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# Recent Advances in Soil Cleanup Technologies for Oil Spills: a Systematic Review

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**Abstract** The mishaps involving oil containers, tanker collisions, leaks as a result of ruptured oil pipelines, etc. that result in crude oil spills are a very significant topic of concern. Recently, hundreds of oil disasters have occurred, causing enormous economic and human harm. The oil spill adheres to the surface of the silt, making it difficult to immediately clean up the soil. The polycyclic aromatic hydrocarbons in oil have harmful consequences that include being teratogenic, mutagenic, and carcinogenic. Additionally, oil spills may adversely affect humans and the environment by getting into the food chain directly or indirectly. Since removing oil from the soil is an expensive process, there is an urgent need for efficient removal techniques. Over time, numerous researchers have examined the effects of these spills on the soil and created a variety of technologies for their remediation. This review article offers a deep analysis of the technologies used to clean up oil-contaminated soil, including bitumen, diesel, crude oil, petroleum, lubricating oil, and bunker oil. Among the techniques covered are chemical oxidation, electrokinetic remediation, bioremediation, phytoremediation, solvent extraction at high temperatures, coal agglomeration, aerogels, and gelators. Each of these technologies was extensively covered, along with both their benefits and drawbacks. As a result, no one remediation technique is thought to be the ideal approach for cleaning up oil-contaminated soils. It has been shown that the choice of cleanup technique depends on the types of contamination, since a poor choice may hinder high removal efficiency.

**Keywords** Oil-contaminated soils · Remediation technologies · Oil spills

## 1 Introduction

The crude oil spills both on terrestrial and aquatic ecosystems are a quite serious matter of concern. The oil tanker accidents and oil leakages due to

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rupturing of oil pipelines while transporting the crude oil from one country to another are the most unforgettable accidents as shown in Fig. 1 (Araruna et al., 2004; Trevors & Saier, 2010). One of the world's largest crude oil spills, estimated at around 287,000 tons, took place in the Caribbean Sea, on Trinidad and Tobago coast in 1979 (Persian Gulf war, 1991). Another oil spill took place in the Persian Gulf, Iraq, in 1991 losing eighty-two thousand tons of oil into the sea. A very little amount of oil was recovered from these accidents (Broekema, 2015).

Furthermore, in the year 2002, the oil tanker carrying crude oil discharged 63,000 tons of oil into the Spain sea, resulting in huge damage to the environment, and sea flora and fauna (Major oil spills, n.d.). In the year 2021, multiple oil spills took place in CA, USA losing 42,442 tons of crude oil on Southern California beaches resulting in many months to clean it properly (Massive California oil spill threatens wildlife and closes beaches, 2021). The thorough literature survey revealed that the largest thirty reported oil spills that took place in the last five decades are summarized in Table 1.

Furthermore, the crude oil is mainly composed of saturated and aromatic hydrocarbon complex mixtures, with low density, emulsifying ability, and high viscosity which enhances the adsorption of oil on the soil surfaces (Saharan et al., 2020). Once, the oil is adsorbed on the soil surface, the soil losses its permeability and porosity (Saharan et al., 2022a). It is C/N, C/P ratio, salinity, pH, EH, and conductivity change making it unfit for plants and microorganism growth (Shan et al., 2014).

In addition to this, the oils float on the water surfaces due to oil spills, greatly affecting marine flora and fauna. The oil layer act as a blanket, preventing sufficient amounts of sunlight from penetrating the water's surface, along with it, oil reduces the level of dissolved oxygen making the water bodies unfit for living organism (Brody et al., 2010). Moreover, the polycyclic aromatic hydrocarbons in the oil have carcinogenic, mutagenic, teratogenic, and other toxic effects. The oil and other pollutants directly or indirectly enter into the human and animal bodies causing various types of diseases and destruction (Shaheen et al., 2019). The numerous researchers have developed and designed various methods and technologies for this problem. At the present time, most oil cleanup technologies from soil and water surfaces may be fast and effective but are mechanical and labor intensive in nature (Lim et al., 2016). The use of toxic chemicals may be quite harsh and deteriorating. The mechanical technologies are time-consuming and tedious to perform.

In the present work, eight remediation methods (as shown in Fig. 2) are discussed in detail with their advantages and disadvantages. Furthermore, this review provides the study of cleanup techniques for diverse oil-contaminated soil, viz., petroleum, diesel, bitumen, bunker, lubricant, and crude oil. Hence, some new and more adaptable methods can be derived for future remediation of oil from contaminated soil.

**Fig. 1** Oil spill on Sergipe state beach, Brazil (8 October 2019) (A barrel of oil leaking on a beach in Barra dos Coqeiros in a Braziilian state of Sergipe, 2019). A barrel of oil leaking on a beach in Barra dos Coqeiros in a Brazilian state of Sergipe 8 Oct. 2019

**Table 1** The top thirty oil spills which took place in the last five decades (1968–2021)

| Sr. no | Oil spill sites around the world | Year | Type of oil spilled | Quantity spilled (tons) | Ref |
|---|---|---|---|---|---|
| 1 | ENE of Durban, South Africa | 13–06-1968 | Crude oil | 46,000 tons | World Glory, 1968) |
| 2 | Sea star, Gulf of Oman, Iran | 19–12-1972 | Crude oil | 115,000 tons | Oil spill history, n.d. |
| 3 | Rincon beach, Puerto Rico | 13–05-1975 | Crude oil | 61,000 tons | Amoco Cadiz, 2008 |
| 4 | Brittany coast, Porrsall, France | 16–03-1978 | Crude oil | 2,598,205 tons | Amoco Cadiz (France, 1978), n.d. |
| 5 | Caribbean Sea, Trinidad and Tobago | 19–07-1979 | Crude oil | 287,000 tons | Persian Gulf war, 1991 |
| 6 | Saldanha bay, South Africa | 06–08-1983 | Crude oil | 2,968,837 tons | Major oil spills, n.d. |
| 7 | North Atlantic off the coast of Canada | 10–11-1988 | Crude oil | 1,626,242 tons | Major oil spills, n.d. |
| 8 | Southeast coast of South Africa | 04–10-1989 | Crude oil | 10,000 tons | Tanker incidents, n.d. |
| 9 | Gulf of Mexico, USA | 08–06-1990 | Crude oil | 16,501 tons | Dent, 2013 |
| 10 | Persian Gulf, Iraq | 23–01-1991 | Dumping oil | 820,000 tons | ITOPF, n.d. |
| 11 | Milford haven, Pembrokeshire, UK | 15–02-1996 | Crude oil | 72,000 tons | Garcia, n.d. |
| 12 | Guanabara Bay, Rio de Janeiro, Brazil | 10–07-2000 | Crude oil | 10,001 tons | Khordagui & Al-Ajmi, 1993 |
| 13 | Guanabara Bay, Rio de Janeiro, Brazil | 24–11-2001 | Crude oil | 1,000,001 tons | M/V mega borg, n.d. |
| 14 | Coast of Galicia, Spain | 15–11-2002 | Crude oil | 63,000 tons | Massive California oil spill threatens wildlife and closes beaches, 2021 |
| 15 | Arabian sea, Karachi, Pakistan | 28–07-2003 | Crude oil | 30,000 tons | van de Veen, 2004 |
| 16 | Yellow sea, South Korea | 07–12-2007 | Crude oil | 10,800 tons | S Korea declares slick, 'disaster', n.d. |
| 17 | Timor sea, Australia | 21–08-2009 | Crude oil | 30,000 tons | Oil leaking 'five times faster' than thought, n.d. |
| 18 | Gulf coasts, USA | 20–04-2010 | Petrol oil | 627,000 tons | U.S. Coast Guard; U.S. Geological Survey, n.d. |
| 19 | Yellow sea, China | 16–07-2010 | Crude oil | 90,000 tons | China oil spill grows, official warns of 'severe threat, n.d. |
| 20 | Alberta provinces, Canada | 29–04-2011 | Buffalo oil | 3800 tons | Calgary Herald, 2011 |
| 21 | Guarapiche River, Venezuela | 04–02-2012 | Crude oil | 41,000 tons | Stabroek editor, n.d. |
| 22 | Lac-Megantic, Quebec Canada | 06–07-2013 | Crude oil | 4830 tons | Lac-Mégantic: What we know and what we don't, n.d. |
| 23 | Eilat Trans-Israel pipeline, Israel | 06–12-2014 | Crude oil | 4300 tons | Benson, n.d. |
| 24 | Illinois near Gelena, USA | 05–03-2015 | Crude oil | 1300 tons | Freight train carrying crude oil derails near Illinois city, n.d. |
| 25 | Shelby country, Alabama, USA | 12–09-2016 | Diesel oil | 1092 tons | EPA says it is 'not known' how long Alabama pipeline leaked gas prior to discovery of break, n.d. |
| 26 | Saronic Gulf, Salamis, Greece | 10–09-2017 | Fuel oil | 2500 tons | Greek oil spill threatens popular Athens beaches, n.d. |
| 27 | East China sea, China | 06–01-2018 | Crude oil | 138,000 tons | Bland, n.d. |
| 28 | North Dakota, USA | 29–10-2019 | Petrol oil | 1240 tons | EGEB: Keystone oil spill in ND, 2019 |

**Table 1** (continued)

| Sr. no | Oil spill sites around the world | Year | Type of oil spilled | Quantity spilled (tons) | Ref |
|---|---|---|---|---|---|
| 29 | North Carolina, Huntersville, USA | 14–08-2020 | Gasoline oil | 38,000 tons | Colonial pipeline spill information – Huntersville, N.C. \| NC DEQ, n.d. |
| 30 | Orange County, California shoreline, USA | 01–10-2021 | Crude oil | 424.42 tons | Pannett and Firozi, n.d. |

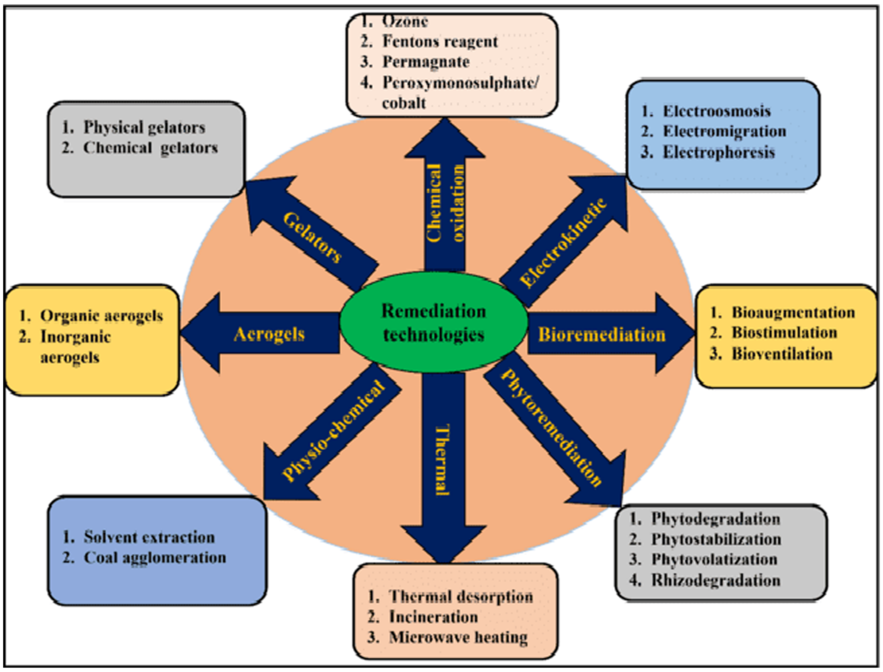


**Fig. 2** Different remediation technologies opted till date for the removal of oil from oil-contaminated soil sample

## 2 Chemical Oxidation Technology

### 2.1 Chemical Oxidation

In this technology, chemical oxidants are applied to the oil-polluted soils, converting the oil contaminants into simple molecules of carbon dioxide and water. The various factors which make this technique quite effective, viz., oil contaminated site, the amount of oxidant taken, the contact time between the oil, and the oxidant. The different chemical oxidants applied by various research groups including ozone, hydrogen peroxide, Fenton's reagents, permanganate, persulfate, and peroxymonosulfate are discussed below (Do et al., 2010; Salavati-Niasari et al., 2002).

