralight, open-cell polyurethane foams are capable of sorbing 100 times their weight in oil from oil-water mixtures (Jarre et al., 1979). Also, Lin et al. (2008)) studied the oil sorption efficiency of tire powders and its applicability in oil spill clean-up. Their study showed that tire is oleophilic and can sorb 2.2 g of oil per unit gram of the sorbent. Because of the re-usability of the tire sorbent – as much as 100 times without the tire powder losing its sorption capacity – tire powder is able to sorb as much as 220 g per gram of sorbent after 100 cycles of usage. However, tire is not biodegradable and thus its usage for oil spill control will be of environmental concerns.

3.5.2.1. Limitations of synthetic organic sorbents. The non-biodegradability of synthetic sorbents is a major disadvantage (Choi and Cloud, 1992; Deschamps et al., 2003; Sun et al., 2002; Teas et al., 2001). As stated earlier, synthetic sorbents are not biodegradable but newer concepts enable polyurethane foam to be broadcast, recovered, cleaned, and reused in a totally mechanized process, thus removing the necessity for disposal and need for biodegradability. For example, one style consists of a floating rope of sorbent material that is freely deployed on the water surface. The rope is drawn through an oil slick, picking up the oil. It is brought aboard a support vessel, passed through squeeze rollers to remove the recovered oil, and then re-deposited on the water surface in a continuous operation (Lehr, 1974). Nevertheless, the mechanized system is an additional cost.

3.5.3. Natural organic (agricultural products)

Most leafy plants contain some natural oils or wax, giving them a greater affinity for oil than water. When dry, they are lightweight enough to float on water. All of these products will become water-wet and sink, carrying the oil with them (U.S. Department of Agriculture, 2008). Natural sorbent are also cheap, abundant, and eco-friendly (Cojocaru et al., 2011). Some examples of such agricultural products are: straws (Johnson et al., 1973; Smith, 1983; Sun et al., 2002); wood (Smith, 1983); sugarcane bagasse (Sun et al., 2003); kenaf (Anthony, 1994); cotton (Anthony, 1994; Choi and Cloud, 1992; Johnson et al., 1973; Smith, 1983); cotton grass fiber (Suni et al., 2004); corn cobs (Tsai et al., 2001); saw dust; peat moss (Cojocaru et al., 2011); milkweed (Choi and Cloud, 1992); pine bark (Haussard et al., 2003; Saito et al., 2003); banana pith; sugarcane bagasse (Hussein et al., 2008); water hyacinth roots; chitosan, bentonite, and activated carbon (Ahmad et al., 2005); recycled wool (Radetic et al., 2003, 2008); Silkworm Cocoon (Moriwaki et al., 2009); Felt (Qi et al., 2011); Coconut shells (Amuda and Ibrahim, 2006); and rice husks (Mahvi et al., 2004; Kumagai et al., 2007, 2009; Foo and Hameed, 2009; Vlaev et al., 2011). It has also been shown that some agriculture products like straws, cellulosic fiber, milkweed, and cotton fiber sorbents can remove significantly more oil than polypropylene (synthetic organic) materials used commercially (Choi, 1996; Kobayashi et al., 1977; Sun et al., 2002).

