Innovations in Agricultural & Biological Engineering

Bioremediation and Phytoremediation Technologies in Sustainable Soil Management

Volume 1

Fundamental Aspects and Contaminated Sites

Editors

Junaid Ahmad Malik | Megh R. Goyal

Khursheed Ahmad Wani

CRC Press
Taylor & Francis Group

APPLE ACADEMIC PRESS

BIOREMEDIATION AND PHYTOREMEDIATION TECHNOLOGIES IN SUSTAINABLE SOIL MANAGEMENT

Volume 1

Fundamental Aspects and Contaminated Sites

Bioremediation and Phytoremediation Technologies in Sustainable Soil Management, 4 volume set:
ISBN: 978-1-77463-720-3 (hbk)
ISBN: 978-1-77491-100-6 (pbk)
ISBN: 978-1-00328-133-7 (ebk)

Volume 1: Fundamental Aspects and Contaminated Sites
ISBN: 978-1-77463-718-0 (hbk)
ISBN: 978-1-77463-958-0 (pbk)
ISBN: 978-1-00328-065-1 (ebk)

Volume 2: Microbial Approaches and Recent Trends
ISBN: 978-1-77463-719-7 (hbk)
ISBN: 978-1-77463-892-7 (pbk)
ISBN: 978-1-00328-068-2 (ebk)

Volume 3: Inventive Techniques, Research Methods, and Case Studies
ISBN: 978-1-77463-987-0 (hbk)
ISBN: 978-1-77463-988-7 (pbk)
ISBN: 978-1-00328-117-7 (ebk)

Volume 4: Degradation of Pesticides and Polychlorinated Biphenyls
ISBN: 978-1-77491-038-2 (hbk)
ISBN: 978-1-77491-039-9 (pbk)
ISBN: 978-1-00328-120-7 (ebk)

Innovations in Agricultural and Biological Engineering

BIOREMEDIATION AND PHYTOREMEDIATION TECHNOLOGIES IN SUSTAINABLE SOIL MANAGEMENT

Volume 1

Fundamental Aspects and Contaminated Sites

Edited by

Junaid Ahmad Malik, PhD

Megh R. Goyal, PhD, PE

Khursheed Ahmad Wani, PhD

AAP APPLE ACADEMIC PRESS

First edition published 2023

Apple Academic Press Inc.
1265 Goldenrod Circle, NE,
Palm Bay, FL 32905 USA

4164 Lakeshore Road, Burlington,
ON, L7L 1A4 Canada

CRC Press
6000 Broken Sound Parkway NW,
Suite 300, Boca Raton, FL 33487-2742 USA

2 Park Square, Milton Park,
Abingdon, Oxon, OX14 4RN UK

Library and Archives Canada Cataloguing in Publication

Title: Bioremediation and phytoremediation technologies in sustainable soil management / edited by Junaid Ahmad Malik, PhD, Megh R. Goyal, PhD, PE, Khursheed Ahmad Wani, PhD.
Names: Malik, Junaid Ahmad, 1987- editor. | Goyal, Megh R., editor. | Wani, Khursheed Ahmad, editor.
Series: Innovations in agricultural and biological engineering.
Description: First edition. | Series statement: Innovations in agricultural and biological engineering | Includes bibliographical references and indexes. | Content: Volume 1: Fundamental Aspects and Contaminated Sites.
Identifiers: Canadiana (print) 20220155194 | Canadiana (ebook) 20220155224 | ISBN 9781774637180 (v. 1 ; hardcover) | ISBN 9781774639580 (v. 1 ; softcover) | ISBN 9781003280651 (v. 1 ; ebook)
Subjects: LCSH: Soil remediation. | LCSH: Phytoremediation. | LCSH: Bioremediation.
Classification: LCC TD878.48 .B56 2022 | DDC 628.5/5—dc23

Library of Congress Cataloging-in-Publication Data

CIP data on file with US Library of Congress

ISBN: 978-1-77463-718-0 (hbk)
ISBN: 978-1-77463-958-0 (pbk)
ISBN: 978-1-00328-065-1 (ebk)

CONTENTS

CHAPTER 9

BIOREMEDIATION OF PETROLEUM CONTAMINATED SOILS

VIKRANT B. BERDE, PALLAVAL V. BRAMHACHARI, and
CHANDA PARULEKAR BERDE

ABSTRACT

Petroleum is an important non-renewable energy source used for various purposes like transportation and in industries. Sometimes accidently or due to human interference, it can contaminate the soil. Cleaning of these polluted soils with mechanical or physicochemical treatments could be very expensive or difficult task. Bioremediation of these petroleum affected soils is an eco-friendly, economic, and efficient option. This chapter focuses on the use of bioremediation in treatment of petroleum-contaminated soils.