#### *2.1.1 Ozone*

Ozone being an excellent oxidizing agent converts the oil molecules into simple hydroxyl radicals via electrophilic and nucleophilic addition, which enhances the hydrocarbon bond-breaking efficiency (Yu et al., 2007a). Furthermore, the metal oxides ($Fe_2O_3$) also assist the ozone decay to form hydroxyl radicals as shown in Eq. 1.

$$\mathrm{RH} + \mathrm{O_3} \rightarrow [\mathrm{R} - \mathrm{O} - \mathrm{O} - \mathrm{O} - \mathrm{H}]^* \rightarrow R^{\cdot} + HO^{\cdot} + \mathrm{O_2} \rightarrow \mathrm{ROH} + \mathrm{R} = \mathrm{O} + \mathrm{ROOH} \tag{1}$$

Shin et al. (2005) and Yu et al. (2007) investigated that ozone enhanced the removal efficiency up to 90–95% and 94% respectively, from oil-contaminated soils (Yu et al., 2007a; Goyat, 2022). Furthermore, Li et al. (2014) mentioned that soil with fine particle size having higher surface area and water content of about 18% to 20% has effective ozonation (Li et al., 2014a). Chen et al. (2016) studied that ozone enhances the biodegradability of hydrocarbon and removed the 50% of total petroleum hydrocarbons from the soil (Chen et al., 2016). Another study by Goi et al. (2006) obtained that 87.5% of diesel oil was removed by Fenton reagents as compared to ozone 48% (Goi et al., 2006b).

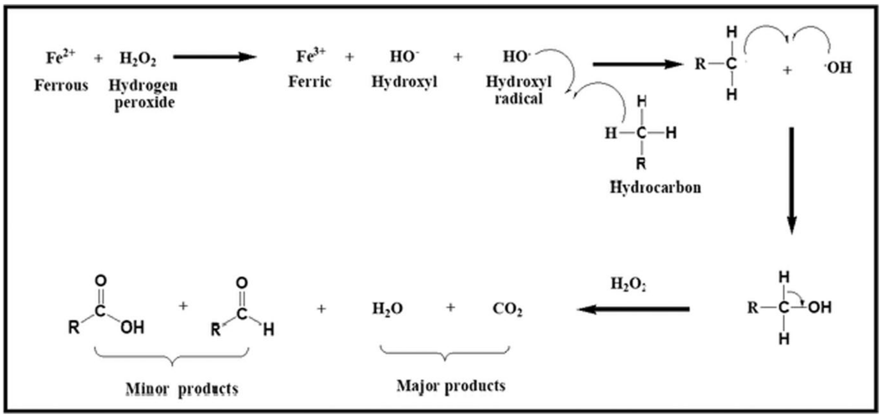
### 2.1.2 *Fenton's Reagent*

Fenton's reagent is a solution of hydrogen peroxide and ferrous ion. In this reagent, the ferrous ions act as a catalyst and promote the formation of hydroxyl ions as shown in Fig. 3. The generated hydroxyl radical ruptures the petroleum hydrocarbon bonds of ethylbenzene, methyl tertiary butyl ether (MTBE), benzene, toluene, xylene, and petroleum aromatic hydrocarbons (PAHs) releasing simple $CO_2$ and $H_2O$ molecules as the major products. Watts et al. (1990), Goi et al. (2009), Villa et al. (2010), etc. studied the effects of various concentrations of $H_2O_2$ along with $Fe^{2+}$ ions in the degradation of oil molecules from oil-added soil samples. The results were quite exciting with degradation efficiency of more than 90% (Villa et al., 2010; Goi et al., 2009). Furthermore, Ershadi et al. (2011) used a 33.7:1 molar ratio of $H_2O_2$:Fe(II) and removed 91% oil from oil-polluted soil samples (Ershadi et al., 2011). Chukwunonye et al. (2012) studied that 96% of polyaromatic hydrocarbons were removed from crude oil-contaminated soil using Fenton's reagent (Ojinnaka et al., 2012). In 2018, Sylvia Adipah used Fenton's reagent for the remediation of total petroleum hydrocarbon contaminants from contaminated soil and removed 48% of contaminants (Adipah, 2018).

### 2.1.3 *Permanganate Oxidants*

The potassium permanganate ($KMnO_4$) and sodium permanganate ($NaMnO_4$) are the main and effective permanganate oxidants commonly employed for oil-polluted soil samples (Salavati-Niasariand & Banitaba, 2003). The permanganate leads to homolytic rupturing of the hydrocarbon bonds to form a free radical hydrocarbon chain. These chains further react with permanganate oxidants and release simple carbon dioxide and water molecules as the major products as shown in Fig. 4. Achugasim et al. (2013) removed 98% polycyclic aromatic hydrocarbons (PAHs) in an acidic medium from the crude oil-contaminated soil (Achugasim et al., 2014). Furthermore, Ola et al. (2017) studied the remediation of the total petroleum hydrocarbons (TPH) in the pilot test area, obtaining the 92.28 to 99.86% oil removal efficiency

**Fig. 3** Mechanism of the oxidation of hydrocarbons by Fenton's reagent



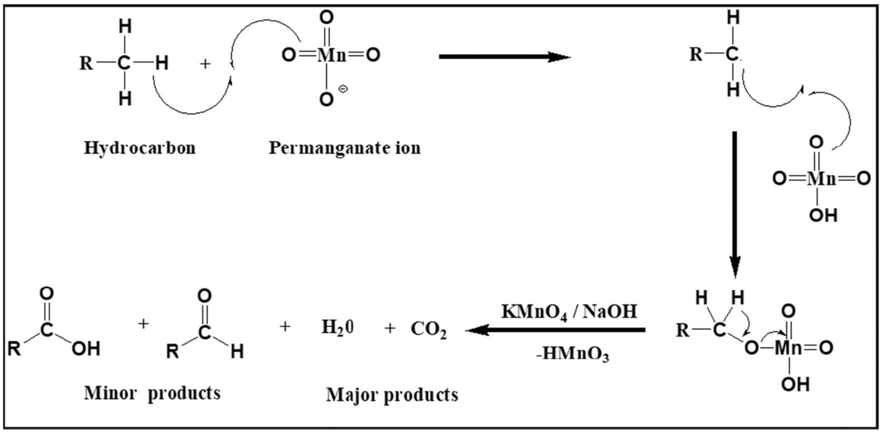


**Fig. 4** Mechanism of the oxidation of hydrocarbons by permanganate oxidant

after 30 weeks (Ola et al., 2018). In addition, Matta and Chiron (2017) investigated that permanganate can be used for the oxidation of petroleum compounds in contaminated soil, and the result showed 77% removal after 24 h of study (Matta & Chiron, 2017). Furthermore, Bajagain et al. (2019) observed that the use of potassium permanganate with bioaugmentation enhances the removal efficiency of diesel oil from 72.1 to 92.1% (Bajagain et al., 2019). In comparison to Fenton's and ozone, the permanganate oxidant reaction proceeds at a quite slower rate.

### *2.1.4 Persulfate and Peroxymonosulfate (PMS)*

Sodium persulfate ($Na_2 S_2O_8$) and PMS ($KHSO_5$) are emerging oxidizing agents which are used for in situ and ex situ degradation of the oil contaminants (Yang et al., 2018). The radicals generated by these oxidants react with oil contents and convert them into $CO_2$ and $H_2O$ molecules as the major final products depicted in Fig. 5.

Moreover, metal ions such as ferrous ions ($Fe^{2+}$) can activate persulfate decomposition at ambient temperature (~293 K). Pignatello J. et al. (1994, 1996) and Kirk R. et al. (1979) used iron chelates as a catalyst in oxidation reactions to enhance their efficiency (Pignatello and Katharina, 1994; Pignatello et al., 1996; Kirk et al., 1979). Do et al. (2009) and Yen et al. (2011) investigated the effect of peroxymonosulfate with ferrous and cobalt ions and observed 88% removal efficiency of the oil from oil-contaminated soil (Do et al., 2009a;

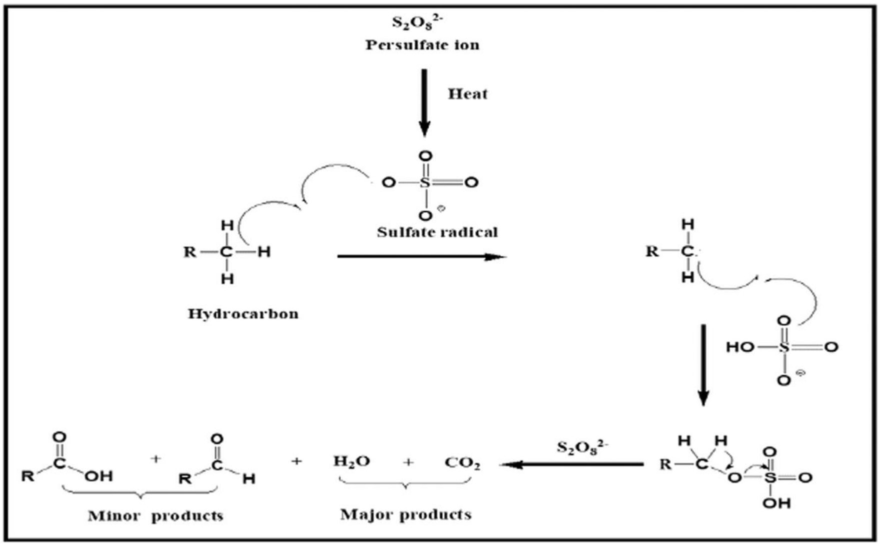


**Fig. 5** Mechanism of oxidation of hydrocarbons by persulfate

**Table 2** Chemical oxidation of oil-contaminated soil

| Chemical oxidants used | Contaminants | % removal efficiency | Reference |
|---|---|---|---|
| Ozone | Diesel oil | 48% | Goi et al., 2006 |
| | Diesel oil | 94% | Yu et al., 2007b |
| | Diesel oil | 95% | Shin et al., 2005 |
| | Diesel oil | 92% | Li et al., 2014b |
| Fenton's reagent | Diesel oil | 96% | Tsai et al., 2010 |
| | Diesel oil | 93% | Goi et al., 2009b |
| | Diesel oil | 80% | Villa et al., 2010b |
| | Diesel oil | 98% | Sherwood & Cassidy, 2014 |
| | Polycyclic aromatic compound (PAH) | 72–93% | Kawahara et al., 1995 |
| | PAH | 70% | Pradhan et al., 1997 |
| | PAH | 85% | Bogan et al., 2003 |
| | PAH | 92% | Goi & Trapido, 2004 |
| | PAH | 98% | Ferrarese et al., 2008 |
| Hydrogen peroxide and Persulfates | Crude oil | > 80% | Usman et al., 2012 |
| | Diesel oil | > 90% | Oh and Shin, 2014 |
| Peroxymonosulfate | Diesel oil | 47% | Do et al., 2009b |
| Persulfate, hydrogen peroxide, permanganate | Diesel oil | 60% | Yen et al., 2011 |