Straw is hollow and can float for a longer time than the other products. Straw is considered the best and most widely used agricultural sorbent. Straw fibers float long enough on water to adequately collect oil. They are readily available, cheap, and can be stored for a long time. Tests have shown that acetylated straw fibers can sorb 16.8–24 times their weights and have greater oil sorption capacity than synthetic sorbent and polypropylene (Adebajo et al., 2003). Lim and Huang (2007) and Abdullah et al. (2010) also carried out an experimental study on the efficiency of Kapok (Ceiba Pentandra) – an agriculture product – in oil spill clean-up. Their results showed that Kapok fibers have sorption capacity higher than the commercial polypropylene for the three types of oil used (diesel, engine oil and hydraulic oil). Lim and Huang's (2007) results showed that Kapok has a high retention capacity of 36–45*x* their weight, while Abdullah et al.'s (2010) results showed sorption capacity in the range of 36.7–50.8*x* their weight. In both cases Kapok exhibited good re-usability, excellent buoyancy, high water repellency, biodegradable, and cheaper than cotton. Similarly, Annunciado et al. (2005) did experimental studies on several vegetable fibers and found out that silk-floss fiber has an outstanding sorption rate and sorption capacity of 85*x* its weight. It also exhibited goo buoyancy, hydrophobicity, oleophilicity and also a good retention capability. The published literature shows the efficacy and adsorption capacity of rice husk in sorbing various kinds of sorbates in polluted waters (Foo and Hameed, 2009; Bhatnagar and Sillanpaa, 2010). Kumagai et al.'s (2007) study showed that rice husk can sorb between 4.6 g and 6.7 g of heavy oil per gram of rice husk. Similarly, Vlaev et al. (2011) studied on rice husk showed that black rice husk ash have crude oil sorption capacity of 6.22 g/g and 5.02 g/g for diesel fuel while white rice husk ash exhibited a sorption capacity of 2.98 g/g for crude oil and 2.78 g/g for diesel fuel. Other products are good sorbents but they tend to become waterlogged easily and sink in a short while, even before reaching their sorption capacity (Schatzberg and Nagy, 1971; Sun et al., 2002). They are thus more effective in cleaning spills on shorelines, land, and beaches (U.S. Department of U.S. Department of Agriculture, 2008). A synthetic material—polyurethane foam—is a much better sorbent than agriculture products and has proven to have the overall highest sorption capacity—100 times its weight (Jarre et al., 1979). However, the natural materials mentioned above (such as straw, Kapok, vegetables fibers, peat, or bark) are more readily available at much lower costs and biodegradable (McLeod and McLeod, 1974; Annunciado et al., 2005; Lim and Huang, 2007).

3.5.3.1. Limitations of natural organic (agriculture) sorbents. The limitations of agricultural sorbents include high cost. This is due to the cost involved in recovering the oil soaked sorbent, removing the oil, and re-dispensing the sorbent. For example, a million gallons of oil spilled will require 200 tones (65,000 bales of straw) to sorb the oil. This means that after use and harvesting (recovery), vessels on location must be able to store 20 times the original weight of the sorbent since the sorbents are now soaked

Table 3
Comparison of sorbents.

Type	Structure	Type of oil	Sorption capacity (x = g/g)[a]	Re-usability (as reported by authors)	Availability	Environmental friendliness	Cost
Minerals							
Organoclay (Buist et al., 2011)	Granular	Diesel Hydraulic Engine	5.2–7.2x 2.2–3.6x 2.1–3.6x	No	Available	Not friendly	Expensive
Cf3-Functionalized silica aerogel (Adebajo et al., 2003)	Powder	Crude	237x	Re-usable for at least 2 times	Available	Friendly	Very expensive
Expanded perlite (Adebajo et al., 2003)	Granular	Light crude Heavy crude	3.5 3.25x	–	Available	Friendly	Very expensive
Exfoliated graphite (Namita et al., 2006)	Device	heavy crude	86x	Yes	Available	Friendly	Expensive
Synthetic organic							
Polyurethane foam	Foam	Crude	100x	Yes	Available	Not friendly	Expensive
Polypropylene (Choi, 1996)	Fiber	Light crude	10x	Yes	Available	Not friendly	Expensive
Natural organic							
Silk-floss fiber (Annunciado et al., 2005)	Fiber	Crude oil	85x	–	Available	Friendly	Cheap
Kapok (Abdullah et al., 2010; Lim and Huang, 2007)	Fiber	Diesel Hydraulic Engine oil	36x 43x 45–50.8x	Yes (4 cycles and 15 cycles reported)	Abundant	Friendly	Very cheap
Recycled wool-based non-woven material (Radetic et al., 2008)		Diesel Crude Vegetable Motor	9.62x 11.06x 13.16x 15.8x	Yes (5 cycles)	Abundant	Friendly	Cheap
Silkworm cocoon (Moriwaki et al., 2009)		Motor oil Vegetable oil	42–52x 37–60x	Yes (5 cycles)	Abundant	Friendly	Cheap
Acetylated rice straw (Adebajo et al., 2003; Namita et al., 2006)	Straw	Machine oil	16.8–24x	–	–	Friendly	Very cheap
Rice husk (Kumagai et al., 2007; Vlaev et al., 2011)		Heavy oil (Kumagai et al., 2007) Crude oil (Vlaev et al., 2011) Diesel oil (Vlaev et al., 2011)	4.6–6.7x 2.98–6.22x 2.78–5.02x	–	Abundant	Friendly	Very cheap
Acetylated sugarcane bagasse (Sun et al., 2002)	Pulp	Oil	18x	Yes (several times)	Abundant	Friendly	Very cheap
Cellulose (Ng et al., 2003)	Device	Crude	18–22x	–	Abundant	Friendly	Very cheap
Cellulose fiber (Namita et al., 2006)	Chips	Heavy crude	5x	–	Abundant	Friendly	Very cheap
Milkweed floss (Choi, 1996)	Granular	Light crude	40x	Yes (3 cycles)	Abundant	Friendly	Very cheap
Bregoil (Adebajo et al., 2003) (waste-wood fibers)	Sponge	Crude	7x	–	Abundant	Friendly	Very cheap
Raw cotton (Choi, 1996; Daling and Indrebo, 1996; Kapoor and Rawat, 1994; Murphey, 2010)	Fiber	Crude	30–40x	Yes (3 cycles)	Abundant	Friendly	Very cheap
Cotton lint (Kapoor and Rawat, 1994)	Fiber	Crude	80x	Yes (3 cycles)	Abundant	Friendly	Very cheap