9.1 INTRODUCTION

Contamination of environment with petroleum hydrocarbons (PHs) occurs on account of accidental spillage, human activities, during refining and processing, transportation, leakage from pipelines and storage tankers and oil-well waxing and overhauling of refineries [20, 115, 120]. Soil is thus affected by petroleum components like hydrocarbons.

Petroleum contaminated soil affects the environment and is hazardous to human health. Treatment of the polluted soil can be done by physical, chemical, and biological methods. The microbiological method is being preferred, because it is efficient, economical, eco-friendly, and adaptable substitute to physicochemical procedures [42]. The indigenous flora of the soil being exposed to the hydrocarbons become adapted to the pollutants. These microorganisms synthesize enzymes for the degradation of the hydrocarbons, for utilizing these compounds for their carbon and energy requirements. Such organisms are useful in the removal of contaminants [59, 62, 84]. Improvements in the bacterial remediation technology have provided solutions for the removal of petroleum pollution from the environments [31, 32].

Bioremediation using bacteria cultures with hydrocarbon-degrading ability is a widely accepted technology. Many bacterial species have been characterized, studied, and applied in bioremediation of soil contaminated with hydrocarbons. However, numerous complications reducing the rate of biodeterioration have been encountered while practically applying the methods.

The present chapter is an overview of bioremediation techniques using various microorganisms in the treatment of petroleum contaminated soils. It describes major environmental issues created due to the petroleum industry and human use of petroleum in day-to-day life. It also highlights the role played by the microorganisms in the rejuvenation of the contaminated sites with suitable examples.

9.2 HAZARDOUS EFFECTS OF PETROLEUM POLLUTION ON ENVIRONMENT

harmful effects of petroleum pollution on the environment are well known [20, 92]. It affects not only humans but also animals as well as the microorganisms [30, 63, 71, 81] disturbing the ecosystems. Petroleum contaminated soil is hazardous to human health [35]. The contaminants from the soil leach out and enter the water bodies, and may even contaminate the water table, thus increasing the risk further. Petroleum contaminated soil has lower crop productivity due to the pollution [114].

Research studies have confirmed that there is a reduction in species richness and phylogenetic diversity of the affected areas following exposure to PHs due to the inhibitory effect of hydrocarbons and their metabolic intermediates, on the microflora [18, 19, 47, 56, 104]. The microorganisms that can tolerate and degrade the hydrocarbons survive in the conditions and are the dominant community in the polluted environments.

9.3 BIOREMEDIATION

Petroleum hydrocarbon pollutants can be removed by physical and chemical methods, which however are either expensive or not effective. Microbial bioremediation is the most promising solution to the total removal of petroleum pollution from any environment [1, 20, 46, 107]. Petroleum degrading microorganisms have enzymes for the breakdown of the complex petroleum components. PHs consist of four classes: the saturates, the aromatics, the asphaltenes and the resins [23]. Thus, hydrocarbon degradation is influenced by the nature of pollutant and its concentration. The more complex the nature of the contaminants, the more difficult and time-consuming is the bioremediation process [65], even though it is less costly as compared to other methods of remediation.

Bioremediation methodologies are largely classified as *in situ* (done at the site) or *ex-situ* (done at somewhere else) [3]. Organic pollutants are degraded to end-products carbon dioxide (CO_2) and water at the site of pollution. This method is called *in situ*, and it is less costly and eco-friendly, as compared to the *ex-situ* bioremediation technique that requires to excavate the contaminated samples and get them to the treatment site, which increases the cost.

Bioremediation process can be carried out using stimulating the growth of indigenous hydrocarbon-degrading bacteria or by adding grown cultures, i.e., by biostimulation or bioaugmentation. Thus, the degraders having the metabolic abilities to utilize the hydrocarbons survive, while the remaining microflora that is sensitive is inhibited. However, there is a need to pay more attention to the research that will add up efficient oil degraders and also standardization of methods for efficient and quick clean-up strategies.