Yen et al., 2011). Bo-Ming Yang et al. (2012) and Chang et al. (2018) studied the use of ferrous ions as the catalyst to activate the persulfate in the oxidation process and removed 61% of total petroleum hydrocarbons from contaminated soils (Yang et al., 2011; Chang et al., 2018). In a recent study, Liu et al. (2020b) observed the performance of biochar-activated persulfate on the degradation of crude oil in contaminated soil (Miserli et al., 2022). The different types of chemical oxidants that were applied in the last few years are mentioned in Table 2.

### 2.2 Advantages and Disadvantages of Chemical Oxidation Technology

The chemical oxidation technology is quite simple to carry out, has a low operational cost, and gives fast results with more biodegradable and nontoxic end products. However, this remediation technology is not suitable for highly alkaline and reactive soil samples. Other major limitation is the evolution of heat during this process, which is difficult to control and the same has a major effect on the natural and biological properties of soil/water bodies.

## 3 Electrokinetic Remediation Technology

The electrokinetic remediation (EKR) is a technology in which the oil-contaminated soils are brought in contact with electrodes made up of graphite/iron which introduces electric current to the oil molecules, and it moves towards the electrodes (Prakash et al., 2021). The substances such as sodium chloride, citric acid, and surfactants enhance the oil separation. The concentration of the oil contaminants, electrode substance, applied electric field voltage, and electrolyte conductivity are a few factors affecting the oil removal via electrokinetic remediation (Yousefi et al., 2011). Tsai et al. (2010) investigated the effect of the above-mentioned factors. He found iron electrodes more superior than graphite electrode with higher concentrations of sodium chloride as an electrolyte (Tsai et al., 2010). EKR technique follows electroosmosis, electrophoresis, and electromigration mechanism as shown in Fig. 6.

In electroosmosis, the direct electric potential gradient was applied for the movement of oil contaminants with respect to a solid wall (Elektorowicz & Boeva, 1996). The process mainly depends

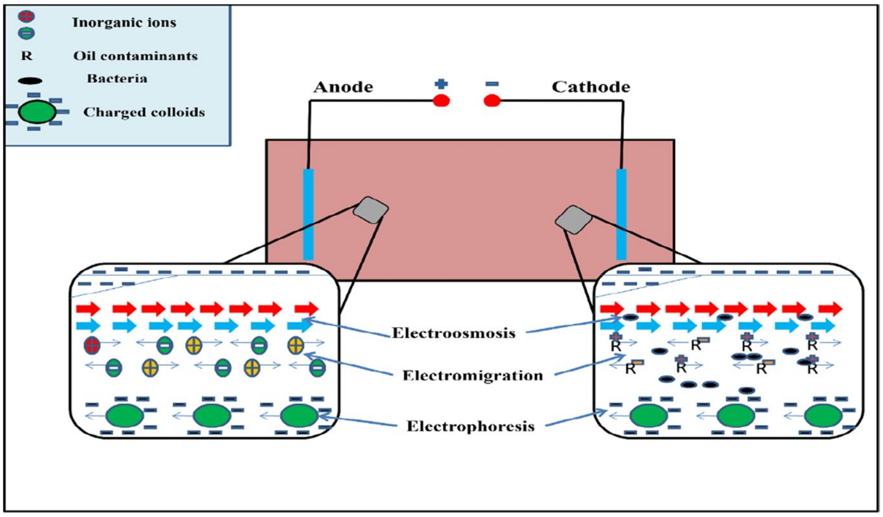


**Fig. 6** Electrokinetic remediation of oil-contaminated soil

upon flow rate, because the increase in flow rate enhanced the migration of contaminants as well as removal efficiency. Pazos et al. (2012b) increased the oil removal efficiency up to 72–74% by applying voltage up to 2 V $cm^{-1}$ and 0.67 M citric acid concentration (Pazos et al., 2012). Furthermore, AsadollahFardi et al. (2018) studied the removal efficiency increased up to 64% when a high voltage gradient (2 V/cm) was applied (Asadollahfardi & Rezaee, 2018).

In electrophoresis, migrations of charged colloids loaded contaminants towards the opposite electrode take place on applying the electric field (Prakash et al., 2021). This process is basically applied to the migration of colloidal or larger-size particles. Jeon et al. (2010) investigated that 39% of diesel removal was achieved when using 0.5 wt% surfactant, 0.1 M NaOH, and 1 V/cm voltage across the electrodes (Jeon et al., 2010). The third mechanism of electrokinetics is electromigration involves the migration of charged ions by applying high-density current applied across the medium. The factors like electrolyte concentration, strength of ionic charge, and electric force voltage control the overall process (Maini et al., 2000). The different types of electrolytes used in the last few years are mentioned in Table 3.

**Table 3** The different types of electrolytes used in the past few years in EKR technology

| Electrolyte | Contaminants | % removal efficiency | Reference |
|---|---|---|---|
| $HNO_3$ and $MgSO_4$ | Vegetable oil | 55.4% | Park et al., 2009 |
| EDTA and NaCl | Diesel oil | 38% | Han et al., 2009 |
| NaCl (0.1 and 0.01 mol/L) | Crude oil | 56% | Tsai et al., 2010 |
| NaOH (0.1 M) | Diesel oil | 39% | Jeon et al., 2010 |
| Fe (0) and zeolite | Polycyclic aromatic compound (PAH) | 47.1% | Fu et al., 2012 |
| $C_6H_8O_7$ (0.67 M) | Diesel oil | 73% | Pazos et al., 2012 |
| Anolyte (2 N NaOH) and Catholyte (1 N $HNO_3$) | Kerosene oil | 75.9% | Lukman et al., 2013 |
| Permeable reactive composite electrode (PRCE) (cathodic), high pure columnar graphite electrodes (anodic) | PAH | 69.3% | Liu, 2013 |
| Chloride ion concentration (6.5 g/L) | PAH | 83.93% | Li et al., 2016 |
| $Na_2SO_4$ (0.1 mol/L) | Industrial oil | 80.2% | Yan et al., 2018 |
| EDTA (0.1 M) and $Na_2SO_4$ (0.1 M) | PAH | 63% | Saberi et al., 2018 |

### 3.1 Advantages and Disadvantages of EKR Technology

The electric field provides a constant flow distribution which enhanced the oil removal efficiency from low-permeability soil samples. However, during the running process, hot spots are generated around the electrodes which alter the pH of the medium within a certain period of time reducing the overall efficiency of the process. In a nutshell, this technology is energy-driven; hence, it is a very costly phenomenon for developing countries.

## 4 Bioremediation Technology

Bioremediation is a natural cleanup phenomenon, in which the hydrocarbons are degraded into less toxic compounds such as carbon dioxide and water under aerobic condition by bacteria and fungi (as shown in Fig. 7). It helps to restore superficially the natural content of oil-contaminated beaches (Liu et al., 2020). This technique was most admired in 1989, when the Exxon Valdez oil spill took place. The addition of nutrients, fertilizers, and biosurfactants along with bioremediation enhances the oil removal efficiency (Saharan et al., 2022b). Further, this method is quite cost-effective and eco-friendly in nature having a high biodegradation potential capacity for oil-contaminated site. The bioremediation follows three mechanisms, viz., bioaugmentation, biostimulation, and bioventilation.

### 4.1 Bioaugmentation

In bioaugmentation, multiple bacterial strains with high specific catabolic activities are used to increase the rate of hydrocarbon degradation (Kogbara et al., 2016). The increase in the number of bacterial strains on a contaminated site will not only increase the degradation of the oil from the particular site but also increases the genetic capacity of the desired site at the same time. The selection of microorganism depends upon the composition and metabolic capability of the microorganism (Bakina et al., 2021). Rahman et al. (2002) designed the bacterial consortium containing five different bacterial strains (*Micrococcus* sp. GS2-22, *Corynebacterium* sp. GS5-66, *Flavobacterium* sp. DS5-73, *Bacillus* sp. DS6-86, and *Pseudomonas* sp. DS10-129) for the remediation of oil from contaminated soil. After 20 days of the sampling period, 78% of the oil degradation was achieved (Rahman et al., 2002). Ruohai et al. (2006) studied the comparison between two *Pseudomonas aeruginosa* strains, and the result obtained showed the degradation of the oil by *P. aeruginosa* S was faster than by P. *aeruginosa* Y from the oil-contaminated soil (Ruohai & Das, 2006). Further addition of fertilizer along with bacterial strains accelerated the oil degradation

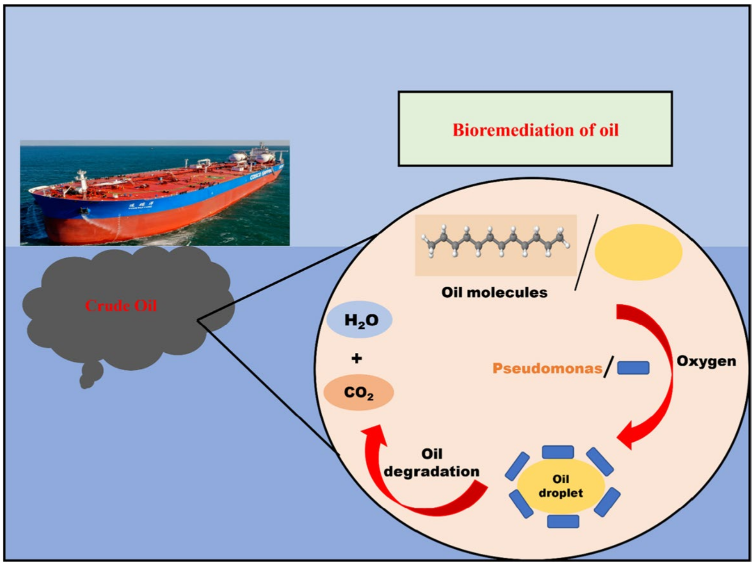


**Fig. 7** Bioremediation process of oil-contaminated soil and water bodies

rate. Another attempt was done by Roy et al. (2014), who used four different bacterial strains along with fertilizers and obtained 80% crude oil degradation from oil-contaminated soil in 24 weeks (Roy et al., 2014). Akbar Ghavidel et al. (2017) studied the degradation of gasoil up to 79% and 93.53% by using bacterial strains from soil and soil sawdust mixture media after 45 days trial (Ghavidel et al., 2017). Furthermore, Chao Zhang et al. (2020) investigated the best ratio of oil strain A to strain B was 7:3, and obtained 68.27 ± 0.71% oil removal efficiency from oil-contaminated soil after 40 days (Zhang et al., 2020).