[a] x means gram of crude per gram of Sorbent, g/g.

with oil and water. An ocean-going vessel with large amounts of deck space for ad hoc storage and sundry material handling equipment that could shuttle back and forth between land and a mother ship without losing any response effectiveness will serve the purpose (Bernard and Jakobson, 1972).

Furthermore, straw and other agricultural products require spreading of dry sorbents and retrieval of soaked ones by hand labor, which is time consuming and costly (Lehr, 1974; McLeod and McLeod, 1974). Hence, their application is limited to small terrestrial or marine spills or cleanup of residual spills after major clean up operations by other techniques like *in-situ* burning (U.S. Department of Agriculture, 2008).

A sorbent is considered reusable (recyclable) if a loaded sorbent can be easily compressed or squeezed to its original size and shape (Melvold et al., 1988). Other limitations of agriculture sorbents are their relatively lower sorption capacity (compared to polyurethane and exfoliated graphite; see Table 2) and also their limited recyclability. However, as discussed previously, some natural sorbents such as Kapok, silk-floss fiber, straw sorb significantly more oil than some synthetic materials used commercially, like polypropylene. Further, Choi and Cloud (1992) showed that milkweed, cotton, and kenaf are able to withstand three cycles of recyclability using suitable mechanical device, while Radetic et al. (2008) showed that recycled base non-woven material can withstand 5 cycles of recyclability (Table 3). Though, sorbents are limited to small water bodies, beaches and shorelines (due to the limitations discussed above), they can be effectively used in small but important small water bodies where impacts of oil spills are as significant as those in larger water due to their ecological and rural significance. Example of such cases is the oil spill in the Kerch strait connecting black sea and the Sea of Azov in 2007 in which 550,000 gallons of fuel oil was spilled and over 30, 000 birds were killed (The Telegraph, 2007). The Kerch Strait is a migration route for birds and fishes migrating between the two seas. Beaches, wildlife preserves, nearby community water sources, migration route (for birds and fishes) were severely hit (Rudomakha and Kucherenko, 2007).

4. Future research guidelines

Because agricultural products are the most environmentally friendly and most available sorbents, numerous research studies have been done, and are still ongoing, to investigate the effectiveness of many natural products for oil spill cleanup. As mentioned earlier, researches so far have covered fibers of different crops—nuts, bagasse, cotton, and several others. Cotton and straw are the most popular and effective agriculture sorbents for cleanup of oil spills. It is likely that other natural fibers from the products of forestry and agriculture could also do a good job. However, their efficacy has not been researched as thoroughly as that of cotton (American Society of Agricultural and Biological Engineers [ASABE], 2010). Moreover, further research into improving their recyclability, sorption capacity, and most effective application and recovery method remains to be done. However, with chemical modifications such as the addition of acetic anhydride (Sun et al., 2002) or Octanoic acid (Deschamps et al., 2003), the sorption capacity of agricultural products can be increased. This process is called acetylation. Examples are acetylated straw, acetylated sugarcane bagasse, acetylated cotton etc. Acetylating agricultural products makes them synthetic and may not be as environmentally friendly as desired. Therefore, the following research guidelines are proposed:

The desired natural sorbents should meet the following guidelines. Current sorbent materials identified in the literature satisfy some of these conditions. However, current spillage control challenges demand all of the following:

i. Hydrophobicity and oleophilicity (ability to repel water and sorb oil);
ii. Sorption capacity (oil sorbed per unit weight-dosage);
iii. Retention capacity over time (the sorbent should be able to hold the oil for long because breakdown of sorbed oil over time releases certain oil fractions into the water);
iv. Application and recovery from the sea (the most effective way to spread sorbent over broad areas and to harvest oil-laden sorbent; float time before it is harvested). Fibrous cellulosic products can be easily formed into mats, pads, and non-woven sheets for convenient applications (Fanta et al., 1986);
v. Recoverability of oil from sorbent (ease of extraction without damaging the sorbent so it can be reused);
vi. Environmental safety, recyclability, and/or biodegradability (Can it be recycled after harvesting? If not, will it biodegrade on the sea bed?);
vii. Availability;
viii. Storage (how long it can be stored and preserved; how much storage space needed);
ix. Economics (cost per square mile; effect of massive use on existing market).

4.1. In the context of the Middle East

The Middle East is a tropical region where straw and cotton are rarely cultivated because of the unfavorable climate conditions. The most abundant natural plants are palm trees. Middle Eastern countries are the world's biggest producers of dates. In 2007, Egypt was the largest producer of date palms, followed by Iran, then Saudi Arabia.

4.2. Date palm

There are about 100 million date palms worldwide, of which 62 million are on the Arabian Peninsula. Parts of the trees have the following uses:

i. Date seeds are soaked and ground for animal feed; burned to make charcoal; used for coffee.
ii. Dates are used in traditional medicine for fever, cataracts, sore throats, etc.
iii. Matured grown leaves are used for making mats, huts, baskets, screens, and fans
iv. The lightweight wood is used for posts and rafters, or burned as fuel.

Several authors have studied the sorption capacity of activated charcoal made from date palm for use as sorbents for metal ions, poisonous gases, etc. (Alaya et al., 2000; Fabiana et al., 2010). The effectiveness of the leaves (dry and wet) to clean up oil spillage has however, not been fully investigated. Hence, in future the efficacy of palm leaves could be studied based on the guidelines outlined above.

4.3. Sustainability of date palm technology

A sustainable technology works toward natural processes. In this paper we adapt Khan and Islam's (2007) "time-tested" model of sustainability, which hypothesizes that sustainability of a technology can be achieved if it emulates nature. In nature, all functions or techniques are inherently sustainable, efficient, and functional for an unlimited time period, i.e. $\Delta t \rightarrow \infty$. By following the same path as functions inherent in nature, we can develop a sustainable technology.

4.3.1. The pathway analysis

Pathway analysis is important for material characterization. The shape and properties of the material depend on its origin and its pathway traveled with time (Hossain et al., 2010). According to Khan and Islam (2007), the pathway of a sustainable technology is marked by long-term durability and environmentally wholesome impact, while an unsustainable technology is marked by $\Delta t \rightarrow 0$.

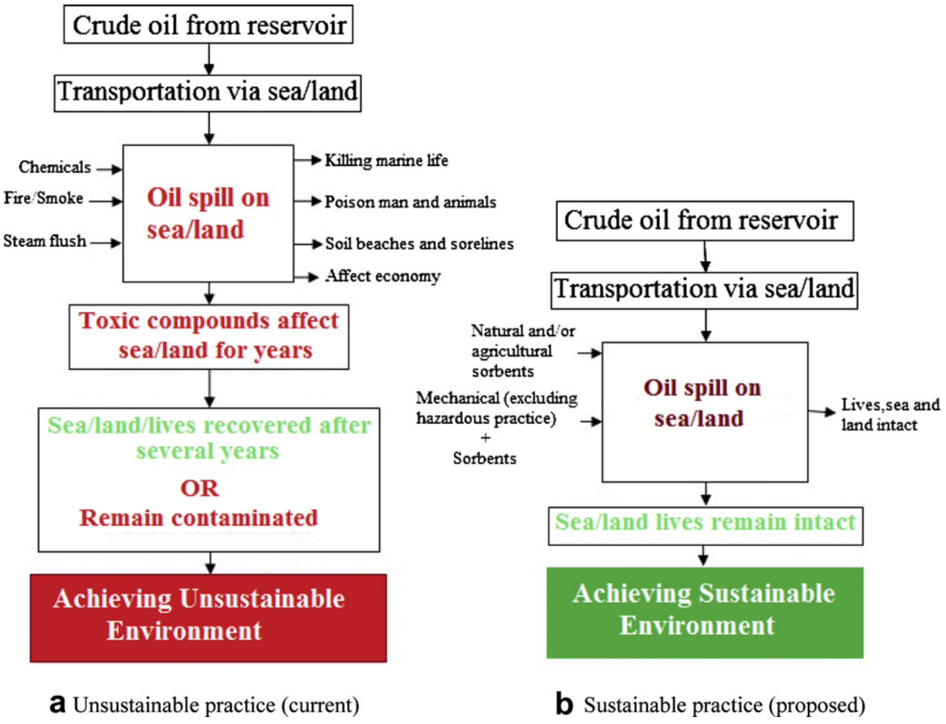
The pathways of all botanical products contain no harmful or toxic operations. All plants produce glucose (organic energy) from sunlight, CO_2, and soil nutrients. When they decompose, they add to the soil nutrients or at least are harmless to the soil or water. They can also be consumed by animals, including fish and other aquatic creatures. If however, plants are mixed with some chemicals along the pathway, as in the case of acetylated straw or activated charcoal, they may be rendered unsustainable in the context of the infinite time concept of natural functions.

