EnvironmentAsia
The international journal by the Thai Society of Higher Education Institutes on Environment

EnvironmentAsia 14(3) 2021 13-22
DOI 10.14456/ea.2021.19
ISSN 1906-1714; ONLINE ISSN: 2586-8861

Marine Oil Spills: Implications on Response Plan

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Received: February 11, 2021; Revised: March 12, 2021; Accepted: May 5, 2021

Abstract

Understanding oil spill detection, modelling is critical in formulating oil spill response to minimize the catastrophic environmental impact due to oil spill. This paper provides the key research results for oil spill response from various published literatures over few decades which are based on case studies, laboratory tests, field visits and modelling work. This paper presents an overview and summary of literature reviews on offshore oil spills, fate of spilled oil, response plans and cleanup methods. A brief discussion on the technological advancements in identifying oil spills and oil spill modelling is presented. Discussions on the response methods include recent advances in spill response plans and cleanup methods. The synthesis of published literatures from various previous work on understanding and mitigation strategies of oil spill disaster would immensely contribute scientific knowledge to deal with the future oil spill.

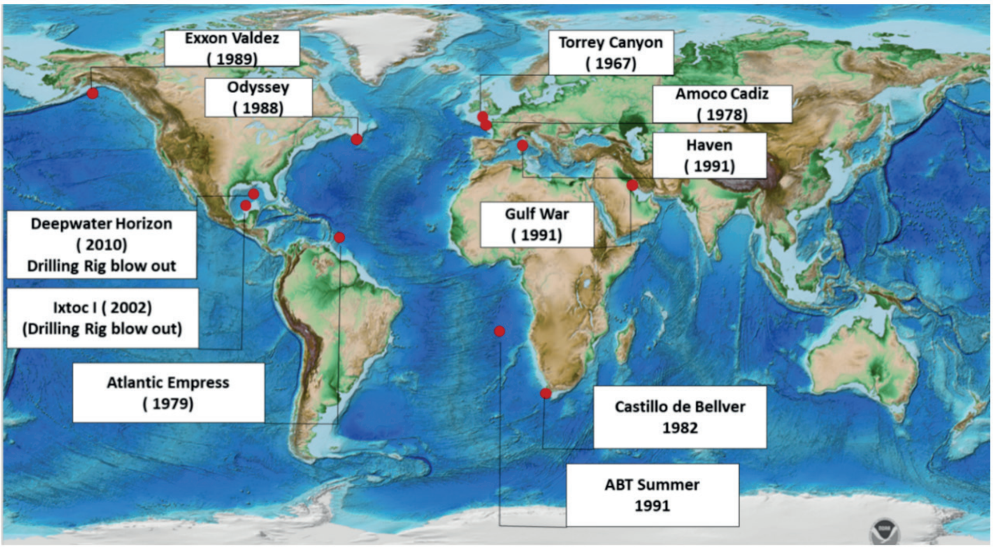
Keywords: Oil spill; Response plan; Cleanup; Environment

1. Introduction

Huge demands for crude oil in recent times have increased offshore exploration and production activities around the world. Exploration and Production (E&P) activities, as well as oil transportation, carry the risk of the oil spill in the marine environment. The marine oil spill has a catastrophic impact on marine ecology, coastal ecosystems, and human health (Jafarinejad, 2017). With the advancement of technology in recent times and the implementation of technological changes like improvements in ship hulls and navigation systems have reduced marine spill cases in many folds (Chang *et al.*, 2014). Although there has been much more advancement in transportation technology and safety measures, still oil transportation continues to be a highly risky activity. Last decade, there have been 62 spills of different sizes resulting in 164,000 tons of oil lost (ITOPF, 2019). This review paper deals with the offshore oil spill, fate of the oil, which could be useful in developing effective response plans. This discussion would help create new strategies to solve the complexity of oil spill events. Many researchers have studied the various aspects of oil spill, new technologies and advancements in response plan, which are being discussed here for better insight.

2. Major oil spills around the world

Marine oil spills can be in the form of few barrels to thousands of barrels. The volume of oil spills is not a measure of the severity of the damage. The geographical location of the discharge and sensitivity of the nearby shore is also crucial. A map showing some of the prominent oil spills around the world in figure 1. Ecological impact related to some of the significant oil spills are presented in table 1.