### 4.2 Biostimulation

In this process, different nutrients such as phosphorus, nitrogen, oxygen, and biosurfactants are applied to the oil-contaminated sites for stimulating the growth of existing bacteria that enhances the degradation of the oil contaminants (Saeed et al., 2021). Adams GO et al. (2015) studied that biostimulation is the most efficient method for the remediation of hydrocarbons as compared to other bioremediation techniques (Adams et al., 2015). Chaineau et al. (2005) obtained 62% oil removal with the additional use of fertilizers (nitrogen, phosphorus, and potassium) and 47% removal without fertilizers (Chaineau et al., 2005). Furthermore, Chin-Chi Lai et al. (2009) studied the uptake of total petroleum hydrocarbons increased up to 63% on increasing the concentration of biosurfactants from 0 to 0.2 mass percentage (Lai et al., 2009). Abed et al. (2015) observed about a 20% hike in the oil degradation rate with the addition of nutrients such as $NH_4Cl$ and $NaH_2PO_4$. In addition to this, Abed et al. (2015) also investigated the effect of temperature along with methylated β-cyclodextrin (RAMEB) bio-surfactant which leads to 2.6% and 4.8% removal efficiency (Abed et al., 2015). Furthermore, Jakubauskaite et al. (2016) studied the effect of chemical additives and removed the diesel oil of up to 90% from chemical industry plant sludge after 120 days of experimental trial (Jakubauskaite et al., 2016).

### 4.3 Bioventilation

In the bioventilation process, the oxygen content around contaminated soil is increased which accelerates the growth of an oil-decaying microorganism. The oxygen creates an aerobic condition for the microorganisms which enhances the metabolism of organic matter. This process is cost-effective for light and middle distillate hydrocarbons from contaminated soil. Urum et al. (2005) investigated the effect of air with biosurfactants and observed more than 80% removal efficiency of the oil from crude oil-contaminated soil (Urum et al., 2005). Thome et al. (2014) studied that 85% removal of diesel oil took place after 60 days of remediation (Thomé et al., 2014). Due to some unique characteristics such as high penetrating power and low permeability of air, it is several thousand times more effective than simple water treatments. Table 4 highlights the different types of additives used by different research groups in the bioremediation process.

### 4.4 Advantages and Disadvantages of Bioremediation Technology

*Bioventilation* is quite a successful technique, both in situ and ex situ conditions degrading oil contents completely without leaving any toxic byproducts. This process is cost-effective and removes the contaminants permanently without disturbing the surrounding environment. The major disadvantage of this process is that it requires a very long time up to several months/years for satisfactory results. Furthermore, the factors, viz., higher soil pH, salinity, nature of the soil, and the higher temperature, hinder the bacterial growth and hence the overall oil removal efficiency.

## 5 Phytoremediation Technology

In this process, numerous types of living plants are used to remove, transfer, stabilize, and degrade toxic oil contaminants from the soil, sludge, sediment, groundwater, surface water, and wastewater. In this technology, plant uses various biological processes to break the oil into simpler molecules so that they can be used in certain metabolic processes. The plant roots have certain enzymes which concentrate the absorbed oil molecules from the soil and water system and deposit them in the plant biomass above the soil (as shown in Fig. 8) (Ayotamuno et al., 2009*)*.

**Table 4** The different types of additives used bioremediation process

| Type of supplement | Contaminants | % removal efficiency | Reference |
|---|---|---|---|
| Corexit 9500 (biosurfactant) | Crude oil | 70% | Tumeo et al., 1994 |
| Ammonium nitrate and Dipotassium hydrogen phosphate | Petroleum refinery sludge | 76% | Vasudevan & Rajaram, 2001 |
| Ammonium nitrate, Su-perphosphate and Inipol SP1 | Fuel oil | 89.3% | Prince et al., 2003 |
| Rhodotorula glutinis var. dairenesis and Nocardia nova | Crude oil | 7.4% | Trindade et al., 2005 |
| Chitosan and osmocote | Arabian light crude oil | 99.7% | Xu et al., 2005 |
| Oleophilic fertilizer | Petroleum oil | 80% | Margesin et al., 2007 |
| Ammonium nitrate | Crude oil | 99.9% | Singh et al., 2012 |
| Ammonium nitrate and disodium hydrogen phosphate | Diesel oil | 49.4% | Dias et al., 2012 |
| Cadmium, copper, and mercury | Crude oil | 32% | Almeida et al., 2013 |
| Guar gum | Diesel oil | 82% | Hernández-Espriú et al., 2013 |
| Oxygen | Diesel oil | 85% | Thomé et al., 2014 |
| Pseudomonas aeruginosa AS03/N108/N002 | Crude oil | 80% | Roy et al., 2014 |
| Sugercane bagasse and fruit bunch, Pseudomonas aeruginosa UKMP14T | Crude oil | 100% | Hamzah et al., 2014 |
| Ammonium nitrate and Dipotassium hydrogen phosphate | Hydrocarbons | 20% | Tamas et al., 2014 |
| Ammonium chloride and disodium hydrogen phosphate | Arabian oil | 9.6% | Abed et al., 2015 |
| Paenibacillus dendritiformis CN5 | Motor oil | 81% | Bezza & Chirwa, 2015 |
| Pseudoallescheria sp., lignocellulosic mixture | Petroleum oil | 79.9% | Covino et al., 2015 |
| S. marcescens UFPEDA 839 and S. saprophyticus UFPEDA 800 | Diesel oil | 69% | Silva et al., 2015 |
| $Mn^{2+}$ + hydrogen peroxide | Hydrocarbons | 24% | Shi et al., 2015 |
| Pandoraea pnomenusa GP3B, Burkholderia cepacian GS3C and Sphingomonas GY2B strain | Crude oil | 64.4% | Shen et al., 2016 |
| Sodium acetate | Hydrocarbons | 34% | Das, 2017 |
| Ammonium nitrate | Hydrocarbons | 53% | Jiang et al., 2018 |

The study conducted by Cook and Hesterberg in 2013 highlighted that the majority of plants used for phytoremediation technology were trees and grasses (Gurajala et al., 2019). This is due to their wider root coverage and greater biomass, which allows for more efficient uptake and accumulation of contaminants in the soil. In addition, trees and grasses are often better suited for phytoremediation in terms of their tolerance to harsh soil conditions and their ability to establish and grow in contaminated soils. The study also found that certain plant species were more effective at the remediation of specific contaminants (Gurajala et al., 2019). For example, poplar trees have been shown to be effective at remediation of volatile organic compounds (VOCs) such as trichloroethylene (TCE), while Indian mustard plants have been found to be effective at remediation of heavy metals such as lead and cadmium. Moreira et al. carried out the removal of paraffin oil with an initial concentration of 32.2 mg/g from contaminated soil using black mangrove plants (Moreira et al., 2013).

Maize (Zea mays) has been shown to be very effective in the phytoremediation of oil-contaminated soils due to its capacity to accumulate and tolerate hydrocarbons. In fact, several studies have shown that maize can accumulate high levels of hydrocarbons, such as polycyclic aromatic hydrocarbons (PAHs), in its roots and shoots, and can degrade these contaminants through the process of rhizodegradation. Furthermore, studies have also found that the presence of hydrocarbons in the soil can enhance the productivity of maize at certain concentrations. This is because hydrocarbons can act as a source of carbon and energy for the plant, leading to increased biomass production and higher yields. However, it is important to note that the effectiveness of maize for phytoremediation

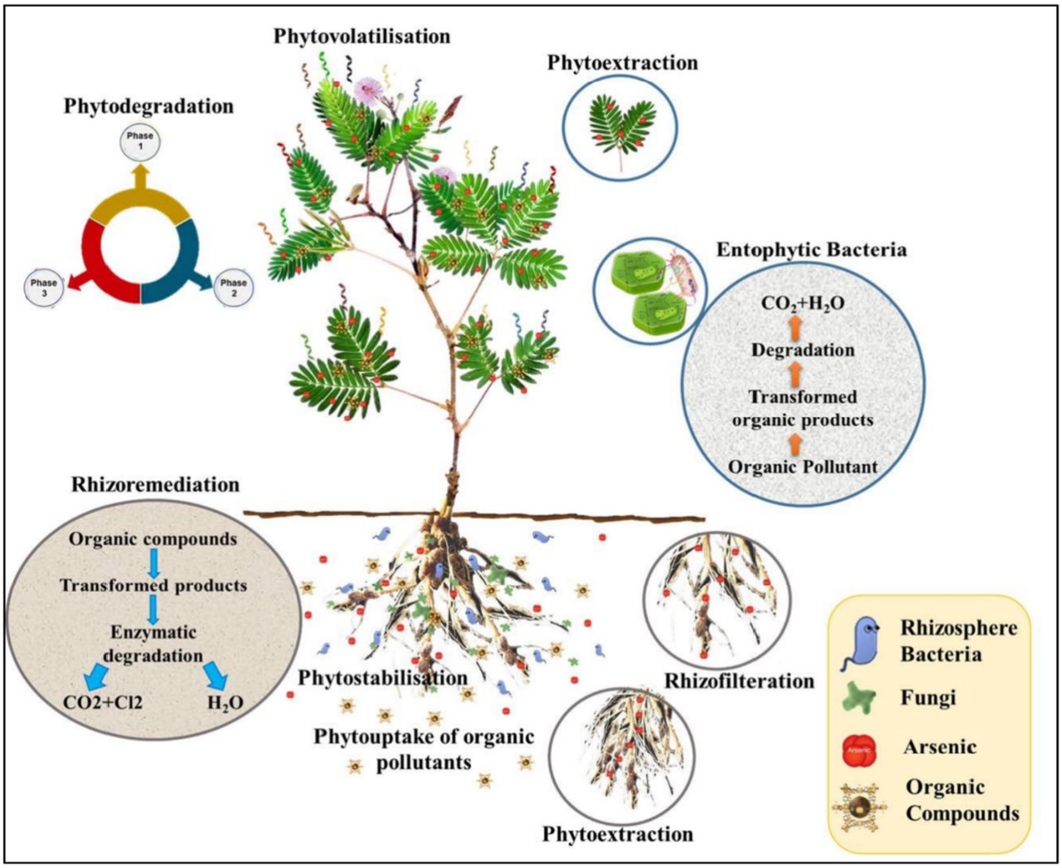


**Fig. 8** Phytoremediation process for oil-contaminated soil (reprinted with permission from the reference number (Atabaki et al., 1500) Atabaki, Narges, Noor Azmi Shaharuddin, Siti Aqlima Ahmad, RosimahNulit, and Rambod Abiri. “Assessment of water mimosa (*Neptunia oleracea* Lour.) Morphological, physiological, and removal efficiency for phytoremediation of arsenic-polluted water.” *Plants* 9, no. 11 (2020): 1500.https://doi.org/10.3390/plants9111500Copyright @ MDPI)

may depend on several factors, including the specific type and concentration of hydrocarbons present in the soil, the duration of exposure, and the growth conditions of the plant (Ayotamuno et al., 2007).

