Chapter 10
Microbes: A Novel Source of Bioremediation for Degradation of Hydrocarbons

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Abstract In our daily life, the demand for liquid petroleum products is increasing day by day. Crude oil-derived hydrocarbons, the largest group of environmental pollutants found worldwide, pollute our environments severely. Oil or hydrocarbons cause drastic impacts on living organisms. The many reports about their toxicity emphasize the ultimate need to remove them from marine and terrestrial environments. For cleaning up pollution by these hydrocarbons, bioremediation seems to be the most acceptable and economically justified method. Bioremediation is considered one of the most sustainable cleanup techniques, but its potential has not been fully expressed in the field because it operates too slowly to meet the immediate demands of a given location. The process of bioremediation is carried out by various microorganisms. Therefore, in this review, we present information about methods of oil degradation by such microorganisms as bacteria, fungi, algae, and actinobacteria. These microbes can help degrade oil or hydrocarbons. This review presents the unique characteristics of oil-degrading microbes. In addition, it is a starting point for

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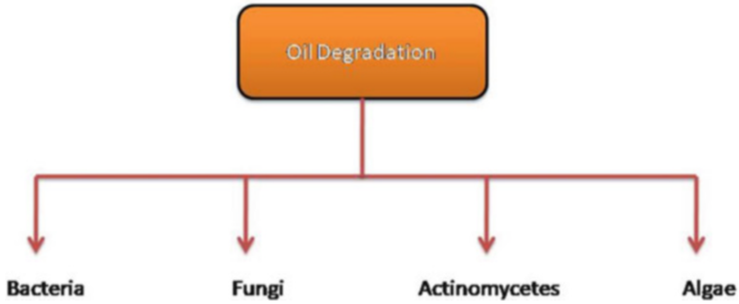

Fig. 10.1 Microbes that degrade oil

wider debate about the limitations and possible improvements of currently employed hydrocarbon bioremediation strategies.

Keywords Hydrocarbons · Degradation · Microorganisms

10.1 Introduction

At the present time, petroleum and its constituent hydrocarbons are widely used as the main energy source in the industrial, transport, and domestic sectors (Varjani and Upasani 2016; Arulazhagan et al. 2010). However, use of these hydrocarbons produces a number of harmful chemical substances that widely affect human beings and the environment. The effectiveness of these substances depends upon the composition, concentration, and biological state of the affected organism at the time of contamination and also on such environmental factors as temperature (Obire and Ayanwu 2009).

In our environment, toxic components of hydrocarbons are released by transport, vehicle factories, thermal plants, oil spills, pipelines, oil well leakages, diesel stations, and contamination by vehicle garages (Costa et al. 2012). The petroleum hydrocarbons are categorized into two broad divisions, aromatic and aliphatic compounds. The simple aliphatic and aromatic compounds are degraded in the environment, but because of their complex structure, the large aliphatic and aromatic constituents of petroleum hydrocarbons are not degraded (Hasanuzzaman et al. 2007). Therefore, different strategies and approaches are used to degrade these hydrocarbons, broadly categorized into three groups: physical, chemical, and thermal approaches (Adnan et al. 2018). All these methods are very costly, and the chemicals required further greatly affect our environment. In the thermal process, large amounts of heat are generated that affect both the flora and fauna of a specific area (Ezeji et al. 2007).