Source: NOAA, 2009

Figure 1. Map showing some of the significant oil spills around the world on a topography map sourced from National Oceanic and Atmospheric Administration

Table 1. Summary of ecological impacts of some of the major oil spills around the world

Incidents	Ecological Impact	References
The Torrey canyon, 1967	25,000 sea birds, other marine organisms	Wells (2017)
Amoco Cadiz, 1978	15000 to 20000 sea birds died, Numerous fishes affected	Wan Fatihah et al. (2019)
Castillo de Bellve, 1983	1,500 gannets, covered in oil.	Moldan et al. (1985)
Exxon Valdez, 1989	Pacific herring and pink salmon spawning streams highly affected. 1300 miles of shoreline damaged.	Liszka (2010)
Arabian Gulf, 1991	56 sea turtles, 32 dugongs, 33 porpoises, 1,500 snakes, birds and fish affected.	Davies (1991)
M/T Haven Tanker, 1991	43% reduction in fish populations, oiling of around 100 birds	Wan Fatihah et al. (2019)
Deep Water Horizon, 2010	2100 km of shoreline affected. large fish species, deep-sea corals, sea turtles and cetaceans affected.	Beyer et al. (2016)

3. Fate of oil

It is critical to understand what happens when oil spills into the water and where the oil will go in order to, devise an effective response plan in case of any marine oil spill. Evaporation, dispersion, emulsification, dissolution, oxidation, sedimentation, and biodegradation of oil mostly change the spill scenarios. These processes collectively term as oil weathering processes (Sebastião and Guedes Soares, 1995). Oil spill models are typically developed by integrating the series of algorithms of the physical processes like transport, spreading, and multiple biological and chemical weathering processes, such as evaporation, dissolution, emulsification, degradation (Shen *et al.,* 2019). A schematic diagram showing the various processes affecting the fate of oil and the generalized time scale is shown in figure 2.

Spreading: Spreading of oil refers to movement of spilled oil in water, depends on the wind intensity and direction, is critical in any trajectory modelling done to understand spilled oil (Shen *et al.,* 2019).

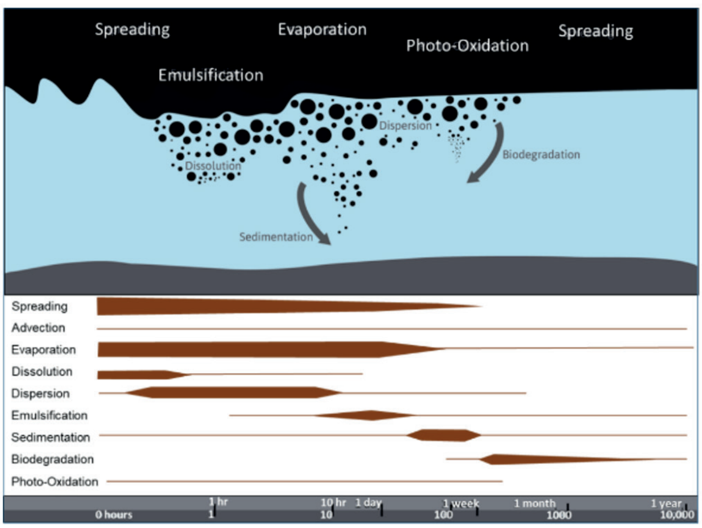
Advection: Advection encompasses wind, wave, and turbulent activities, which help in spreading. A study by Kelly *et al.* (2018) concluded that a detailed understanding of ocean circulation is critical for determining the long-term fate of pollutants.

Evaporation: Evaporation is the process of converting liquid to the gaseous phase, where the lighter fraction of oil is lost. Loss of oil by evaporation can vary from 10% to 100%, depending on the oil density. It is found that the light oils could evaporate 30 to 60 % of total oil's mass over two days (Fingas, 2017).

Dispersion: Dispersion is a natural process where oil slick breaks into small droplets, thereby separating oil from water. Evaluation of natural dispersion is also useful for estimating the spreading of oil-in-water and water-in-oil emulsions formed, in the water column (Trakis *et al.,* 2011).

Emulsification: Emulsification occurs when oil falls into the water; small water droplets are mixed to oil, increasing the water content (can be 50 - 80%). Emulsification with 80 % of water content may have increased the oil volume to 5 times its original volume (Xie *et al.,* 2007).