In the other different mechanism, plant uses oil in their metabolic process speeded up by certain enzymes such as dehalogenase, nitro reductase, and laccase, resulting in the breaking of the oil molecules. The main advantage of this process is that reduction and degradation take place inside the plant as a physiological process. Furthermore, the success of phytoremediation depends upon the use of fertilizer along with nutrients available for microorganisms that degrade toxins efficiently. It is worthwhile to mention that an appropriate amount of nutrients/fertilizers in addition to the soil/water is a must to support plant growth and microbial population along with soil salinity balance (Ayotamuno et al., 2007). Jagtap et al. (2014) used fertilizers for growing *Pinus densiflora*, *Thuja orientalis*, and *Populus tomentiglandulosa* plants on diesel-contaminated soil which showed 75.2% oil removal efficiency (Liao et al., 2015). The different types of plants used in the last few years are mentioned in Table 5.

## 5.1 Advantages and Disadvantages of Phytoremediation Technology

Phytoremediation is a quite easy process to carry out and is cost-effective. It can be easily employed

**Table 5** Different types of plants opted for the phytoremediation process

| Plant types | Contaminants | % removal efficiency | Reference |
|---|---|---|---|
| Black mangrove plant | Paraffin oil | 87% | Moreira et al., 2013 |
| Endophyte-infected and non-infected grasses | Petroleum oil | 72% | Ayotamuno et al., 2007 |
| Poplar, alfalfa and reed plants | Diesel oil | 86.8% | Liao et al., 2015 |
| Tropical pasture grass | Crude oil | 18.4% | Merkl et al., 2005a |
| Salt marsh plant | Crude oil | 16% | Ribeiro et al., 2014 |
| Scots pine, poplar and legumes mixture | Diesel oil | 67–74% | Palmroth et al., 2002 |
| Soybean, maize, sunflower and mixed grasses | Motor oil | 100% | Dominguez-Rosado et al., 2004 |
| Alfalfa and reed plants | Bitumen oil | 82% | Muratova et al., 2003a |
| Ditch reed and alfalfa plants | Bitumen oil | 82% | Muratova et al., 2003b |
| Rubber seed and neem | Lubricating oil | 67.3% | Agamuthu et al., 2010 |
| Herbaceous plant | Crude oil | 57.7% | Moubasher et al, 2015 |
| Willow stand plant | Mineral oil | 57% | Vervaeke et al., 2003 |
| Tall rescue plant | Petroleum oil | 50% | Huang et al., 2005 |
| Legumes, grasses | Crude oil | 57.69% | Merkl et al., 2005b |
| Crop plants, wild grasses, legume | Crude oil | 52% | Muratova et al., 2008 |
| Brachiaria brizantha and paspalum notatum | Petroleum oil | 63.2% | Peng et al., 2009 |
| Jatropha and rubber seed | Diesel oil | 99% | Dadrasnia & Agamuthu, 2013 |
| Karanja, rubber seed and neem | Lubricating oil | 91.8% | Abioye et al., 2012 |
| Perennial ryegrass | Diesel oil | 57.3% | Chuluun et al., 2014 |
| Fire Phoenix plant | Hydrocarbons | 99.4% | Liu et al., 2014 |

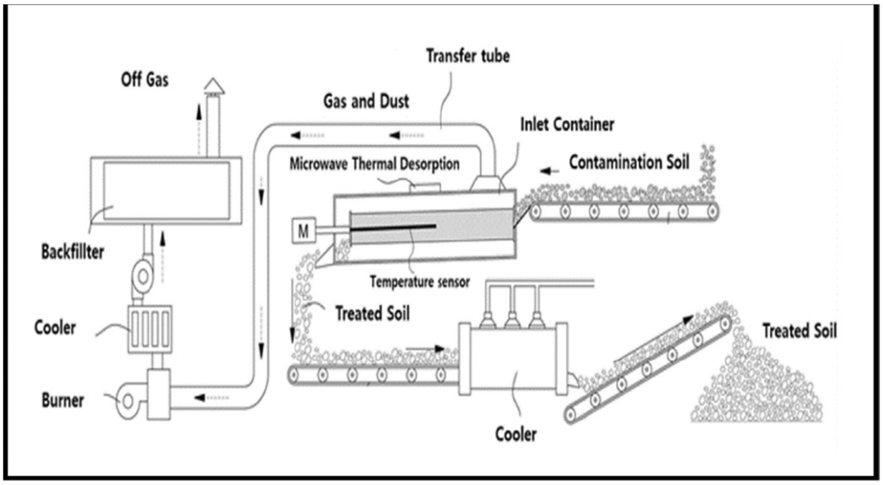


**Fig. 9** Thermal remediation process for oil contaminated soil (reprinted with permission from the reference number (Saharan et al., 2022c) Jeehyeong K. and Jongpil J., Design and implementation of OPC UA-based VR/AR collaboration model using CPS server for VR Engineering process, Applied sciences 2022,*12*(15), 7534, https://doi.org/10.3390/app12157534, Copyright @ MDPI)

over the oil-contaminated soil that supports plant growth. Furthermore, the addition of fertilizers and manures can enhance the plant growth which ultimately degrades the oil contents from the soil following one or the other mechanism of phytoremediation. In the long run, this technology is quite handy; it will make the oil-contaminated soil site green and enrich it with the passage of time. The only disadvantage of the technology is that it is a slow and time-consuming process that needs months/years to show its effects and efficiency.

## 6 Thermal Remediation Technologies

In this technology, heat is applied under a controlled temperature condition into the oil-contaminated soil samples. The heat mobilizes volatile and semi-volatile contaminants from the soil as shown in Fig. 9 (Ren et al., 2020; Saharan et al., 2022c). Furthermore, this technique is of three types such as thermal desorption, incineration, and microwave heating.

### 6.1 Thermal Desorption

Thermal desorption is a temperature-driven technology; the temperature is increased continuously which further increases the vapor pressure of the oil contaminants leading to the desorption of oil from the oil-contaminated soils (Ren et al., 2020). Furthermore, the factors affecting oil removal efficiency include temperature, heating time, and composition of the contaminants on soil/water surfaces. Lee et al. (1998, 1999) developed a fluidized bed desorber at low temperature (294 °C) and desorbed 95% of diesel oil from diesel-contaminated soils (Pignatello & Katharina, 1994; Ma et al., 2022). Piña et al. (2002) studied that the chemical contents of the soil vastly affect the removal efficiency of gas oil via thermal remediation at temperatures between 200 and 900 °C (Piña et al., 2002). Furthermore, Merino and Bucalá (2007) observed that the removal efficiency of hexadecane increased up to 99.9% when increasing in temperature up to 300 °C (Merino & Bucalá, 2007). Falciglia et al. (2011) increased the temperature from 100 to 250 °C which leads to the 100% removal efficiency of diesel; earlier at 100 °C, it was 47% (Tatàno et al., 2013). Bulmau et al. (2014) studied the effect of heating temperature on polyaromatic hydrocarbons (PAHs) in contaminated soils and found that removal efficiency increased from 5 to 80% when increased in temperature from 350 to 650 °C at the same time (Bulmău et al., 2014).

### 6.2 Incineration

In this process, the destruction of the oil contents took place via rapid heating of the oil-contaminated soil at high temperatures. Bucala et al. (1994) used a laboratory-scale electrically heated foil reactor for achieving a temperature of up to 1000 °C/s and removed 100% of oil impurities from the soil (Bucala et al., 1994). Furthermore, Anthony and Wang et al. (2006) studied the pilot scale experiment in the combustor having temperatures up to 800 °C in which the entire oil compound was removed from oil-contaminated gravel and coal–tar-contaminated soil (Liu & Wang, 2022). This remediation is non-eco-friendly in nature as it requires high energy and a large remediation area.

### 6.3 Microwave Frequency Heating

In this technology, microwave energy is converted into thermal energy to remove the oil contents via heating and volatilization (Ren et al., 2020). The microwave heats the water phase and converts it into steam. This steam acts as a mass transfer medium that desorbs oil from the soil. However, many organic substances and soil particles are resistant to absorbing the microwaves and are not capable of directly heating up the contaminants. Furthermore, the microwave absorbers, viz., activated carbon/fiber, graphite fiber, $MnO_2$, and $Cu_2O$ were mixed with the contaminates to convert microwave energy into thermal energy (Li et al., 2009b; Chen & Yang, 2021). The results obtained showed 100% oil removal. Li et al. (2009b) studied that 99% oil was recovered after the addition of 10% activated carbon (Li et al., 2009b). Supplementary studies by Chang et al. (2011a) and Falciglia et al. (2013) observed 92.5% and 95% oil removal efficiency respectively (Chen & Yang, 2021; Falciglia et al., 2013). Falciglia et al. (2017) investigated the remediation of polycyclic aromatic hydrocarbons from the contaminated soil and removed 70 to 100% when a 1000 W microwave was applied for 10-min remediation times (Falciglia et al., 2017). Donggeun Lee et al. (2022) observed that 99.8% total petroleum hydrocarbon was removed, when 32 kW of electric power at 600 °C temperature was applied for 3 h (Lee et al., 2022). The unique characteristics such as rapid selective heating and eco-friendly nature make this process handy over other remediation processes. Furthermore, Table 6 shows the work already reported by thermal remediation technology.