9.4 ENVIRONMENTAL COMPONENTS REQUIRED FOR BIOREMEDIATION

9.4.1 ABIOTIC COMPONENTS

Bioremediation involves various mechanisms of degradation, eradication, immobilization, or detoxification of chemicals and hazardous materials that can pollute the environment. Bioremediation technology makes use of microbial cultures to get rid of toxic contaminants to harmless products (mainly CO_2, water, and other inorganic compounds) [73]. It is thus the application of microorganisms that degrade and transform the pollutants including hydrocarbons, oil, heavy metal (HM), pesticides, dyes, etc.

The rate of biodegradation depends on biotic and abiotic factors, such as pollutant concentration, nature of the pollutant, environmental conditions, physicochemical parameters, etc. [33]. Biodegradation reactions are highly influenced by temperature, nutrients, electron acceptors, and the pollutants, which play a key role in hydrocarbon bioremediation [108]. Hence, the results obtained in the laboratory and under field conditions will vary [45]. The bioremediation process also requires the availability of the substrate that the bacteria can degrade [90]. The rate at which the degradation of the hydrocarbons occur follows the order as linear [8, 58]:

alkanes > branched alkanes > low-molecular-weight alkyl aromatics > monoaromatics > cyclic alkanes > polyaromatics (such as asphaltenes)

The polycyclic aromatic compounds are degraded incompletely [6]. They are broken down into intermediate compounds; and for the complete degradation, more than one microorganism is involved. Other factors, such as soil type, presence of other contaminants, type, and amount of organic matter present, also play an important role in determining the bioremediation rate [12, 89].

Physical factors, such as, temperature affect the bioremediation process as the bacterial strains involved are temperature sensitive and also affect the hydrocarbons [2, 60, 119]. It was observed that PHs were degraded efficiently under laboratory conditions, whereas the same effects were not observed *in situ*. This was attributed to the on-site temperature variations, which could not be controlled [82, 83]. At low temperatures, petroleum products persist for a longer period. Low temperatures reduce the solubility, increase the viscosity of hydrocarbons, and delay the onset of degradation, and vice versa for elevated temperature. The increased degradation rate of hydrocarbons ensues at 30–40°C [4, 7, 11, 24, 38, 70]. However, at higher temperatures, again degradation rate is lowered as the elevated temperature will inhibit microbial growth [99].

Bacterial growth in the soil depends on nutrient availability, which includes nitrogen, phosphorus, carbon, hydrogen, etc. [21, 39]. Hydrocarbons are utilized by bacterial strains as carbon and energy sources. However, if other nutrients are deficient, the growth of the degraders is hampered, and consequently the degradation process is also affected. The addition of fertilizers is used as a stimulatory method in the bioremediation process [44, 69, 83, 84]. The use of hydrocarbon-degrading bacteria having the ability to fix nitrogen replaces the need for fertilizer supplementation [100].

The onset of hydrocarbon degradation is by incorporation of oxygen in the aromatic ring with the help of oxygenases. A step-by-step degradation process follows, whereby the enzymes act on the compound aerobically.

Thus, the presence of oxygen is the key requirement for the onset and rapid degradation of hydrocarbons [39]. In a study carried out under controlled aeration, 75% degradation was observed [41]. Aerated degradation processes however increase the cost associated with the process. Alternatively, methods to increase the soil permeability (such as the addition of a bulking agent) may be used. Another option is degradation under anaerobic conditions, which is less expensive as compared to the aerobic bioremediation method [15, 125].

9.4.2 BIOLOGICAL COMPONENTS: MICROORGANISMS AND THEIR ROLE IN BIOREMEDIATION

Bioremediation of petroleum hydrocarbon pollutants is an ecofriendly, less costly, and effective biological treatment. The microorganisms found in mesophilic conditions cannot function properly in harsh conditions and show reduced metabolism and hence can lower degradation abilities. Removal of pollutants from environments under extreme conditions is dependent on the microorganisms present in that niche, i.e., the extremophiles belonging to the archaea group, and they can grow in conditions unfavorable to eubacteria. Therefore, for the bioremediation of contaminated soils (such as estuarine mudflats, etc.), the focus is on members of archaea. *In situ* bioremediation can make use of a single or combination of microorganisms (i.e., consortia) [29]. This ensures complete breakdown of the pollutant.