The pathway of crude oil from production to transportation and processing is inherently harmful, unless some precautions and safe remediation methods are included. If, on the other hand, more harmful influences form parts of its pathway, for example in transportation, then that part of the pathway becomes unsustainable. Fig. 3 compares the pathway of crude oil with natural elements and unnatural elements in its pathway. Fig. 3(a) shows the conventional way of cleaning up the oil spillage from sea including mechanical and chemical processes where hazardous actions might be applied. Some of the conventional processes are very efficient in terms of oil removal capacity from the water. However, due to the nature of technology used, the usages become a threat for the environment. On the other hand, Fig. 3(b) is proposed based on the concept of using a technology which will not harm the environment while removing the oil spill from the sea water. It may combine both mechanical and chemical methods. For example, if we use any environmentally friendly mechanical method along with natural sorbent as proposed earlier (date palm leaves), the method will become sustainable and more efficient. Finally the pathway analyses show that both sustainable and unsustainable methods have their own advantages and disadvantages. The main challenge underlying with the sustainable process is the finding out an efficient natural sorbent for controlling oil spill.

4.3.2. Conditions of sustainability

As mentioned earlier, any new technology should be functional for an infinite time. This is the only way it can achieve true sustainability. In this study, a criterion is formulated to test the sustainability of new oil spill technology as followed by Khan and Islam (2007), and Islam et al. (2010). According to this criterion, to consider any technology sustainable in the long term, it should be environmentally appealing, economically attractive, and socially responsible. In addition, the proposed technology should continue for infinite time. This idea forms the new assessment framework for oil spill technology which is shown in Fig. 4. The new technology should be evaluated and assessed by using this model. In this model, two levels of selection are introduced: i) the primary level – time, and ii) the secondary level – sustainability.

The new oil spill technology must fulfill the primary selection criterion, time (i.e. $\Delta t \rightarrow \infty$) before being taken to the secondary level of selection (Fig. 4). If the technology is time tested and is not durable for infinite time, it is rejected as an unsustainable technology. In such case, it would not be considered for further testing. On the other hand, if the new oil spill technology is acceptable with respect to this time criterion, it may be taken through the next process to be assessed according to the second set of criteria. The initial set of the secondary criteria analyzes environmental variants. If it passes this stage, it goes to the next step. If the technology is not acceptable in regard to environmental factors, then it might be rejected, or further improvements might be suggested to its design. After environmental evaluation, the next three steps involve technological, economic, and societal variants analyses, each of which follows a pathway similar to that used to assess environmental suitability. Also at these stages, either improvement on the



a Unsustainable practice (current) **b** Sustainable practice (proposed)

Fig. 3. Pathway comparison for (a) current (unsustainable) and (b) natural (sustainable) methods of spill control.