Dissolution: Dissolution is the process where the water-soluble component of oil gets mixed with water in case of an oil spill. It has been found that the water-soluble component of the oil is found to be most toxic. Dispersion, dissolution, and emulsification processes greatly influence the behavior of oil in water (Fingas, 2017).



Source: ITOPF, International Tanker Owners Pollution Federation Limited

Figure 2. Schematic diagram showing various processes affecting oil fate when it comes in contact with water

Biodegradation: Microbes present in water can breakdown oil to smaller compounds, this process is called biodegradation. Bacteria get energy and carbon from petroleum hydrocarbons for their growth, reproduction, degrade and metabolize hydrocarbon to relieve the physical stress of petroleum hydrocarbon in the microbial environment (Xu *et al.,* 2018).

Sedimentation: Sedimentation is a process of adhesion of oil to the solid particles in water. Oil is absorbed onto the solid particles can be found to be deposited at the bottom sediments.

All of the above processes are critical in understanding the fate of oil in case of a spill.

4. Oil spill management plan

The offshore oil spill management plan includes various methods to prevent the spreading of the oil. Some of the methods to find out the oil spill incidents and their behavior, the control measures are discussed below.

4.1 Identification of Spill

4.1.1 Aerial observation

Efficient monitoring and early identification of oil slicks plays a vital role to control the pollution and the damage. Remote sensing and satellite data can provide the near real-time data by operational satellite-based monitoring systems so the authorities could use it as an effective tool for manmade hazards like illegal oil spill discharges that need a synoptic view when there is an emergency status and where on-site surveying is not possible (Akkartal and Sunar, 2008). Quantification and characterization of the oil spills are also nowadays possible with newly developed technology of remote sensing devices like SLAR, (Side-looking airborne radar, long-range detection) IRLS (infrared line scanner), UVLS (ultra-violet line scanners), LLLTV (Low light level Television, short-range investigation, and evaluation), and Micro wave radiometry. These devices are used for long-range and short-range detection as well as quantification of spill oil. Optical and microwave remote sensing techniques are mostly used to monitor marine oil spills (Jha *et al.,* 2008). The laser fluorosensor uniquely detects oil on substrates that include shoreline, water, soil, plants, ice, and snow.

4.1.2 Oil fingerprinting

Oil fingerprinting is a method to characterize oil through geochemical analysis. The process is critical to understand the nature of oil, which dictates the spill's fate, behavior and correlate the spilled oil to the source of contaminants. Fingerprinting can be qualitative or quantitative. In the qualitative method, we can get the chromatographic data as fingerprints by GC-FID (Gas Chromatography with Flame-Ionization Detection) and GC-MS (Gas Chromatography-Mass Spectrometry) analysis of oil from spilled source and presented in ASTM (American Society for Testing and Materials) method (Wang *et al.,* 2006).

4.2 Spill response plan

When there is an offshore oil spill, the most likely areas at risk are fisheries or fishing harbor, wetland, lagoon, power station, and the beaches (beauty and recreational facilities). Hence there must be a response plan for these places which might be affected by the spill. Although prediction and planning to deal with such disasters always have many challenges and limitations, there are some preventive steps to reduce the risk on the coast and marine ecosystems. The critical steps to prepare an effective response plan are:

Understanding oil movement: Monitoring and prediction of the oil movement enables understanding the possible region in the marine and coastal area which could be in threat by the oil spill. Oil spill simulation forecasting models consider various physio-chemical processes like spreading, horizontal turbulent diffusion, advection, vertical dispersion, emulsification, and evaporation in order to predict the horizontal movement slick, vertical distribution, the concentration in the water column and mass balance so that the oil spill recovery process can be efficient.

Various softwares can be used to predict oil spill movement and fate modelling. Oil trajectory models provide valuable support for making predictions about the movement of oil, the fate of spilled oil, and estimating the likely sensitive resources threatened (Kankara and Subramanian, 2007). Movement of oil depends upon the wind, current condition. Various studies have been done worldwide to model oil spill movement in real and hypothetical spill situations. Trajectory model is the best option for quick response for oil spill incidents, which gives results considering winds, ocean currents, and tide movement of the location (Toz and Koseoglu, 2018). Simulation of the oil spill has been carried out by different kinds of software like OIL MAP, EUROSPILL, GNOME, ADIOS (Lopez *et al.,* 2006). Remyalekshmi and Hegdge (2013) conducted a GNOME (General NOAA Operational Modelling Environment) modelling to forecast the movement of a possible crude oil spill in Northwestern offshore India.