**Table 6** Different thermal remediation processes used for oil-contaminated sand

| Remediation process | Types of oil contaminants | % removal efficiency | Reference |
|---|---|---|---|
| Thermal desorption | Diesel oil | 99.9% | Lee et al., 1998) |
| | Diesel oil | 100% | Ma et al., 2022) |
| | Diesel oil | 98% | Piña et al., 2002) |
| | Volatile and semi-volatile hydrocarbons | Dna | Khan et al., Jun. 2004) |
| | Hydrocarbons | Dna | Yeung et al., 2010) |
| | Hydrocarbons | Dna | Falciglia et al., 2011) |
| | Diesel oil | 98% | Li et al., 2018) |
| | Diesel oil | 99.5% | Tatàno et al., 2013) |
| | Crude oil | 90% | Gao et al., 2021) |
| | Crude oil | 99.7% | Vidonish et al., 2016) |
| Incineration | Fuel oil | 100% | Bucala et al., 1994) |
| | Crude oil | 100% | Liu & Wang, 2022) |
| | Saudi crude oil | 100% | Liu & Wang, 2022) |
| | Hydrocarbons | Dna | Hinchee & Smith, 1992) |
| Microwave frequency heating | Low molecular weight hydrocarbons | Dna | Fann et al., 1998) |
| | Crude oil | Dna | Li et al., 2008) |
| | Crude oil | 99% | Chien, 2012) |
| | Crude oil | 99% | Liu & Wang, 2022) |
| | Diesel/marine fuel | 92.5/89.5% | Chen & Yang, 2021) |
| | Petroleum oil | 75.6–98.4% | Griffin, 2013) |
| | Diesel oil | 95% | Falciglia et al., 2017) |
| | Diesel oil | 90% | Falciglia & Vagliasindi, 2015) |

**Dna*, data not available

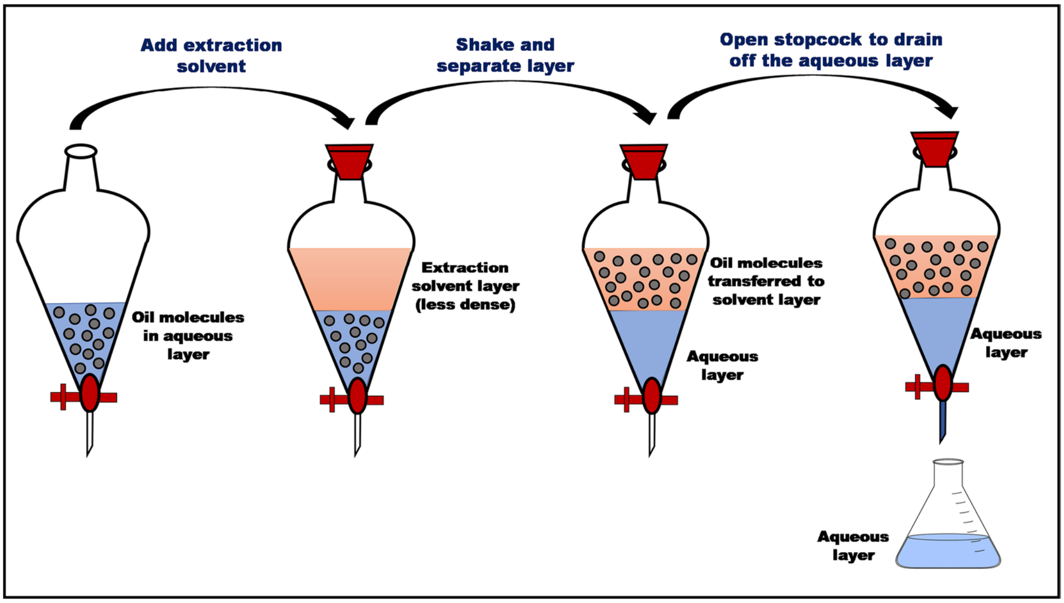


**Fig. 10** Solvent extraction remediation process for oil-contaminated soil

### 6.4 Advantages and Disadvantages of Thermal Remediation Technology

All the three thermal remediation techniques are fairly quick, reliable, and effective in taking oil contaminants from oil-contaminated soils at elevated temperatures. The major drawback of the thermal remediation is the destruction of the microbial and other necessary contents of the soil which make the soil totally barrel, i.e., unfit for any further use. The second drawback is that a large amount of constant energy is required which makes this process unfit for the developing countries.

## 7 Solvent Extraction

In this process, single along with a combination of solvents are used to extract the oil contaminants from oil-contaminated soil/water surfaces as shown in Fig. 10. The removal efficiency of the oil molecules mainly depends upon the close contact between the oil-contaminated soil and the solvents in use (Haleyur et al., 2016). The overall effectiveness of the solvent extraction depends upon the selectivity of the solvent, concentration, and polarity of the solvent (Yan et al., 2021). The commonly used solvents are water/organic solvents, surfactant-aided solvents, etc. as mentioned in Table 7 for the removal of oil from contaminated soil.

In the year 2005, Silva et al. used ethyl acetate/acetone/water in the different ratios in the batch studies and achieved 85% and 97% removal of the hydrocarbon and oil molecules respectively from the oil-contaminated soil samples (Haleyur et al., 2016). Furthermore, Li et al. (2012) used hexane/acetone in the ratio of 4:1 for the removal of the crude oil from the oil-contaminated soil and water systems (Yan et al., 2021). Sui et al. (2014) worked on petroleum ether as a solvent and removed

**Table 7** Different solvents used singly as well as in combination for the remediation of oil-contaminated soil

| Solvent/solvent in combinations | Contaminants | % removal efficiency | Reference |
|---|---|---|---|
| Ethyl acetate/acetone/water | Petroleum oil | 85% | Haleyur et al., 2016) |
| Hexane/acetone/water | Crude oil | 97% | Yan et al., 2021) |
| Petroleum ether/water | Petroleum oil | 94% | Liu et al., 2021) |
| Rhamnolipid | Crude oil | 80% | Zhao et al., 2015) |
| Sodium dodecyl sulfate (SDS) | Polycyclic aromatic hydrocarbon (PAH) | 100% | Rongsayamanont et al., 2020) |
| SDS | Diesel oil | 96% | Olasanmi & Thring, 2020) |
| Alkyl polyglucosides (APG) | Crude oil | 97% | Gitipour et al., 2015) |
| Tween 80 | Crude oil | 62% | Datta et al., 2020) |
| Fatty alcohol polyoxyethylene ether sulfate | Gasoline | 93% | Albergaria et al., 2008) |
| SDS | Petroleum oil | 88% | Lee et al., 2002) |
| Sodium dodecyl benzene sulfonate (SDBS) | Crude oil | 20% | Malina et al., 2002) |
| Triton X-100 | Diesel oil | 20% | Poppendieck et al., 1999) |
| Tween 80 | Diesel oil | 68% | Schramm et al., 2003) |
| Triton X-100 | Petroleum oil | 31% | Zhang et al., 2000) |
| SDS | Petroleum oil | 58% | Park et al., 2005) |
| Tween 80 | Diesel oil | 50% | Poppendieck et al., 1999) |
| Rhamnolipid | Petroleum oil | 59% | Al-Maamari et al., 2009) |
| Cetyltrimethylammonium bromide (CTAB) | Crude oil | 88% | Kirtland & Aelion 2000) |
| Superheated water | Lubricating oil | 62% | Javanbakht & Goual, 2016) |
| Carbon dioxide and acetone | Crude oil | 75% | Wang et al., 2017) |
| Carbon dioxide (only) | Crude oil | 73% | Chen et al., 2017) |

76–94% petroleum oil from the soil within 20 min (Liu et al., 2021). Maoxin Wang et al. (2019) used the toluene/AES-D-OA (solvent/surfactant) combination and obtained 97% crude oil uptake from the contaminated soil samples (Couto et al., 2009).

### 7.1 Advantages & Disadvantages of Solvent Extraction Technology

Solvent extraction has established itself as an effective, fast high-efficiency technique for oil-contaminated soil samples. Furthermore, it has low energy consumption demand. The key disadvantage of this technology is the intake of secondary pollutants from the solvents employed, which may persist in the remediated soil and subsequently create an environmental jeopardy due to their little biodegradability. In addition to this, the solvent extraction technology devours huge amounts of solvents which leads to a high operational cost.

## 8 Coal Agglomeration

In this remediation process, the fine coal particles were used to remove the oil from contaminated soil via the formation of hydrophobic oil-coal agglomeration. This remediation process has four stages as shown in Fig. 11. In the first stage, coal particles make a layer upon the exterior part of oil-contaminated soil. In the second stage, the compressed of layer the oil is adsorbed onto the coal. In the next stage, high mechanical force is applied to remove the coal from the soil. In the fourth stage, oil coal particles are agglomerated with liquid phase agglomeration. The factors affecting oil removal efficiency are milling time, milling speed, temperature, and the amount of coal added (Agarwal & Liu, 2015). Rahnama and Arnold (1993) used this remediation process for the removal of hydrocarbons from crude oil-contaminated soil and removed residual 0.1% hydrocarbons (Rahnama & Arnold, 1993). Furthermore, Yu-Jen Shin et al. (2010) observed that 90% of oil removal took place when 6 wt% of coal addition

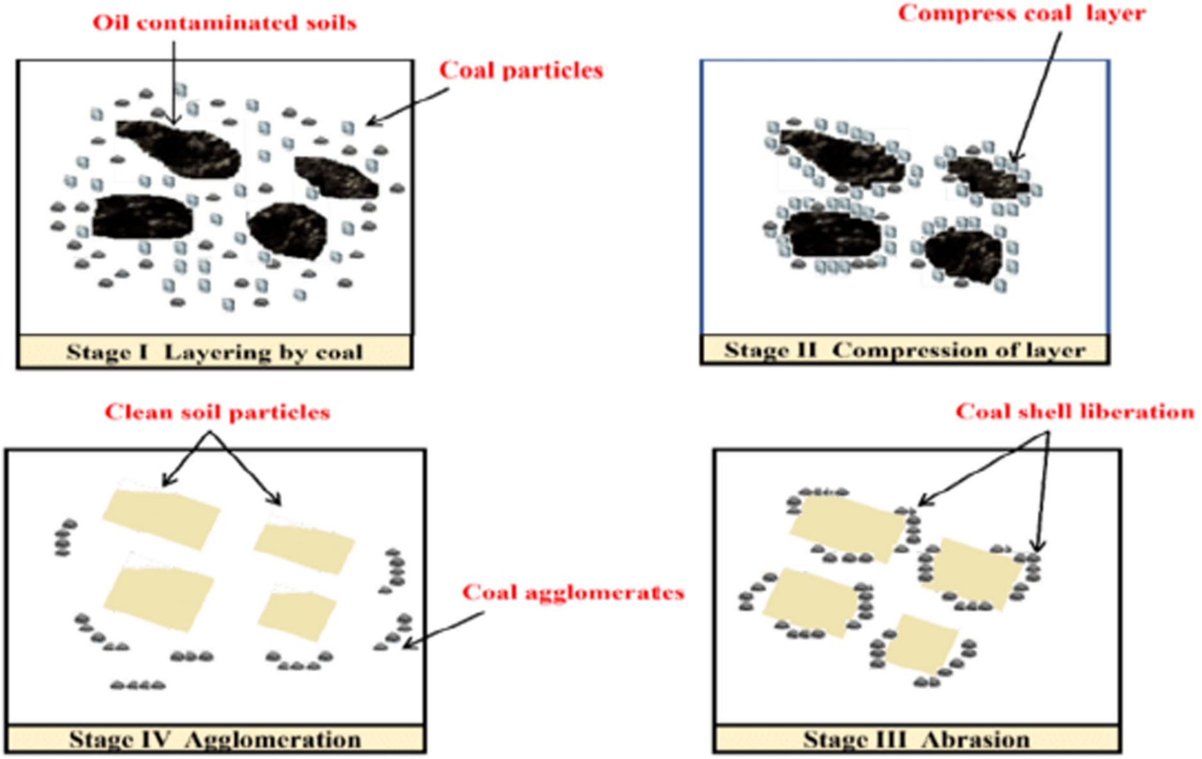


**Fig. 11** Four stages of coal agglomeration process for remediation of oil from oil-polluted soil

with 200 rpm milling speed for 20 min milling time (Rainis et al., 1983).