9.4.2.1 BACTERIA

The primary degraders of petroleum during oil spills are bacteria [14, 78]. These bacterial cultures can utilize hydrocarbons as the carbon source [121], for metabolism and growth. There is an increase in their numbers as the breakdown occurs. Once the hydrocarbons are removed, the microbial count reduces with a simultaneous reduction in the physiological stress on the environment [43, 53, 124].

Several factors decide the fate of the contaminant in the environment and the degrader type and abundance will also depend on the type of petroleum product, degradation pathways/enzymes present in the organisms, physico-chemical parameters, etc. [40, 110].

The oil-degrading bacteria found in the ocean waters and sediments are subject to temperature and salinity variations. The oil-degrading organisms isolated are mostly from the domain bacteria [17] and few groups of

Archaea belonging to Marine Group II Archaea (namely: Euryarchaeota and Thaumarchaeota) [79]. Unculturable archaeal members were identified in marine sediments belonging to strains of Euryarchaeota [28, 48, 51].

These findings suggest that unculturable Archaea includes the haloarchaea and Methanogens, which are involved in the removal of oil contamination in most of the marine environments [126]. There are reports of an increase in the haloarchaeal species such as *Haloferax*, on the addition of oil droplets and nitrate [16, 116, 123].

According to Tremblay et al. [103], 79 genera having the hydrocarbon utilizing potential, have been studied, which includes [49, 62, 68, 87, 109, 111, 119]:

- *Achromobacter;*
- *Acinetobacter;*
- *Alkanindiges;*
- *Alteromonas;*
- *Arthrobacter;*
- *Burkholderia;*
- *Dietzia;*
- *Enterobacter;*
- *Kocuria;*
- *Marinobacter;*
- *Mycobacterium;*
- *Pandoraea;*
- *Pseudomonas;*
- *Rhodococcus;*
- *Staphylococcus;*
- *Streptobacillus;*
- *Streptococcus*.

Some investigators have reported the efficient bioremediation by consortia of cultures, such as OHCB (obligate hydrocarbon clastic bacteria). The bacterial members included in the consortia were: *Alkanindiges* sp., *Alcanivorax, Marinobacter, Thallassolituus, Cycloclasticus, Oleispira* [40, 121]. These reports also stated that almost negligible number of bacterial species were present during pre-exposure and their abundance was increased post-exposure in the presence of contaminants. A particular strain cannot use all the petroleum products or cannot breakdown the contaminants completely.

Wang et al. [118] studied the bacterial strain *Dietzia* sp. DQ12-45-1b that consumes n-alkanes (C6–C40) and related compounds utilizing them as the sole sources of carbon. Similarly, *Acinetobacter* sp. could metabolize n-alkanes having chain length C10–C40 [102]; while Ma et al. [61] reported *Achromobacter xylosoxidans* DN002 that could utilize a number of mono- and polyaromatic hydrocarbons efficiently. Some more bacterial genera, namely, *Gordonia*, *Brevibacterium*, *Aeromicrobium, Dietzia*, *Burkholderia,* and *Mycobacterium, Sphingomonas*, have also been reported with petroleum bioremediation activities [11, 26, 37].

Varjani et al. [113] worked with a consortium of halotolerant bacteria, named HUBC, which included *Ochrobactrum* sp., *Stenotrophomonas maltophilia*, and *Pseudomonas aeruginosa,* having very good degradation rates and similar work was reported by Tao et al. [98]; and Wang et al. [115]. These reports demonstrated that in the consortium, the bacterial strains had crude oil bioremediating potential in marine ecosystems. Szulc et al. [97] reported a hydrocarbon-degrading efficiency of 89% by consortia of bacterial cultures that included *Aeromonas hydrophila, Alcaligenes xylosoxidans, Gordonia* sp.*, Pseudomonas putida, Pseudomonas fluorescens, Rhodococcus equi, S. maltophilia,* and *Xanthomonas* sp.

Therefore, bioremediation of petroleum waste can be improved by the application of consortia of bacteria having the ability to degrade these compounds and as a result, can degrade the pollutants completely.

9.4.2.2 FUNGI

Fungal cultures with petroleum bioremediation abilities are said to be better bioremediation agents as compared to bacteria [10, 11, 37, 101]. The fungal hyphae provide an advantage of penetration into the soil contaminated with hydrocarbons, thus reaching the deeper layers of soil. Fungal cultures can adapt to different variations in the environments and have mechanisms to cope with the hydrocarbon contaminants in the environment and bring about its degradation.