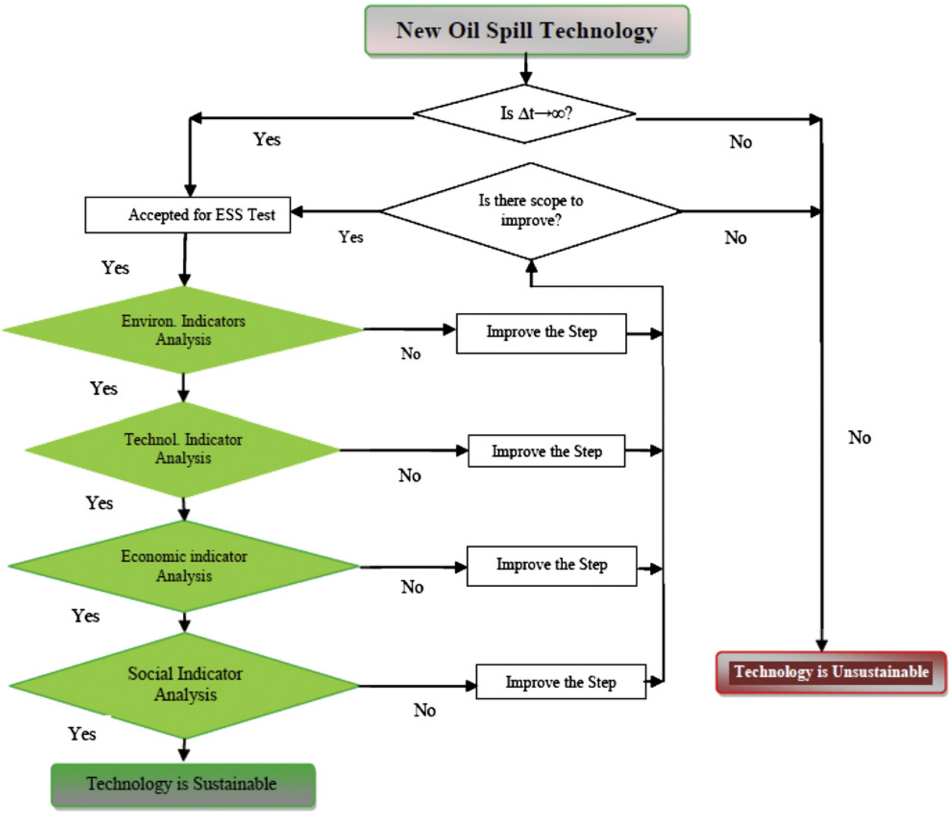


Fig. 4. Proposed sustainable oil spill control technology flow chart (modified from Khan and Islam, 2005).

technology will be required or the technology might be rejected as unsustainable. As example, if we now test the above current oil spill technologies, unfortunately, all these techniques become unsustainable. Some of them are not even crossing the primary stage.

Based on the proposed newly developed pathway (Fig. 3b) and the proposed method (Fig. 4), a practical tool for testing the oil spill technology is proposed and presented as shown in Fig. 5. Based on the sustainability criteria as mentioned earlier, these conditions can be imposed to test the sustainability of a 'Sustainable Oil Spill Control Technology'. In addition, a time criterion can be used by subjecting the method to the following time dependent criteria namely *environment, social, economic and technological* as given by equation (1) and depicted in (3).

$$C_n + C_e + C_s \geq C \tag{1}$$

where C = Constant for all time horizons; C_n = Total natural (i.e. environment) capital of the life cycle process of oil spill technology; C_e = Total economic benefit (i.e. capital) of the life cycle process of oil spill technology; C_s = Total societal benefit (i.e. capital) of the life cycle process of oil spill technology.

Equation (1) can be further extended for any time "t" with some specific conditions as:

$$(C_n + C_e + C_s)_t \geq C_t \tag{2}$$

where C_t = Constant for any time "t".

Equation (2) is applicable only when the following conditions are fulfilled.

$$\frac{dC_{n_t}}{dt} \geq 0, \quad \frac{dC_{e_t}}{dt} \geq 0, \quad \frac{dC_{s_t}}{dt} \geq 0 \tag{3}$$

These conditions are also shown in a flow chart format in Fig. 5. The above derivatives mean that the proposed technology should continue for infinite time, maintaining that the indicators function for all time horizons. For example, in the case of environmental benefits, burning green bio-diesel produces "natural" CO_2 that can be readily synthesized by plants (Islam et al., 2010). On the other hand, CO_2 coming from chemical processing plants cannot be synthesized by plants due to the different source and process. Therefore, the environmental capital derivative, dC_{n_t}/dt will always be positive with time or at worst case it would be zero. However, for any unsustainable case (such as the above example), the derivative will always be negative because it is always adding negative impact on environment. The above example is true for other two (i.e. economic and social benefit) criteria where the derivatives would positive or nullified. It will never be negative again.