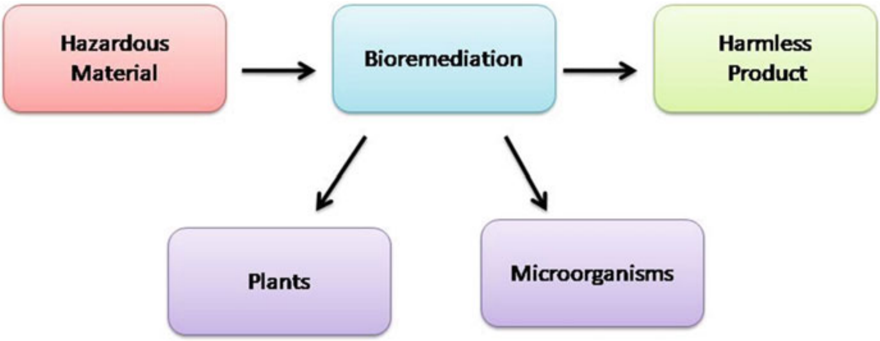

Fig. 10.2 Process of bioremediation

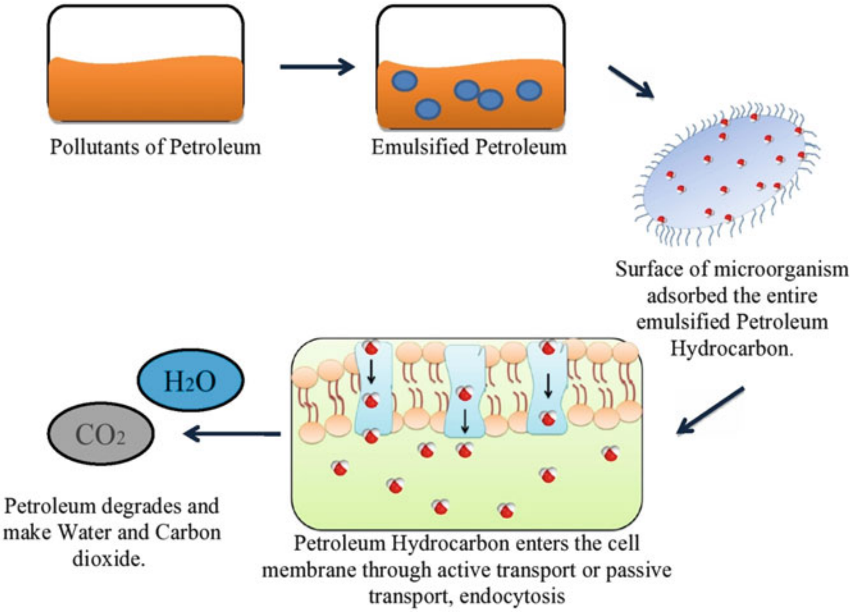

Fig. 10.3 Mechanism of oil degradation

Therefore, the preferred method for degradation of hydrocarbons is biological treatment because of reliability, feasibility, and the high potential for eco-friendly degradation. The biological methods are very simple to use and require low energy for operation. A variety of microorganisms can be used for the process in in vitro as well as in in vivo conditions (Fig. 10.1). Different types of microorganisms—bacteria, fungi, algae, and yeasts—degrade the hydrocarbons in a green revolution for removing hazardous contaminants from the environment (Zhang et al. 2013; Rahman et al. 2003). Native microorganisms have great potential for degradation as compared to others because of the specific metabolic pathways that metabolize the oil content.

Crude oil is composed of several compounds, including aliphatic, aromatic, and polycyclic aromatic hydrocarbons (PAH) and also sulfur-, oxygen-, and nitrogen-containing compounds. PAH compounds are toxic and may be carcinogenic. High concentrations of such pollutants, by their poisonous and carcinogenic nature, can affect cellular metabolism (Tanti et al. 2009). The biodegradation of petroleum hydrocarbons may be contained by considering many factors. An essential limiting factor in the biodegradation of polluted soils is often the low bioavailability and solubility of the hydrocarbons. Crude oil is one of the most significant pollutants in the environment, able to cause extreme damage to human beings and ecosystems. Excessive oil concentration causes serious problems in our body such as liver or kidney disorders, visible harm to bone marrow, and an increased risk of cancer (Mishra et al. 2001). The use of microorganisms in degradation of petroleum and its products has been established as a green, cost-effective, flexible, and environmentally sound remedy. The search for effective and green strategies of oil removal from polluted infected sites has intensified in recent years because the microbial cleanup of untreated oil spills is a slow process (Grangemard et al. 2001). In microbial

Table 10.1 List of hydrocarbon- or oil-degrading bacteria

Sample no.	Bacteria	Degradation	Reference
1	*Pseudomonas*	Hydrocarbons	Leahy and Colwell (1990)
2	*Acinetobacter*	Hydrocarbons	Adebusoye et al. (2007)
3	*Alcaligenes*	Hydrocarbons	Floodgate (1995)
4	*Vibrio*	Hydrocarbons	Leahy and Colwell (1990)
5	*Flavobacterium*	Hydrocarbons	Adebusoye et al. (2007)
6	*Achromobacter*	Hydrocarbons	Floodgate (1995)
7	*Micrococcus*	Hydrocarbons	Leahy and Colwell (1990)
8	*Nocardia*	Hydrocarbons	Adebusoye et al. (2007)
9	*Corynebacterium*	Hydrocarbons	Floodgate (1995)
10	*Pseudomonas stutzeri*	*n*-Tetradecane	Adel et al. (2012)
11	*Bacillus thuringiensis*	*n*-Tetradecane	Abou-Shanab et al. (2016)
12	*Bacillus pumilus*	*n*-Tetradecane	Awad et al. (2011)
13	*Bacillus cereus*	*n*-Tetradecane	Bayoumi et al. (2010)
14	*Pseudomonas* sp.	Hydrocarbons	Brito et al. (2006)
15	*Marinobacter* sp.	Hydrocarbons	Akpoveta et al. (2011)
16	*Alcanivorax* sp.	Hydrocarbons	Juhasz and Naidu (2000)
17	*Microbulbifer* sp.	Hydrocarbons	Bishnoi et al. (2008)
18	*Sphingomonas* sp.	Hydrocarbons	Snape et al. (2001)
19	*Micrococcus* sp.	Hydrocarbons	Lloyd and Cackette (2001)
20	*Cellulomonas* sp.	Hydrocarbons	Chaillan et al. (2004)
21	*Dietzia* sp.	Hydrocarbons	Akpoveta et al. (2011)
22	*Gordonia* sp.	Hydrocarbons	Bishnoi et al. (2008)

remediation, organization of numerous microbes present in the soil can degrade a wide range of oily sludge (Barathi and Vasudevan 2001).

Oil spills affect many species of plants and animals within the surrounding areas as well as humans. The search for green and powerful approaches to defining the rate and overall extent of biodegradation of waste lubricating oil in soils or contaminated sites has intensified in current years (Umar et al. 2013). Microorganisms can metabolize oil much as humans convert their food into energy or power. The soil is the habitat of many organisms, so any changes or variations in soil may further destroy our environment. The impact of an oil spill is enrichment of the soil-degrading microbial populations. No single microorganism has been observed to completely degrade a petroleum hydrocarbon molecule, but particular species or traces of equal species may be capable of degrading concentrations of oil hydrocarbons (Facundo et al. 2001). Species of *Pseudomonas* are known for their capability of hydrocarbon degradation (Jewetz et al. 1999) (Fig. 10.2).

10.2 Mechanism of Oil Degradation by Microorganism

The biodegradation of hydrocarbons by microorganisms in nature has four main steps (Fig. 10.3).

In the first step, pollutants of petroleum are emulsified by surfactant secreted by a microorganism. Then, the surface of the microorganism adsorbs the entire emulsified petroleum hydrocarbon. Now, the petroleum hydrocarbon, which is adsorbed onto the surface of the cell membrane, enters the cell membrane through active transport or passive transport, endocytosis. In the last step, the petroleum hydrocarbon enters into the cell, and undergoes an enzymatic reaction that causes its degradation (Li et al. 2019).