Fungal cultures (such as *Amorphoteca*, *Graphium, Neosartorya*, *Talaromyces, Candida, Yarrowia, and Pichia* sp.) were found to have hydrocarbon-degrading ability [19]. In another report, terrestrial fungi *Aspergillus*, *Cephalosporium,* and *Penicillium* were isolated and found to utilize crude oil efficiently [93].

Some yeast species for their petroleum degradation ability are: *Geotrichum* sp.*, Candida lipolytica, Trichosporon mucoides* and *Rhodotorula mucilaginosa* that were isolated from contaminated waters [13]. Barnes et al. [10] has described studies on 10 fungal isolates that could degrade the crude oil. They were isolated from sediments from mangroves, the Arabian Sea and from tarballs. The fungal isolates were identified as *Aspergillus, Fusarium Penicillium*, and *Acremonium* species using its rDNA (recombinant deoxyribonucleic acid) sequencing.

Ezekoye et al. [36] have described the studies on petroleum hydrocarbon bioremediation using the fungal cultures, such as *Aspergillus fumigates*, *Aspergillus terrens*, *Aspergillus niger*, *Aspergillus nidulans*, *Aspergillus versicolor*, *Acremonium* sp., *Bipolaris* sp., *Candida tropicalis*, *Candida globrata*, *Cladosporium* sp., *Cladophialophora carrionii*, *Geotrichum candidum*, *Gliocladium* sp., *Phoma* sp., *Paecilomyces variotii*, *Scopulariopsis brevicaulis*, *Sepedonium* sp., *Trichophyton tonsurans*, *Trichophyton terrestre* and *Rhodotorula* sp. Additional reports describe the hydrocarbon degradation ability and their applications in bioremediation [22, 66, 75, 86, 122]. These isolates, along with bacterial cultures with good bioremediation efficiency can be utilized together for the clean-up of oil spills and other environmental contaminants, such as tarballs. Oil-Zapper is one such application used in the environmental cleanup (TERI, India).

Therefore, there is a need to conduct in depth study of the bioremediation process of both bacteria and fungi, the enzymes involved, efficiencies of different consortia, etc., to optimize the *in-situ* bioremediation of petroleum pollutants.

9.4.2.3 GENETICALLY MODIFIED ORGANISMS

As compared to natural isolates, the genetically engineered microorganisms (GEMs) have a higher capacity of environment cleanup. There are several reports on the biodegradation of pollutants by GEM according to Das and Chandran [25]. The GEMs include mostly strains of *Pseudomonas* species [34, 72, 95].

The GEMs have applications in monitoring the bioremediation process, monitoring the response of stress on the strains, toxicity analysis, etc. [25]. For process monitoring in PCB contaminated soils, *A. eutrophus* H850Lr is used [105]. Other strains used in process monitoring are: *P. putida* TVA8 and *P. fluorescens* HK44 for TCE, BTEX, and naphthalene, anthracene degradation, respectively [5, 88].

B. cepacia BRI6001L was used for the strain monitoring for 2,4-D degradation [64]. There is a report on the use of GEM strain *P. fluorescens* 10586s/pUCD607 to study response to stress during BTEX degradation

[94]. During the degradation of 2,4-dinitrophenol hydroquinone, Kelly et al. [52] has reported the application of the P*seudomonas* strain Shk1 for the toxicity assessment studies. Layton et al. [57] described the application of *A. eutrophus* 2050 for endpoint analysis during the degradation of non-polar narcotics.

The only constraints involved are the environmental concerns and regulatory obligations. Before the application of the GEMs, a thorough study is needed on: the ecological consequences of the release of these strains, the biochemical pathways and enzymes involved, and the possibilities of strain reversion, etc.

9.5 PROS AND CONS OF BIOREMEDIATION FOR PETROLEUM CONTAMINATED SOILS

Most importantly, bioremediation is known for being safe to the environment and less costly [9, 74, 77]. It may be carried out in two ways: bioaugmentation (seeding, inoculation) and biostimulation [106], wherein either there is the addition of petroleum degraders to the site or the growth of indigenous flora is encouraged by supplementing with nutrients (mostly fertilizers) [21, 91, 112].