The coal agglomeration technique is simple and cost-effective. This technique requires low pressure and low temperature for recovering oil from the contaminated soil. Furthermore, this process allows for a high-capacity treatment to be performed effectively in a very short time. However, clay-rich sediments cannot be easily treated by this technique, as are low boiling-point hydrocarbons in the coal agglomeration due to fire hazards, and it is quite costly to process as the coal required should be activated.

## 9 Aerogel Technique

Aerogels are open, three-dimensional, and solid porous materials, having unique characteristics, viz., low density, high porosity, and high surface area with high absorption capacity, ideal for oil sorption from oil-water emulsions. The three-dimensional microporous network structure can be obtained via the intramolecular and intermolecular physical crosslinking of hydrogen bonds (Reynolds et al., 2001). Furthermore, the oil sorption to the aerogels happens mainly due to the intramolecular interaction and Vander Waal's forces between the aerogel and oil molecules as shown in Fig. 12. The different sorption capacity was attributed to the density, the molecular dimension, the surface tension, and hydrophobicity of the oil types (Bi et al., 2022; Salavati-Niasari, 2004; Salavati-Niasari et al., 2004, 2009).

Reynold et al. (2001) prepared powdered $CF_3$-functionalized aerogels for absorbing crude oil from the oil-water mixture and absorbed 234 times oil of its own weight (Reynolds et al., 2001). Chin, S.F et al. (2014) developed a magnetic and porous cellulose aerogel and absorbed oil up to about 28 times its weight within 10 min (Bi et al., 2022). In addition, Yujie Meng et al. (2014) used ultralight carbon aerogel from nanocellulose and recovered 86 g/g paraffin oil from water bodies (Meng et al., 2014). Furthermore, Y. Meng et al. (2015) prepared a sponge-like nanocellulose carbon aerogel with ultra-low density (0.01 g/cm$^3$), high recyclability as well as fast oil absorption of up to 99% (Yujie et al., 2015). Shenjie Han et al. (2016) reported a carbon aerogel from a cellulose-based waste newspaper with low density (18.5 mg/cm$^3$) and absorbed 29–51 times hydrocarbons of its own weight (Han et al., 2016). S Salimian

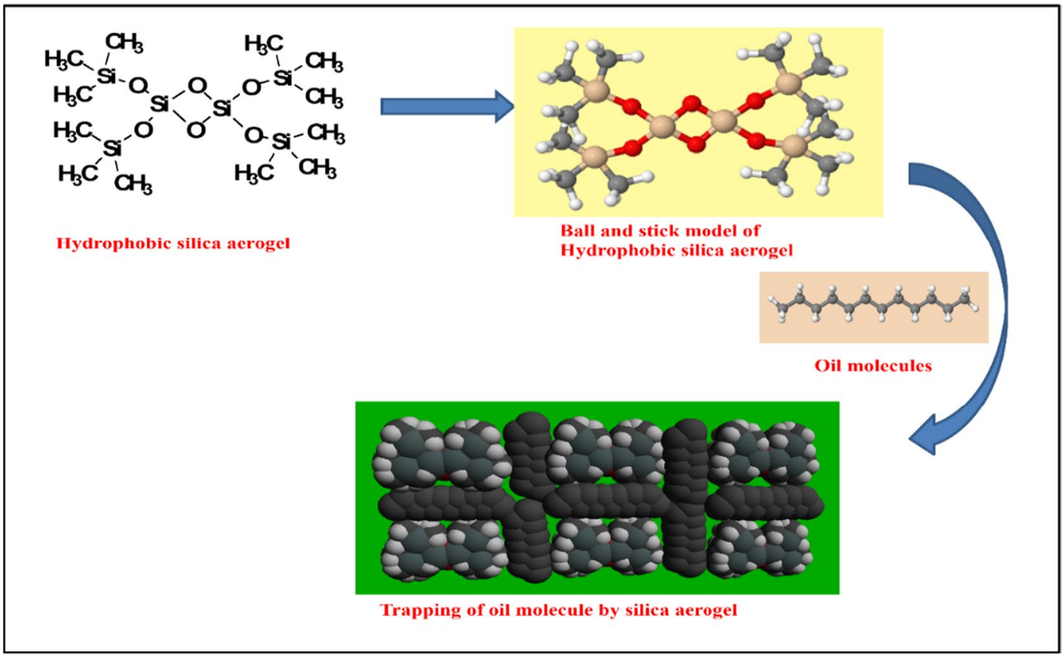


**Fig. 12** Intramolecular hydrogen bonding and Vander Waal's forces of interaction holding oil molecules by silica aerogel

**Table 8** Aerogels used for the removal of oil from contaminated soil/water system

| Raw materials used for making aerogel | Oil removal capacity (g/g) | Oil recovery process | Number of cycles | Reference |
|---|---|---|---|---|
| Waste napkin paper | 14–45 | Squeezing | 10 | Amaret et al., 2020) |
| Banana peel powder | 5–7 | Mechanical | 20 | Alaa et al., 2018) |
| Cellulose | 70–200 | Mechanical | 30 | Laitinen et al., 2017) |
| Cotton/cellulose | 40–100 | Distillation | 5 | Cheng et al., 2017) |
| Bamboo pulp fibers | 50–150 | Distillation | 5 | Wei et al., 2017) |
| Cellulose acetate | 15–30 | Mechanical | 10 | Tripathi et al., 2017) |
| Waste newspaper | 29–51 | Distillation | 5 | Shenjie et al., 2016) |
| Lettuce | 3–11 | Oil pumped | Dna | Wang et al., 2016) |
| Cellulose nanofibers | 80–190 | Mechanical | 10 | Huazheng et al., 2015) |
| Chitosan and silica | 14–30 | Evaporation | 10 | Qian et al., 2015) |
| Cellulose nanofibers | 88–228 | Mechanical | 30 | Wang et al., 2015) |
| Cellulose microfiber | 50–86 | Extraction | 10 | Jin et al., 2015) |
| Waste newspaper | 16 | Squeezing | 5 | Jin et al., 2015) |
| Rice straw cellulose | 135–356 | Distillation | 6 | Jiang & Hsieh, 2014) |
| Cellulose fibers $Fe_2O_3$ nanoparticles | 25–27 | Extraction | 5 | Wang et al., 2022) |
| Cotton with $SiO_2$ nanoparticles | 16–50 | Distillation | 5 | Li et al., 2014) |
| Raw cotton | 50–190 | Distillation | 5 | Hengchang et al., 2013) |
| Cellulose nanofibers | 20–40 | Extraction | 10 | Korhonen et al., 2011) |
| Ceiba pentandra (L.) Gaertn (kapok) | 36–45 | Mechanical | 15 | Abdullah et al., 2010) |
| Barley straw | 6.5–12 | Squeezing | Several times | Husseien et al., 2009) |
| Rice husk | 6 | Mechanical | Dna | Kumagai et al., 2007) |
| Tetramethyl orthosilicate | 14 | Squeezing | 2 | John et al., 2001) |

**Dna*, data not available

et al. (2019) prepared a sodium silicate-based aerogel having ultra-lightweight (0.23 g/cm$^3$) and highly porous (90%) in nature and obtained 100% oil after 10 cycles (Mazrouei-Sebdani et al., 2019). In the same year, Guangyu Shi et al. (2019) synthesized a pomelo peel-based aerogel for the absorption of crude oil from the oil-water emulsion and recovered 94.92% oil after 10 cycles (Guangyu et al., 2019). Furthermore, Bo Fu et al. (2020) synthesized an oleophobic cellulose aerogel with high reusability and durability and absorbed oil up to 99.8% from the water system (Bo et al., 2020). Similar studies in which aerogels are used for oil uptakes from oil-contaminated water and soil bodies are given in Table 8.

## 9.1 Advantages and Disadvantages of Aerogel Technique

The advantage of aerogel materials is of interest due to the possibility of a complete collection of oil from the oil-contaminated water/soil bodies. It is a convenient method with high recyclability. Furthermore, the biomass aerogels possess high flexibility and enlarged surface area with reduced economic losses. The highlighting quality of these natural aerogels is that they degrade themselves without a secondary environmental pollution. However, the natural sorbents exhibit many drawbacks, viz., poor buoyancy, low water-repelling ability, and selectivity of oil sorption, which reduces the effectiveness of their microporous structure to absorb oil. Furthermore, the mineral products such as activated carbon and zeolite use for the formation of gels also show low buoyancy that is inconvenient to recycle. The major drawback of synthetic aerogel is that it degrades very slowly in comparison to mineral or natural products.

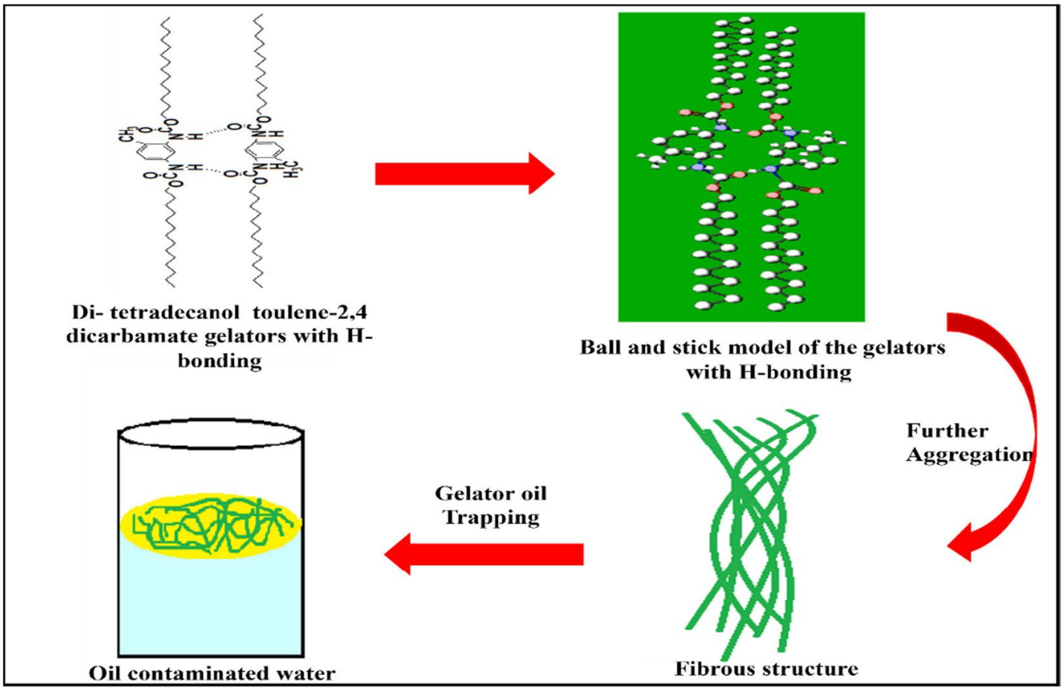


**Fig. 13** Mechanism of gelator employed for cleaning oil from oil-contaminated soil/water bodies

## 10 Gelator Technique

Gelators are composed of many molecules like supramolecular compounds having the ability to gelate with hydrocarbons forming gels which can be easily separated from the oil-water mixtures. The gelators undergo self-assembled three-dimensional porous network structures. The oil molecules are trapped in these pores forming gels as shown in Fig. 13. Many external parameters control the process of formation of gels such as temperature, pH, and light (Wang et al., 2016). In addition to the above mechanism, the phase-selective gelation processes are also reported in the literature where the gelator can be dissolved into the oil by heating and then cooling to form the gel, or the gelator can be directly dissolved in an oil/water mixture (Bhattacharya & Krishnan-Ghosh, 2001).