10.2.1 Degradation of Oil and Hydrocarbon by Bacteria

Different species of bacteria are widely used to biologically degrade petroleum hydrocarbons and also to help remove oil spills by degradation (Abou-Shanab et al. 2016). Many studies have shown that bacteria can degrade hydrocarbons such as asphaltenes (phenols, ketones, esters, porphyrins, fatty acids), resins (carbazoles, sulfoxides, pyridines, quinolines, amides) (Steliga 2012), and aliphatics, aromatics, and resins (carbazoles, sulfoxides, pyridines, quinolines, amides) (Table 10.1). The bacterial strains *Pseudomonas fluorescens*, *P. aeruginosa*, *Bacillus subtilis*, *Bacillus* sp., *Alcaligenes* sp., *Acinetobacter lwoffi*, *Flavobacterium* sp., *Micrococcus roseus*, and *Corynebacterium* sp. isolated from polluted areas in Nigeria were observed for degradation of crude oil (Adebusoye et al. 2007).

Petroleum bioremediation is completed by microorganisms that can utilize hydrocarbons as a source of energy (Rosenberg et al. 1998). These bacteria are ubiquitous

Table 10.2 List of oil- or hydrocarbon-degrading fungi

Sample no.	Fungus	Degradation	References
1	*Aspergillus flavus*	Petroleum oil	Adekunle and Oluyode (2002)
2	*A. niger*	Petroleum oil	Bartha and Atlas (1997)
3	*Mucor*	Petroleum oil	Battelle (2000)
4	*Rhizopus*	Petroleum oil	Nwachukwu (2000)
5	*Talaromyces*	Petroleum oil	Ojo (2005)
6	*Penicillium*	Hydrocarbons	Ahmad et al. (2016)
7	*Amorphoteca*	Hydrocarbons	Throne-Holst et al. (2007)
8	*Candida*	Hydrocarbons	Farag and Soliman (2011)
9	*Fusarium*	Hydrocarbons	Al-Nasrawi (2012)
10	*Neosartorya*	Hydrocarbons	Jawhari (2014)
11	*Mycotypha*	Hydrocarbons	Okafor et al. (2009)
12	*Rhizopus*	Hydrocarbons	Mittal and Singh (2009)
13	*Botrytis*	Hydrocarbons	Joshi and Pandey (2011)
14	*Polyporus* sp.	Crude oil	Kristanti et al. (2011)
15	*Amorphoteca* sp.	Hydrocarbons	Jones et al. (2001)
16	*Neosartorya* sp.	Hydrocarbons	Chaillan et al. (2004)
17	*Paecilomyces* sp.	Hydrocarbons	Ramasamy et al. (2014)
18	*Talaromyces* sp.	Hydrocarbons	Wang et al. (1998)
19	*Graphium* sp.	Hydrocarbons	Balaji et al. (2014)
20	*Popularia* sp.	Oil	Sandhu et al. (2016)
21	*Geotrichum* sp.	Oil	Sandhu et al. (2016)

in nature and able to degrade numerous hydrocarbons including short-chain, long-chain, and numerous aromatic compounds, including PAHs. These compounds have low solubility in water. Thus, as the first step in hydrocarbon degradation entails a membrane-bound oxygenase, it is important for microorganisms to be in direct contact with the hydrocarbon substrates. One biological approach to accomplish contact between the microorganisms and water-insoluble hydrocarbons is emulsification of the hydrocarbon. Therefore, it is not unexpected that microorganisms growing on petroleum typically produce emulsifiers. These surfactants assist to disperse the oil and to detach the bacteria from the oil droplets after utilizable hydrocarbon has been depleted (Ron and Rosenberg 2002).

10.2.2 Biodegradation of Oil and Petroleum by Fungi

Crude oil is a primary source of profits for Iraq, which is certainly one of the most important international oil producers and exporters, ranked nearly fourth internationally in terms of oil reserves. Incidental spills of crude oil and frequent illegal disposal of oil wastes lead to serious damage to environments. Cleaning up oil contaminants is a priority project for the restoration of our natural environment.

Chemical, physical, and thermal strategies are available but these methods are very costly and require site recovery. Several physicochemical and biological methods have been assessed for treating oil-contaminated environments (Ezeji et al. 2007). Organic treatment is desired for physicochemical strategies for reasons of its feasibility, reliability, and capability to achieve high elimination efficiency with low price. Other reasons include the simplicity of its low-power layout, creation, operation, and use; biodegradation of hydrocarbons is a cost-effective method compared to chemical methods (Liu et al. 2013). In a biological technique, microorganisms can use hydrocarbons as their sole energy and carbon source and degrade them instead of gathering them at every other level (Zhang et al. 2015). Biological treatment may have an advantage over physicochemical treatment in the removal of spills because it affords crucial biodegradation of oil parts through microorganisms, is a "green" alternative for treating risky contaminants without environmentally degrading effects, and may be cheaper than other strategies (Zhang et al. 2011). Diverse microorganisms, including bacteria, algae, yeasts, and fungi, can degrade hydrocarbons. Indigenous microorganisms with particular metabolic capacities have a considerable role in the biodegradation of crude oil (Rahman et al. 2003). Rahman et al. (2002) suggested that bacterial consortia isolated from crude oil-infected soils have the potential to degrade crude oil fractions. In addition to bacteria, fungi are one of the best oil-degrading organisms. Numerous studies have identified many fungal species able to use crude oil as their sole source of energy, including *Cephalosporium*, *Rhizopus*, *Paecilomyces*, *Torulopsis*, *Pleurotus*, *Alternaria*, *Mucor*, *Talaromyces*, *Gliocladium*, *Fusarium*, *Rhodotorula*, *Cladosporium*, *Geotrichum*, *Aspergillus*, and *Penicillium* (Jawhari 2014). Hanafy et al. (2017) observed that the *Aspergillus* and *Penicillium* isolated from oil-contaminated sites close to the Red Sea within the Yanbu region have been extremely useful in crude oil degradation. Using fungi as a means of bioremediation gives a powerful alternative for cleansing the environment of contaminants (Hanafy et al. 2017). Data are shown in Table 10.2.