Environmental sensitive index map: ESI (Environmental sensitive Index) map is another critical tool to assess potential environmental damage in case of a spill. Environmental sensitivity mapping is an essential step for protecting sensitive habitat along the coast and an important tool to put in place the response and preparedness plan for oil pollution caused by the oil spill. Environmental sensitive Index maps prepared from field observations, remote sensing data are efficient tools to identify higher risk areas in case of a spill (Gundlach and Hayes, 1978). Environmental sensitivity maps are developed using the GIS environment, where the collected data have been presented and, it is the best method to adopt or propose any cleaning techniques according to their effectiveness and environmental impact (Bello Smith *et al.,* 2011). The sensitivity region could be classified spatially. The higher sensitivity is receiving the environment have lesser chances to cope with human-induced change. There are three ways to carry out the sensitivity analysis for several regions: 1) analyze a system or region characteristics which are influenced by change, 2) analyze resulting impacts, and 3) analyze the exposure, sensitivity, and interactions between components (Pärssinena *et al.,* 2018). Sowmya and Jayappa (2016) constructed ESI maps for Karnataka coast classifying the coast line based on various factors. The study identified many sensitive shorelines using GIS and Remote sensing techniques. Estuaries along the coast are assigned at high-risk index, especially as those areas carry the mapping project's dense biodiversity.

4.3 Oil spill cleanup methods

Cleaning up could be various types depending on the area of spread, weather condition, and type of pollutant. It is always preferred to check the spreading from the origin, but in most cases, it is difficult and challenging.

4.3.1 Booms and Skimmers

Booms are floating objects or barriers which restrict the floating of oil and are placed in oil spreading area to limit the movement (figure 3a). The Booms are made with oil and water-resistant fire-resistant material (Fingas, 2017) and available in different shapes and sizes according to weather conditions, wave height, and current

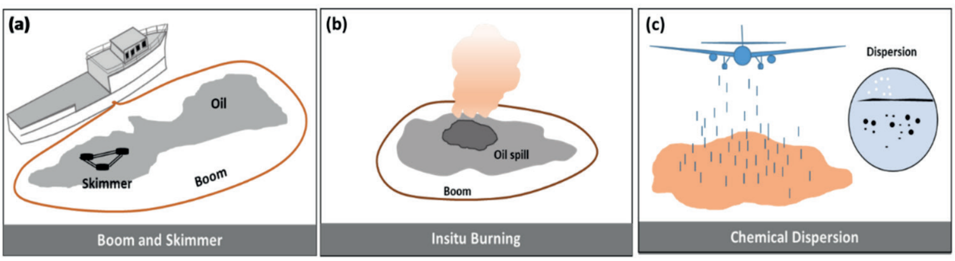


Figure 3. Schematic diagram of some of the oil spill cleanup methods

speed. The hybrid system of floating boom integrated with weir skimmers could be a better option for the cleanup process (Abdel-Naby, 2018). Skimmers are used to collect oil from water. These can be boats, vacuum machines, sponges or oil-absorbent ropes that skim spilled oil from the water's surface within the booms. These come in many shapes and sizes like disk skimmer, belt skimmer, brush skimmer, and drum skimmer and others (Hoang and Chau, 2018). Abidli *et al.* (2020) suggested that development of an environmentally friendly, cost-effective and efficient oil–water separation (OWS) technology is highly urgent to deal with the oil spill cases and designed a pilot-scale oil-water separator skimmer (OWSS) prototype to separate oil and water mixture from large area oil spill.

4.3.2 Sorbents

Sorbents are the materials or combinations of materials used to recover oil from water through the mechanism of absorption or adsorption, especially in rough seas. Natural organic materials like pulp, hay, straw, sawdust, reeds, peat, bagasse, gorse, dried palm fronds, cotton, kenaf, corn cob, wood fiber, milkweed floss, peat moss, pine bark are mostly used as sorbent materials (Choi and Cloud, 1992). Synthetic polymeric materials like foams of polyurethane, urea-formaldehyde, polyethylene, nylon, polyester materials are also used as effective sorbents. Lin *et al.* (2008) proposed that Tire powder also has sufficient sorption potency for cleaning up the spilled oil as it is oleophilic in nature. The fabricated synthetic materials and modified organic sorbents are in current research of oil water separation. Recent studies found that a wide variety of cellulosic materials such as banana fibers, corn stalk, cotton, milkweed fiber, curauna fibers, kapok, luffa, nettle fibers, orange peel, palm fibers, pineapple leaves, pistia leaves and roots, pomelo peel, rice husks, sawdust, wheat straw, sugarcane bagasse, and walnut shell have good result in oil spill treatment (Zamparas *et al.,* 2020).