Finally, it can be seen that most current spill cleanup techniques do not meet the proposed conditions. Their sustainable criteria derivatives or capitals become negative for the long run due to the sources of the chemicals used and the process itself. On the other hand, only a well prepared agriculture sorbents or nature-based technology that maintains its integrity as purely natural as shown in Fig. 3b satisfy these conditions.

5. Conclusions

1. The study reviewed and compared various oil spill cleanup methods and highlighted the limitations and environmental impacts of current cleanup techniques.
2. The study of applicability of agricultural products is motivated by their abundance (which at times results in mere waste products) and biodegradability. Hence, the possibility of complementing other commercial and expensive sorbents.

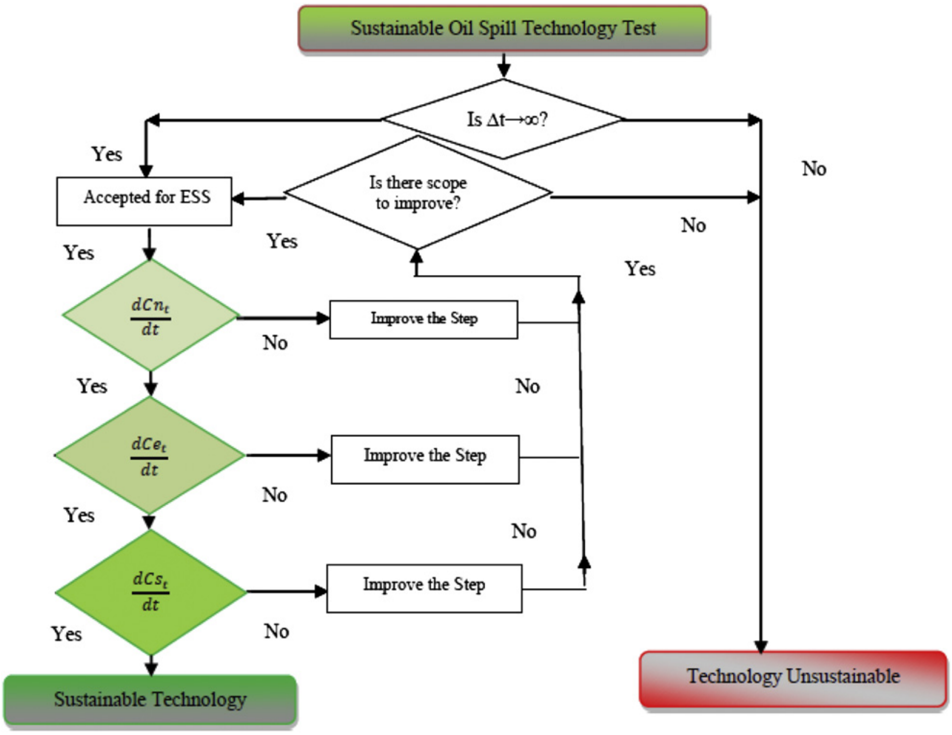


Fig. 5. Proposed sustainable technology diagnostic test flow chart.

3. The study also found the efficacy and efficiency of natural products to be among the best and most sustainable sorbents and, at the same time, most eco-friendly compared to other techniques. However, synthetic sorbents are most commonly used commercially because of the extremely high sorption capacity of polyurethane foam and, of course, its recyclability.
4. Agricultural products, such as straw and Kapok, sorb significantly more oil than polypropylene materials that are normally used commercially.
5. Straws and Kapok are not readily available in some tropical regions and hence, more cost is incurred to import them. As an alternative, research into the applicability of abundant tropical products like date palm in Saudi Arabia is proposed.
6. The paper reviewed the need to use palm leaves, human and animal hair, and animal skins, which are abundant waste products in Saudi Arabia as a replacement of artificial sorbent. These natural sorbents are best for Saudi Arabian water and land, which serve as hosts and passages for production and transportation of the world's largest oil producing country.
7. Finally, some guidelines have been mapped out for future research into the applicability of natural/agricultural sorbents for sustainable oil spill control.

6. Conversion

1 Barrel (U.S Liquid) = 31.5 U.S. Gallons
1 Barrel (U.S Liquid) = 119.24 L
1 Gallon (U.S Liquid) = 3.79 L
1 Tone = 31.75 U.S. Gallons

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