10.2.3 Biodegradation of Oil and Petroleum by Algae

Natural contamination has been stated to be the most significant issue affecting the world (Reyes et al. 2016). One of the main causes of environmental pollution is hydrocarbon contamination in soil and water (El-Sheekh et al. 2013). Unrefined petroleum, also called dark gold, is the most significant asset in industrialized nations; however, its handling and transport can cause genuine ecological contamination and interfere with many populations of organisms (Xaaldi et al. 2017). Many recorded data attest to the real genuine harm brought about by oil slicks in ecosystems and to marine creatures, silt, higher-level organisms, fish, coral reefs, avian species, reptiles, and surface water bodies (Afshar-Mohajer et al. 2018). When oil is spilled in the ocean or other waterways, it creates a film that decreases the proportion of daylight reaching the underwater world, which affects the process of

Table 10.3 List of oil- and hydrocarbon-degrading algae

Sample no.	Algae	Degradation	References
1	*Amphora* sp.	Crude oil	Kvenvolden and Cooper (2003)
2	*Prototheca zopfii*	Crude oil and hydrocarbons	Aditi et al. (2015)
3	*Porphyridium* sp.	Petroleum waste	Vidyashankar and Ravishankar (2016)
4	*Microcoleus* sp.	Hydrocarbons	Yakimov et al. (2007)
5	*Agmenellum* sp.	Petroleum waste	Walker et al. (1975)
6	*Anabaena* sp.	Hydrocarbons	Cerniglia et al. (1980)
7	*Coccochloris* sp.	Hydrocarbons	Bibi et al. (2017)
8	*Nostoc* sp.	Hydrocarbons	Lohitesh et al. (2013)
9	*Cylindretheca* sp.	Petroleum waste	Srivastav et al. (2013)
10	*Aphanocapsa* sp.	Hydrocarbons	Shankar and Suneetha (2013)
11	*Chlorella* sp.	Petroleum waste	Rath et al. (2012)
12	*Chlamydomonas* sp.	Crude oil	Venkata Gopichand et al. (2013)
13	*Ulva* sp.	Hydrocarbons	Lohitesh et al. (2013)
14	*Petalonia*	Crude oil and hydrocarbons	Aditi et al. (2015)

photosynthesis. Additionally, total petroleum hydrocarbon (TPH), a natural toxin in the Earth, is poisonous for all human beings and numerous other organisms (Lee et al. 2015). Polycyclic aromatic hydrocarbons (PAHs) are the most lethal components of unrefined petroleum and are related to cancer-causing agents (Duran and Cravo 2016). Bioremediation suggests the utilization of living organisms and their biochemical apparatus to debase or change poisons into less dangerous forms, which has been demonstrated to be a powerful, confined, and more affordable technique (Sharma et al. 2018). In any case, a limitation of the bioremediation procedure with microorganisms is the accessibility of supplements, for example, nitrogen and phosphorus, which influences the speed of oil degradation (Ron and Rosenberg 2014), although advances in atomic innovations on recombinant DNA have permitted the hereditary improvement of numerous organisms and support the speed of remediation. The fundamental segments of raw petroleum are naphthenes, asphaltenes, waxes, pavements, aromatic hydrocarbons, tars, and other unstable mixes, for example, benzene, toluene, ethylbenzene, and xylene. Many mixes, for example, pyrene, benzo(*a*)pyrene and chrysene, are cancer causing, mutagenic, and teratogenic (Sammarco et al. 2013). Numerous microorganisms, including a few types of microalgae (*Monoraphidium braunii*, *Chlamydomonas reinhardtii*, *Chlorella* sp.), parasites (*Trametes versicolor*, *Pleurotus eryngii*, *Phanerochaete chrysosporium*), and bacteria (*Pseudomonas aeruginosa*, *Rhodococcus erythropolis*), have catabolic pathways for the debasement of contaminants (Sharma et al. 2018). Algal growth is fundamental in seagoing biological systems and in light of the fact that they are essential markers, are important in the trophic chain,

Table 10.4 List of oil- and hydrocarbon-degrading actinomycetes

Sample no.	Actinobacteria	Degradation	References
1	*Actinoplanes*	Oil	Cappuccino and Sherman (2002)
2	*Nocardia*	Hydrocarbons	George et al. (2011)
3	*Streptomyces*	Oil	Rahman et al. (2002)
4	*Streptosporangium*	Hydrocarbons	Rifaat and Yosery (2004)
5	*Rhodococcus*	Oil	George et al. (2011)
6	*Nocardia*	Hydrocarbons	Watanabe et al. (2002)
7	*Gordonia*	Oil	Essien and Udosen (2000)
8	*Dietzia*	Oil	Beerka and Steinbuchel (2000)
9	*Micromonospora*	Hydrocarbons	George et al. (2011)
10	*Actinomyces octodloyts*	Petroleum Hydrocarbons	
11	*Saccharomyces cerevisiae* (yeast)	Petroleum Hydrocarbons	

providing oxygen and natural substances to other living things. *Chlorella vulgaris* is a significant species because it adsorb an assortment of natural pollutants (Kong et al. 2010), so the development of microalgae in wastewater treatment is spreading widely for the disposal of supplements, control of physical substance parameters, as feedstock for the generation of biofuel, and expulsion of phenol and polycyclic aromatic compounds, because of its high adsorption limit, bioaccumulation, biotransformation, and biodegradation (He et al. 2016). For this reason, it was proposed here to determine the capability of biodegradation of unrefined petroleum by the microalgae *Chlorella* sp. (Deimer et al. 2018). Data are shown in Table 10.3.