4.3.3 Insitu-burning

The spilled oil can be collected to one place by the fire-resistant containment boom and then are burnt (figure 3b). The combustion results in many solid, liquid, and gaseous compounds from the oil layer. Gases like CO, SO_2, NOx, a wide range of organic compounds are released to the atmosphere in smoke during the burning process. It is estimated that approximately 220,000 to 310,000 barrels of oil was burned in more than 400 separate burns, carried out during three months of BP oil spill (Allen *et al.,* 2011).

4.3.4 Chemical dispersion

A chemical dispersant consists of emulsifiers and solvents or a mixture of both, which break oil into small droplets. Dispersants contain the chemical compositions made from surfactants and other additives that help to reduce the interfacial surface tension between oil and water (Idris *et al.,* 2013). The oil spill dispersant products have undergone three development stages in terms of surfactant and solvent. First generation is anionic surfactant and the major solvent light aromatic hydrocarbon, the second generation is nonionic surfactant with lower toxicity (mainly ether surfactant) and for the third generation D-sorbite, fatty acid, and other raw materials come from agricultural and sideline products to make surfactant less toxic, and the solvent is polyethylene glycol (Guodong *et al.,* 2015). The use of dispersants has to be decided by considering several factors like the type of oil, its state of weathering, the thickness, and shape of slick. It is found that the most commonly used dispersant Corexit 9500 and its modified form (after adding hexylamine or 1-octanol) have shown better results of oil removal from water (John and Hayworth, 2019). Aircraft are used to pour dispersant (figure 3c) faster, uniformly and mostly followed by skimming or in situ burning. The efficiency rate of oil spill dispersant mainly includes emulsification rate, biodegradability and biotoxicity. The dispersed oil degrades more quickly because it enhances the oil availability to natural microorganisms. Xu *et al.* (2018) provided an overview of the recent literature on the usage of bacteria to degrade the oil, the problems regarding the implementation of this microbial technology, and the further developments on this research.

4.3.5 Shore cleanup operations

Shoreline affected by the oil spill can be cleaned using various equipment, methods, and work forces. The cleaning method which should be followed depends upon the nature of the shore. Pumping is an easy way to collect liquid oil at the shore. The vacuum device effectively pumps the thin layer of oil by pumping equipment. Earth moving devices like graders, bulldozers, scrapers are mostly used to remove the strain of oil and oiled sand at the beach. These activities could sometime result in excessive removal of sand. Skimming of oil material on the beach can lead to beach erosion, and removal of sand is not applicable for sensitive shorelines (Exxon Mobil, 2014). The sensitive and inaccessible areas are not suitable for heavy machinery applications, so here mostly manual removal is preferred.

5. Discussion on development in oil spill management plan

Synthetic Aperture Radar (SAR) has become the main means of oil spill detection, as it is minimally affected by sunshine and clouds, and has all-day and all-weather imaging capability with wide swath and high resolution (Song *et al.,* 2017). Krestenitis *et al.* (2019) studied that Black spots of oil spills can be clearly captured by SAR sensors, yet their discrimination from look-alikes poses a challenging objective. According to authors there are many automated methods which are proposed to detect and classify spills. Most of them employ custom-made datasets, which are the major drawback of these methods. To overcome these limitations, semantic segmentation with deep convolutional neural networks (DCNNs) is proposed as an efficient approach. DCNN segmentation models, trained and evaluated on the provided dataset, can be utilized to implement efficient oil spill detectors.