Bhattacharya and Krishnan-Ghosh prepared the first phase selective gelator based on an alanine amphiphile for oil gelation from oil/water systems (Bhattacharya & Krishnan-Ghosh, 2001). Furthermore in 2006, Darshak R. Trivedi and Parthasarathi Dastidar synthesized a novel supramolecular gelator which has an effective instant gelation ability at room temperature for organic fluids (Trivedi & Dastidar, 2006). Debnath S et al., in the year 2008, reported dipeptide-based low-molecular-weight organogelators applied for the purification of sea waters (Debnath et al., 2008). Annamalai Prathap and Kana M. Sureshan in 2012 prepared a phase selective supergelators using mannitol for cleaning marine oil spills (Prathap & Sureshan, 2012). Vibhute et al. (2016) reported the formation of a gelator using D-glucose as a fine powder and recovered all benzene and crude oil from a benzene/crude oil-seawater mixture (Vibhute et al., 2016). Similarly, Wang, Y et al. in 2016 synthesized a supramolecular oil gelator using toluene diisocyanate (TDI), and uptake of 97% of the crude oil from oil-polluted water bodies (Wang et al., 2016). Raju et al. (2017) prepared a xylitol-based phase selective organogelators and recovered 53% crude oil from the sea water (Raju et al., 2017). Furthermore, Chintam Narayana et al. (2019) reported a gelator using triazole-linked N-acetylglucosamine for crude oil trapping, and gelation took place in less than 15 min (Narayana et al., 2019). Similar, studies in which gelators are used for oil uptakes from oil-contaminated water and soil bodies are given in Table 9.

**Table 9** Different raw materials used for making gelator and their oil recovery process

| Raw material | Gelation time | Co-solvent used | Temperature (°C) | Oil recovery process | Reference |
|---|---|---|---|---|---|
| Isoxazole | < 1 min | Ethanol/tetrahydrofuran (THF) | 40 | Distillation | Singh et al., 2020) |
| Isoleucine and valine | 2 min | Ethyl acetate/acetone/tetrahydrofuran | Room temperature | Dna | William et al., 2018) |
| Lauric acid | < 1 min | N-methylacetamide | 25 | Dna | Debnath et al., 2008) |
| Xylitol | 2 min | Warm toluene | 25 | Distillation | Raju et al., 2017) |
| N-acetyl glucoseamine | 1–3 min | Tetrahydrofuran | 0–25 | Distillation | Narayana et al., 2019) |
| D-glucose | 60 min | Dna | 25 | Distillation | Prathap & Sureshan, 2012) |
| N-acetyl glucosamine | 45 s | Tetrahydrofuran | 0–25 | Distillation | Mukherjee et al., 2014) |
| Galactose | 0–45 min | Tetrahydrofuran | 25 | Vacuum distillation | Mukherjee & Mukhopadhyay, 2013) |
| Mannitol | 15–30 min | Methanol and acetic acid | 25 | Distillation | Prathap & Sureshan, 2012) |
| Mannitol Sorbitol | 0–60 min | Ethanol | 25 | Vacuum distillation | Jadhav & Vemula, 2010) |
| Primary amine/cinnamic acid | Instant | Methanol and dimethylformamide | 58–108 | Dna | Cui et al., 2017) |

**Dna*, data not available

### 10.1 Advantages and Disadvantages of Gelator Technique

The major advantage of this process is that the use of co-solvent in the formation of gels decreases in gelling time and increases in gel strength as well as a high oil removal rate. It is easy to handle for the recovery of the oil and gelator, and furthermore, the gelator can be reused multiple times. However, the use of a co-solvent is obviously a drawback considering a real-life application due to the high amount of potentially hazardous co-solvent discharge into the environment and the lack of control over the temperature in the environment. Some gelators formed from sugar derivatives do not provide good strength to the gel and not are easy to recover the gelator and oil. Furthermore, this process takes high time during gelation as well as low oil removal efficiency.

## 11 Conclusions and Future Directions

A serious and pressing issue of concern is the contamination of land and water resources by crude oil. Different types of materials, methods, and technologies have been proposed, studied, and employed for the uptake of spilled oils in the last few decades. To remove oil quickly and effectively, we must first analyze the nature of the oil contamination, which will lead to the optimum cleanup technique option. Additionally, soil characteristics such as soil type, permeability, pH, and nutrient concentration all influence oil removal efficiency from polluted soil. This chapter provides brief overviews of eight various methods, their percentage removal efficiency, pros and drawbacks, and the time period required (briefed in Table 10).

As a result, it has been determined that the selection of cleanup technique is dependent on the contamination kinds, as an incorrect choice may hinder high removal efficiency. The bioremediation and phytoremediation techniques are simple and inexpensive to carry out. But, they are slow and time-consuming methods that take months or years to achieve satisfactory results. Thermal treatments are dependable and effective at high temperatures, but they also render the soil unusable for future use. In the same way, the solvent extraction method is a high-efficiency process for oil-polluted soil samples, but it produces secondary pollutants due to the use of toxic solvents and is expensive also. The aerogel and gelators uptake the oil completely from oil-contaminated soils and show satisfactory results but possess a low water-repellent

**Table 10** Overall summary of different remediation processes with their advantages and disadvantages

| Remediation process | Advantages | Disadvantages | Maximum contaminant level | % removal efficiency | Time | Reference |
|---|---|---|---|---|---|---|
| Chemical oxidation | Low operational cost, easy to operate and high removal efficiency | Highly dependent on pH, destroys natural microorganisms and non-effective for low permeability soil | 5–15% | More than 80% | Up to 72 h | Goi et al., 2006b; Goi et al., 2009) |
| Electrokinetic remediation | Uniform flow distribution, Low operational cost and power consumption | Depends upon contaminants, time consuming and non-eco-friendly nature | 10–20% | 40–70% | 14–45 days | Prakash et al., 2021; Pazos et al., 2012; Jeon et al., 2010) |
| Bioremediation | Highly effective for on-site treatments, Cost effective, and eco-friendly nature | Provide unsatisfactory results, high time consuming and less biodegradable | 2–10% | 50–90% | Several months/years | Saharan et al., 2022b; Kogbara et al., 2016; Adams et al., 2015; Lai et al., 2009) |
| Phytoremediation | Cost effective, eco-friendly in nature and helps in maintaining soil fertility | Time-consuming, needs of a specific plant, dependent on various environmental parameters and only applied for less amount of contaminants | 1–8% | 90% | Few months/years | Atabaki et al., 1500; Ayotamuno et al., 2007; Liao et al., 2015) |
| Thermal remediation | High removal efficiency, quick, reliable and applicable for large contaminated soil | Need of high cost, release of greenhouse gases and highly affected by soil moisture | 2–10% | More than 95% | Few seconds to 2 h | Liu & Wang, 2022; Falciglia et al., 2013) |
| Solvent extraction | Easily implemented, quick and high removal efficiency | Need of high cost, non-eco-friendly nature and consumes large amount of solvent | 0.5–30% | 60–98 | Several hours to 10 months | Liu et al., 2021; Rongsayamanont et al., 2020) |
| Coal agglomeration | Simple, cost-effective and time-consuming technique, not need of high pressure and temperature | Clay sediments cannot be easily treated | Dna | 90 | 20 min | Agarwal & Liu, 2015; Rainis et al., 1983) |

**Table 10** (continued)

| Remediation process | Advantages | Disadvantages | Maximum contaminant level | % removal efficiency | Time | Reference |
|---|---|---|---|---|---|---|
| Aerogels | Convenient method with high recyclability and avoid secondary pollution | Poor buoyancy, low water repelling ability, selectivity of oil sorption and low degradability | Dna | More than 95 | Few seconds to minutes | Reynolds et al., 2001; Meng et al., 2014; Han et al., 2016) |
| Gelators | Time-consuming, reused multiple times, easy and high oil recovery | Non-eco-friendly nature, not easy to recover the gelator and selectivity of the oil need | Dna | More than 90 | Several minutes to hour | Kumagai et al., 2007; Wang et al., 2016; Debnath et al., 2008) |

**Dna*, data not available

property and take a long time for gelation, hence decreasing the oil removal efficiency.

In the final conclusion, no single remediation approach is satisfactory for the remediation of oil from oil-contaminated soils; thus, in the future, a combination of technologies may be an alternative answer, or we may need to create and build another feasible solution for fast and effective adsorption of oil from the soil.

Based on recent advances in soil cleanup technologies for oil spills, some potential future directions for further research and development may include:

- Integration of multiple technologies: Recent studies have shown that combining different technologies, such as bioremediation and chemical oxidation, can achieve more efficient and sustainable remediation outcomes. Future research could focus on the optimization of integrated technologies and their long-term effectiveness in cleaning up contaminated soils.
- Development of novel materials: The use of novel materials such as nanomaterials and magnetic particles has shown promising results in soil cleanup. Future studies could focus on developing and optimizing these materials for enhanced performance and sustainability.
- Assessment of the long-term impact of remediation: While current technologies have shown promising results in cleaning up contaminated soils, their long-term impact on soil health and ecological systems remains unclear. Future research could focus on evaluating the long-term effects of remediation technologies on soil microbial communities, plant growth, and ecosystem functioning.
- Remediation of complex mixtures: Oil spills often result in complex mixtures of contaminants that are difficult to remediate using traditional methods. Future research could focus on the development of technologies that can effectively remediate these complex mixtures, such as bioelectrochemical systems or phytoremediation.
- Integration of artificial intelligence: The integration of artificial intelligence (AI) has the potential to enhance the efficiency and accuracy of soil cleanup technologies. Future research could focus on the development of AI-based decision support systems for soil cleanup that can predict the effectiveness of different remediation technologies under different conditions.

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**Declarations**

**Conflict of Interest** The authors declare no competing interests.

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