10.2.4 Biodegradation of Oil and Hydrocarbons by Actinomycetes

The tragic history of soil and water pollution by way of oil spillage from the oil industry, tankers, offshore systems, related pipelines, garage tanks and wells, and unlawful oil bunkering has caused essential environmental and fitness defects in oil-structured countries (Ordinioha and Brisibe 2013). Pollution through crude oil, inclusive of oil spills and toxic wastes, is a persistent struggle that has prompted serious threats to human fitness with issues regarding the viability and productiveness of ecosystems (Okoh and Trejo-Hernandez 2006). Mechanical and chemical techniques for the remediation of hydrocarbon-polluted surroundings are frequently costly and technologically complex. Increasing attention has been paid to the growing innovative era for cleaning up this contaminant, with bioremediation being a completely useful method (Vidali 2001). There are many herbal and natural microorganisms that thrive on the decomposition of those toxic compounds. Usage of microorganisms for cleanup efforts, referred to as bioremediation, has been shown to be a successful method for the cleanup of marine regions suffering from oil spills (Coulon et al. 2006). Bioremediation strategies are currently receiving favorable exposure as low-cost and promising environmentally friendly technologies for the remediation of crude oil hydrocarbons without difficulty. Biodegradation of crude oil and derived aromatic hydrocarbons in marine sediments has been reported (Jones et al. 2008). The maximum fast and complete degradation of general organic pollution is introduced under cardiac conditions and the biodegradation system is mediated by unique enzyme structures (Das and Chandran 2011). Extracellular and intracellular assault of organic pollution by microbes through oxidation is catalyzed by peroxidases and oxygenases. The cleanup of toxic natural compounds through numerous microorganisms and fungi takes place through oxidative coupling mediated via oxidoreductases together with peroxidases (Karigar and Rao 2011). Microbes derive power via power-yielding biochemical reactions mediated by these enzymes to cleave chemical bonds and help transfer of electrons from a reduced natural substrate (donor) to some other chemical compound (acceptor). For this reason, it is essential to analyze the function and organization of enzymes for crude oil biodegradation. Actinobacteria have several characteristics that are vital for surviving in extreme situations, including dry environments and nutrient lack, and produce biosurfactants that boost contaminant bioavailability and facilitate the manner of biodegradation (Beilen and Funhoff 2005): these promote the prevalence of Actinobacteria in pristine and hydrocarbon-polluted soil (Quatrini et al. 2008). Consequently, it is important to observe crude oil biodegradation of actinobacterial isolates, particularly from oil-contaminated sites (Table 10.4).

10.3 Conclusion

Bioremediation is the main natural mechanism that can cleanse petroleum and oil pollutants from the environment. This process uses microscopic organisms such as bacteria, fungi, algae, and actinomycetes that live in soil and consume oil or hydrocarbons. A number of factors influencing degradation have been identified to reduce the toxicity of oil contamination in the environment by removing, degrading, or transforming contaminants. Therefore, successful bioremediation treatment requires understanding of those factors.

References

Abou-Shanab RA, Eraky M, Haddad AM, Abdel-Gaffar ARB, Salem AM (2016) Characterization of crude oil degrading bacteria isolated from contaminated soils surrounding gas stations. Bull Environ Contam Toxicol 97(5):684–688

Adebusoye SA, Ilori MO, Amund O, Teniola OD, Olatope SO (2007) Microbial degradation of petroleum hydrocarbons in a polluted tropical stream. World J Microbiol Biotechnol 23 (8):1149–1159

Adekunle AA, Oluyode TF (2002) Biodegradation of crude petroleum and petroleum products by fungi isolated from two oil seeds (melon and soybean). J Environ Bot 26(1):37–42

Adel E, Shahaby AF, Awad NS, Bahobial AS, El Abib OA (2012) In vitro screening for oil degrading bacteria and evaluation of their biodegradation potential for hydrocarbon. Afr J Microbiol Res 6(49):7534–7544

Aditi S, D'Souza Shalet NM, Pranesh R, Katyayini T (2015) Microbial production of polyhydroxyalkanoates (PHA) from novel sources: a review. Int J Res Biosci (IJRBS) 4:16–28

Adnan BA, Jawadayn T, Alkooraneea C, Hayder A, Abboodd JZ, Jin S, Xiaoyu Z (2018) Fuying Maa isolation and characterization of two crude oil-degrading fungi strains from Rumaila oil field, Iraq. Biotechnol Rep 17:104–109

Afshar-Mohajer N, Rule AM, Katz J, Koehler KA (2018) Laboratory study of particulate and gaseous emissions from crude oil and crude oil-dispersant contaminated seawater due to breaking waves. Atmos Environ 179(4):177–186

Ahmad A, Burghal N, Wijdan H (2016) Mycodegradation of crude oil by fungal species isolated from petroleum contaminated. Int J Innov Res Sci Eng Technol 5(2):1517–1524

Akpoveta OV, Egharevba F, Medjor OW (2011) A pilot study on the biodegradation of hydrocarbon and its kinetics on kerosene simulated soil. Int J Environ Sci 2(1):54–67

Al-Nasrawi H (2012) Biodegradation of crude oil by fungi isolated from Gulf of Mexico. J Bioremed Biodegr 3:1–6

Arulazhagan P, Vasudevan N, Yeom I (2010) Biodegradation of polycyclic aromatic hydrocarbon by a halotolerant bacterial consortium isolated from marine environment. Int J Environ Sci Technol 7:639–652

Awad NS, Sabit HH, Abo-Aba SEM, Bayoumi RA (2011) Isolation, characterization and fingerprinting of some chlorpyrifos-degrading bacterial strains isolated from Egyptian pesticides-polluted soils. Afr J Microbiol Res 5(18):2855–2862

Balaji V, Arulazhagan P, Ebenezer P (2014) Enzymatic bioremediation of polyaromatic hydrocarbons by fungal consortia enriched from petroleum contaminated soil and oil seeds. J Environ Biol 35(3):521–529