Currently the oil fingerprinting is based on profiling, specific source biomarkers by GC–MS (Bayona *et al.,* 2015). Although in case of the heavy oil fingerprinting, asphaltene profiling could be done by the Pyrolysis Gas Chromatography Mass Spectrometry (Py-GC-MS) method, still it is not suitable for weathered oil (Riley *et al.,* 2018). The new developments in gas chromatography and mass spectrometry like GC-MS/MS (Gas Chromatography tandem mass spectrometry), GC×GC–FID–TOF (Comprehensive two-dimensional gas chromatography-flame ionization detector-time of flight mass spectrometry), GC–IRMS (Gas Chromatography - isotopic resolution mass spectrometry) have allowed an enhanced sensitivity, selectivity, resolution and isotopic determination of oil biomarkers, providing additional tools for oil fingerprinting (Bayona *et al.,* 2015), and authors suggested, the spectroscopic fluorescence FT-IR (Fourier Transform Infrared Spectroscopy) and ultra-high resolution mass spectrometry methods FT-ICRMS (Fourier transform ion cyclotron mass spectrometry) have also shown a great potential in oil characterization.

In oil spill modelling study, OILMAP has been validated on a global scale and it has been used to model spill in Gulf region (Persian Gulf War), Indian Ocean and Mersin Bay in Mediterranean Sea (Keramea *et al.,* 2020). Toz and Koseoglu (2018) carried out modelling using PISCES 2 and suggested that the efficiency of any predictive oil spill model needs reliable data. The uncertainties related to the various factors affecting an oil spill are complicated due to environmental variables and oil characteristics. Keramea *et al.* (2020) studied various advanced, new-generation, operational, three-dimensional numerical models which integrates meteorological, hydrodynamic, and wave data to forecast the transport and fate of oil with high-resolution and with high accuracy. This study discussed the limitations of identifying the time of release of oil or when the oil slick is formed. The study outlined various changes in oil properties due to the chemical and biological fluctuations which impacts the fate and transport of oil spill. The authors suggested that in order to minimize the model sensitivity derived from uncertainties in the emulsification rates and slick thickness, the use of the droplet size distribution formulation could be proven helpful in operational models.

Shavykin and Karnatov (2018) discussed importance of vulnerability maps of sea-coastal zones in oil spill response plans, environmental support for offshore projects, preparation of the Environmental Impact Assessment, and integrated marine environmental management plans. The authors concluded different map scales, season limits, units of biota abundance, the calculation of relative vulnerability coefficients for the considered biotic components, the summation of the vulnerability of objects of different types should be considered in vulnerability mapping. Doshi *et al.* (2018) carried out a comprehensive review of the biobased materials of oil spill treatment and suggested that the gelators and sorbents can be used to immobilize the oil and recovery of oil from water surface for reuse purposes. The authors also suggested that in comparison to other sorbents, use of magnetic particles for recovery of oil could be economically more viable. The effective biobased sorbents can be prepared but modification costs and feasibility are the future challenge to produce effective sorbent materials.

6. Conclusions

Reviews of number of publications related to various aspects of oil spill are diligently used to understand the recent developments in identifying spill, predicting spill movement, and effective response plan. Significant development has been made in identifying oil spill in the offshore region using satellite carried Radar images. The basic structure of spill modelling and identification of oil spill provide the concise information to deal with spill incident. Oil spill simulation is used recent time to predict the horizontal movement of surface oil slick with the mass balance of the spills which could guide to achieve the best strategies for preparedness plan. Advance in computing as well use of cutting-edge software have significantly enhanced the quality of spill simulation models. Advance trajectory models are capable of predicting movement of the spill to a greater accuracy. More accurate prediction of variables like wind and wave had been helped immensely in minimizing the error in prediction. Trajectory modelling integrating with geospatial applications and ESI maps are very helpful for tracking oil movement as well as predicting the area of impact. Geospatial applications have become the platforms for generating detailed ESI maps which are immensely useful to prepare response plans accordingly. Tremendous R&D has been going on oil spill cleanup methods. The review of cleanup identifies number of coast effective and environment friendly methods which are being used worldwide. Various ecofriendly dispersant and sorbents are effectively used for many oil spills around the world. The learned lessons from the review study on cleanup method could guide for further development in this field. New, improved cutting-edge technologies have been proposed for a better cleanup and response plans.

Although recent researches are being carried out to address challenges associated with various aspects of oil spill resulting in some noteworthy break throughs, the research community could think for the development and enhancement of these technology in a more cost effective and environment friendly manner by adding new data and ideas.

Acknowledgement

Authors are thankful to Department of Environmental Science, Utkal University, Odisha, India for giving the opportunity for an ongoing research work on Oil Spill modelling.

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