Barathi S, Vasudevan N (2001) Utilization of petroleum hydrocarbons by *Pseudomonas fluorescens* isolated from a petroleum-contaminated soil. Environ Int 26(5–6):413–416

Bartha R, Atlas RM (1997) Biodegradation of oil in seawater: writing factor and artificial stimulation. In: Ahern DG, Meyers SP (eds) The microbial degradation of oil pollutants. Centre for Wetland Resources, Louisiana, pp 147–152

Battelle CD (2000) Mushrooms: higher macrofungi to clean up the environment. Environ Issues Fall:1–4

Bayoumi RA, Awad NS, Ibrahim MMM (2010) Molecular genetics characterization of some biosurfactant producing bacteria isolated from Egyptian red sea mangrove forests. Arab J Biotechnol 13(2):209–222

Beerka M, Steinbuchel A (2000) Microbial degradation of the multiply branched alkenes 2, 6, 10, 15, 19, 23-hexamethyltetracosane (squalene) by *Mycobacterium fortuitum* and *Mycobacterium ratisbonne*. Appl Environ Microbiol 66:4462–4467

Beilen JB, Funhoff EG (2005) Expanding the alkane oxygenase toolbox; new enzymes and applications. Curr Opin Biotechnol 16(3):308–314

Bibi R, Ahmad Z, Imran M, Hussain S, Ditta A, Mahmood S, Khalid A (2017) Algal bioethanol production technology: a trend towards sustainable development. Renew Sust Energ Rev 71:976–985

Bishnoi K, Kumar R, Bishnoi NR (2008) Biodegradation of polycyclic aromatic hydrocarbons by white rot fungi *Phanerochaete chrysosporium* in sterile and unsterile soil. JSIR 67:538–542

Brito EMS, Guyoneaud R, Goñi-Urriza M, Ranchou-Peyruse A, Verbaere A, Crapez MA, Duran R (2006) Characterization of hydrocarbonoclastic bacterial communities from mangrove sediments in Guanabara Bay, Brazil. Res Microbiol 157(8):752–762

Cappuccino J, Sherman GN (2002) Microbiology: laboratory manual, 7th edn. Benjamin Cummings, San Francisco

Cerniglia CE, Gibson DT, Van Baalen C (1980) Metabolism of naphthalene by the cyanobacterium, *Oscillatoria* sp., strain JCM. J Gen Microbiol 116(2):495–500

Chaillan F, Le Flèche A, Bury E, Phantavong YH, Grimont P, Saliot A, Oudot J (2004) Identification and biodegradation potential of tropical aerobic hydrocarbon-degrading microorganisms. Res Microbiol 155(7):587–595

Costa AS, Romão L, Araújo B, Lucas S, Maciel S, Wisniewski A, Alexandre MDR (2012) Environmental strategies to remove volatile aromatic fractions (BTEX) from petroleum industry wastewater using biomass. Bioresour Technol 105:31–39

Coulon F, McKew BA, Osborn AM, McGenity TJ, Timmis KN (2006) Effects of temperature and biostimulation on oil-degrading microbial communities in temperate estuarine waters. Environ Microbiol 9:177–186

Das N, Chandran P (2011) Microbial degradation of petroleum hydrocarbon contaminants: an overview. Biotechnol Res Int 2011:1–13

Deimer VR, Alexander PC, Yorly OG (2018) Biodegradation activity of crude oil by *Chlorella* sp. under mixotrophic conditions. Indian J Sci Technol 11(29):1–8

Duran R, Cravo LC (2016) Role of environmental factors and microorganisms in determining the fate of polycyclic aromatic hydrocarbons in the marine environment. FEMS Microbiol Rev 40 (6):814–830

El-Sheekh MM, Hamouda RA, Nizam AA (2013) Biodegradation of crude oil by *Scenedesmus obliquus* and *Chlorella vulgaris* growing under heterotrophic conditions. Int Biodeterior Biodegradation 82:67–72

Essien JP, Udosen ED (2000) Distribution of actinomycetes in oil-contaminated ultisols of the Niger Delta (Nigeria). J Environ Sci 12:296–302

Ezeji U, Anyadoh SO, Ibekwe VI (2007) Cleanup of crude oil-contaminated soil. Terr Aquat Environ Toxicol 1(2):54–59

Facundo JMR, Vanessa HR, Teressa ML (2001) Biodegradation of waste lubricating oil in soil by microbial consortium. Water Air Soil Pollut 128:313–320

Farag S, Soliman NA (2011) Biodegradation of crude petroleum oil and environmental pollutants by Candida tropicalis strain. Braz Arch Biol Technol 54(4):821–830

Floodgate GD (1995) Some environmental aspects of marine hydrocarbon bacteriology. Aquat Microb Ecol 9:3–11

George M, Chandraja CV, Immanuel G, Chandran RP (2011) Petroleum-degrading activity of *Actinomycetes* isolated from the coastal areas of Tamil Nadu. IJAEB 4(1):59–65

Grangemard IJ, Wallach R, Marget-Dana F, Peypous (2001) Lichenysin. Appl Biochem Biotechnol 90:199

Hanafy EL, Anwar Y, Sabir JS, Mohamed SA, Garni SM, Ahmed MM (2017) Characterization of native fungi responsible for degrading crude oil from the coastal area of Yanbu, Saudi Arabia. Biotechnol Rep 31:105–111

Hasanuzzaman M, Ueno A, Ito H, Ito Y, Yamamoto Y, Yumoto I, Okuyama H (2007) Degradation of long-chain n-alkanes (C 36 and C 40) by *Pseudomonas aeruginosa* strain WatG. Int Biodeterior Biodegradation 59(1):40–43

He N, Sun X, Zhong Y, Sun K, Liu W, Duan S (2016) Removal and biodegradation of nonylphenol by four freshwater microalgae. Int J Environ Res Public Health 13(12):1239

Jewetz E, Melnick JL, Adelberg EA, Brooks GF, Buttel SJ, Ornston LN (eds) (1999) Review of medical microbiology, 19th edn. Appleton and Langue Publishing, Prentice Hall, CA, pp 224–229

Jawhari IFH (2014) Ability of some soil fungi in biodegradation of petroleum hydrocarbon. J Appl Environ Microbiol 2(2):46–52

Jones DM, Watson JS, Meredith W, Chen M, Bennett B (2001) Determination of naphthenic acids in crude oils using nonaqueous ion exchange solid-phase extraction. Anal Chem 73(3):703–707
Jones DM, Head IM, Gray ND, Adams JJ, Rowan AK, Aitken CM, Bennett B, Huang H, Brown A, Bowler BFJ, Oldenburg T, Erdmann M, Larter SR (2008) Crude oil biodegradation via methanogenesis in subsurface petroleum reservoirs. Nature 451:176–180
Joshi PA, Pandey GB (2011) Screening of petroleum-degrading bacteria from cow dung. Res J Agric Sci 2(1):69–71
Juhasz AL, Naidu R (2000) Bioremediation of high molecular weight polycyclic aromatic hydrocarbons: a review of the microbial degradation of benzo [a] pyrene. Int Biodeterior Biodegradation 45(1-2):57–88
Karigar CS, Rao SS (2011) Role of microbial enzymes in the bioremediation of pollutants: a review. Enzyme Res 2011:1–11
Kong Q, Zhu L, Shen X (2010) The toxicity of naphthalene to marine *Chlorella vulgaris* under different nutrient conditions. J Hazard Mater 178(1–3):282–286
Kristanti RA, Hadibarata T, Toyama T, Tanaka Y, Mori K (2011) Bioremediation of crude oil by white rot fungi *Polyporus* sp. S133. J Microbiol Biotechnol 21(9):995–1000
Kvenvolden KA, Cooper CK (2003) Natural seepage of crude oil into the marine environment. Geomarine Lett 23(3–4):140–146
Leahy JG, Colwell RR (1990) Microbial degradation of hydrocarbons in the environment. Microbiol Rev 54:305–315
Lee K, Boufadel M, Chen B, Foght J, Hodson P, Swanson S, Venosa A (2015) Expert panel report on the behaviour and environmental impacts of crude oil released into aqueous environments. Royal Society of Canada, Ottawa
Li X, Li H, Qu C (2019) A review of the mechanism of microbial degradation of petroleum pollution. IOP Conf Ser Mater Sci Eng 484:012060
Liu GH, Tong ZK, Zhang YH (2013) Biotreatment of heavy oil wastewater by combined upflow anaerobic sludge blanket and immobilized biological aerated filter in a pilot-scale test. Biochem Eng J 72:48–53
Lloyd AC, Cackette TA (2001) Diesel engines: environmental impact and control. J Air Waste Manage Assoc 51(6):809–847
Lohitesh K, Behera AK, Alexander AA, Suneetha V (2013) Detection and removal of hydrogen sulphide gas from food sewage water collected from Vellore. Der Pharm Lett 5(3):163–169
Mishra S, Jyot J, Kuhad RC, Lal B (2001) Evaluation of inoculum addition to stimulate in situ bioremediation of oily-sludge-contaminated soil. Appl Environ Microbiol 67:1675–1671
Mittal A, Singh P (2009) Studies on biodegradation of crude oil by *Aspergillus niger*. South Pac J Nat Sci 27(1):27–60
Nwachukwu SC (2000) Enhanced rehabilitation of tropical aquatic environment polluted with crude petroleum using *Candida utilis*. J Environ Biol 21(3):241–250
Obire O, Ayanwu EC (2009) Impact of various concentrations of crude oil on fungal populations of soil. Int J Environ Sci Technol 6:211–218
Ojo OA (2005) Petroleum–hydrocarbon utilization by nature bacterial population from a waste water canal in Southwest Nigeria. Afr J Biotechnol 5(4):333–337
Okafor UG, Tasie F, Muotoe-Okafor F (2009) Hydrocarbon degradation potentials of indigenous fungal isolates from petroleum contaminated soils. J Phys Nat Sci 3:1–6
Okoh AI, Trejo-Hernandez MR (2006) Remediation of petroleum hydrocarbon polluted systems: exploiting the bioremediation strategies. Afr J Biotechnol 5:2520–2525
Ordinioha B, Brisibe S (2013) The human health implications of crude oil spills in the Niger delta, Nigeria: an interpretation of published studies. Niger Med J 54:10–16
Quatrini P, Scaglione G, De Pasquale C, Reila S, Puglia AM (2008) Isolation of gram-positive *n*-alkane degraders from a hydrocarbon contaminated Mediterranean shoreline. J Appl Microbiol 104:251–259
Rahman K, Thahira J, Lakshmanaperumalsamy P, Banat I (2002) Towards efficient crude oil degradation by a mixed bacterial consortium. Bioresour Technol 85(3):257–261

Rahman K, Rahman TJ, Kourkoutas Y, Petsas I, Marchant R, Banat I (2003) Enhanced bioremediation of *n*-alkane in petroleum sludge using bacterial consortium amended with rhamnolipid and micronutrients. Bioresour Technol 90(2):159–168

Ramasamy S, Mathiyalagan P, Chandran P (2014) Characterization and optimization of EPS-producing and diesel oil-degrading *Ochrobactrum anthropi* MP3 isolated from refinery wastewater. Pet Sci 11(3):439–445

Rath K, Mishra B, Vuppu S (2012) Biodegrading ability of organo-sulphur compound of a newly isolated microbe *Bacillus* sp. KS1 from the oil contaminated soil. Arch Appl Sci Res 4 (1):465–471

Reyes Y, Vergara I, Torres OE, Díaz M, González EE (2016) Contaminación por metales pesados: implicaciones en salud, ambiente y seguridad alimentaria. Revista Ingeniería Investigación y Desarrollo 16(2):66–77

Rifaat HM, Yosery MA (2004) Identification and characterization of rubber degrading actinobacteria. Appl Ecol Environ Res 2(1):63–70

Ron EZ, Rosenberg E (2002) Biosurfactants and oil bioremediation. Curr Opin Biotechnol 13 (3):249–252

Ron EZ, Rosenberg E (2014) Enhanced bioremediation of oil spills in the sea. Curr Opin Biotechnol 27:191–194

Rosenberg E, Navon-Venezia S, Zilber-Rosenberg I, Ron EZ (1998) Rate-limiting steps in the microbial degradation of petroleum hydrocarbons. In: Soil and aquifer pollution. Springer, Berlin, pp 159–172

Sammarco PW, Kolian SR, Warby RAF, Bouldin JL, Subra WA, Porter SA (2013) Distribution and concentrations of petroleum hydrocarbons associated with the BP/Deepwater Horizon oil spill, Gulf of Mexico. Mar Pollut Bull 73(1):129–143

Sandhu SS, Shakya M, Deshmukh L, Aharwal RP, Kumar S (2016) Determination of hydrocarbon degrading potentiality of indigenous fungal isolates. Int J Environ Sci 6(6):1163–1172

Shankar SS, Suneetha V (2013) Analysis of soil fertilizing capabilities, growth and enzyme production statistics for symbiotic nitrogen fixing bacteria VIT SS5 screened from Palar Region, Vellore. Int J Pharm Biol Sci 4(2):B795–B802

Sharma B, Kumar A, Shukla P (2018) Contemporary enzyme-based technologies for bioremediation: a review. J Environ Manag 210:10–22

Snape I, Riddle MJ, Stark JS, Cole CM, King CK, Duquesne S, Gore DB (2001) Management and remediation of contaminated sites at Casey Station, Antarctica. Polar Rec 37(202):199–214

Srivastav AK, Agarwal P, Kaushik JT, Suneetha V (2013) Water quality analysis of agricultural water from the villages of Vellore district. Der Pharm Lett 5(3):481–491

Steliga T (2012) Role of fungi in biodegradation of petroleum hydrocarbons in drill waste. Pol J Environ Stud 21(2):471–479

Tanti B, Buragohain AK, Dutta S, Gurung L, Shastry M, Borah SP (2009) Studies on the cytotoxic effect of oil refinery sludge on root meristem. Adv Environ Biol 3:10–14

Throne-Holst M, Wentzel A, Ellingsen TE, Kotlar HK, Zotchev SB (2007) Identification of novel genes involved in long-chain *n*-alkane degradation by *Acinetobacter* sp. strain DSM 17874. Appl Environ Microbiol 73(10):3327–3332

Umar H, Umar A, Ujah UJ, Hauwa B, Sumayya BI, Shuaibu M, Yakubu MS (2013) Biodegradation of waste lubricating oil by bacteria isolated from the soil. J Environ Sci Toxicol Food Technol 2013:32–37

Varjani SJ, Upasani VN (2016) A carbon spectrum utilization by an indigenous strain of *Pseudomonas aeruginosa* NCIM 5514: production, characterization and surface active properties of biosurfactant. Bioresour Technol 221:510–516

Venkata Gopichand T, Saranya C, Suneetha V, Ramalingam C (2013) Decolorization of azo dyes from Ranipet textile industrial spent wash using Bacillus VIT SSG5. Res J Pharm Biol Chem Sci 4(2):358–368

Vidali M (2001) Bioremediation. An overview. Pure Appl Chem 73:1163–1172

Vidyashankar S, Ravishankar GA (2016) Algae-based bioremediation: bioproducts and biofuels for biobusiness. In: Bioremediation and bioeconomy. Elsevier, Amsterdam, pp 457–493

Walker JD, Colwell RR, Vaituzis Z, Meyer SA (1975) Petroleum degrading achlorophyllous alga *Prototheca zopfii*. Nature 254(5499):423–424

Wang Z, Fingas M, Blenkinsopp S, Sergy G, Landriault M, Sigouin L, Westlake DWS (1998) Comparison of oil composition changes due to biodegradation and physical weathering in different oils. J Chromatogr A 809(1–2):89–107

Watanabe K, Fumata H, Harayama S (2002) Understanding the diversity in catabolic potential of microorganisms for the development of biodegradation strategies. Anton van Leeuwenhoek 81:655–663

Xaaldi A, Movafeghi A, Mohammadi-Nassab AD, Abedi E, Bahrami A (2017) Potential of the green alga *Chlorella vulgaris* for biodegradation of crude oil hydrocarbons. Mar Pollut Bull 123 (1–2):286–290

Yakimov MM, Timmis KN, Golyshin PN (2007) Curr Opin Biotechnol 18(3):257–266

Zhang Z, Hou Z, Yang C, Ma C, Tao F, Xu P (2011) Degradation of *n*-alkanes and polycyclic aromatic hydrocarbons in petroleum by a newly isolated *Pseudomonas aeruginosa* DQ8. Bioresour Technol 102(5):4111–4116

Zhang X, Wang Z, Liu X, Hu X, Liang X, Hu Y (2013) Degradation of diesel pollutants in Huangpu-Yangtze River estuary wetland using plant–microbe systems. Int Biodeterior Biodegradation 76:71–75

Zhang M, Liu GH, Song K, Wang Z, Zhao Q, Li S, Le Z (2015) Biological treatment of 2,4,6-trinitrotoluene (TNT) red water by immobilized anaerobic–aerobic microbial filters. Chem Eng J 259:876–884