Degradation by indigenous microflora increases the microbial count during degradation. The pollutant is utilized by the microbes for their growth. Once the compound is degraded, their number start declining. CO_2 and water are the non-toxic end-products of the degradative process. Thus, the contaminants are removed completely, and not simply transferred to different environmental sites [91]. Bioremediation of pollutants by microorganisms is an eco-friendly natural way of treating the contaminants, and it is sustainable as the microbial cultures involved in the process remain in the site and can act on waste if added to the site again [27]. The sites can be used continuously. Hence the methods are non-intrusive, and there is ease of implementation [55].

The bioremediation process can be carried out *in situ*, and hence the efforts of carrying the contaminated soil can be avoided, and no transport charges are involved [67]. Physicochemical methods of bioremediation of petroleum contaminated soils are available [54, 117], but they are costly. These methods also lead to the generation of other waste and hence are not eco-friendly [85]. Successful examples are the disposal of contaminants by incineration, which leads to the production of toxic gases. More complications go with the combustion of petroleum contaminants.

Although it is known that biodegradation also leads to CO_2 formation, yet the quantity produced is negligible. Some workers have reported the ill-effects of landfilling with such contaminants [50, 80]. Over time, the contaminants leach out causing further harm to the water table [76, 96].

The bioremediation process has its drawbacks also. Firstly, it can be carried out for those compounds that can be broken down by microorganisms. Some compounds may not be completely degraded and the intermediates thus formed may be more toxic than the compound itself. These are called recalcitrant compounds. Sometimes 2 or more compounds may be involved in the degradation of a particular contaminant. Through *in-situ*, the situation is very different from laboratory conditions. The concentration of the contaminants is not known, the physicochemical parameters cannot be controlled, other biotic factors are involved, the contaminated site may have more than one compounds present, and also the state in which they are present, i.e., solids, liquids, and gases. Thus, the degree of success cannot be judged.

Application method and environmental conditions also matter such as in summer the temperature will be high while in monsoon, there are chances of wash off. The biggest drawback is the time factor, as these methods are very time-consuming. Being natural and dependent on the microbial activity, the degradation processes take long. The cultures to be used in the bioremediation process need to be cultured on a large scale, and hence there is a requirement to follow all set SOPs (standard operating procedure) for culture growth and application methods, along with the requirement of skilled labor [55].

9.6 ECOLOGICAL AND ECONOMIC IMPORTANCE OF BIOREMEDIATION

Using the endogenous microflora of the contaminated site by the biostimulation method of bioremediation, it does not affect the biotic components of the environment. After removal of the contaminant, the number of microflora start reducing and survive on the nutrients available. This is thus a natural process with no formation of harmful components or no side effects. As it is carried out on-site, the cost and dangers of transportation can be avoided. A lot of expenses are reduced due to the almost nil energy requirements, minimal equipment or instrumentation involved, and also low maintenance. Hence, bioremediation is economically feasible. Bioremediation has a higher acceptance from regulatory authorities as well as the public.

9.7 COMMERCIAL APPLICATIONS OF BIOREMEDIATION

Bioremediation can be used in several sites, where there is spillage of petroleum or its related products. It can be used in petroleum stations, where the spillage problem is well known. Another application is at the industrial sites and the sites used for landfills. Petroleum and petroleum-related compounds enter the environments through these portals. The products may leach out from the landfills and contaminate the water bodies. Thus, the bioremediation of these sites is necessary. Oils spills occurring at the sea, ports, oil rigs can affect marine life.

The removal of the spills requires the use of bioremediation. The successful implementation of bioremediation for the revival of hydrocarbon contaminated environments is the need of the day. Further, bioremediation technology should be well established with intense research and field trials with effective petroleum degrading microorganisms, including the much efficient genetically engineered organisms.

9.8 SUMMARY

The overuse of petroleum products leads to contamination of soils. Soil organisms play a crucial role in the hydrocarbon degradation in contaminated environments. The present chapter is based on the hazardous effects of petroleum contaminated soils and the remedial measures taken to treat these soils with microorganisms.

KEYWORDS

- **bioremediation**
- **genetically engineered microorganisms**
- **microorganisms**
- **obligate hydrocarbon clastic bacteria**
- **petroleum**
- **pollution**
- **toxicity**

REFERENCES

1. Abbasian, F., Lockington, R., Mallavarapu, M., & Naidu, R., (2015). A comprehensive review of aliphatic hydrocarbon biodegradation by bacteria. *Applied Biochemistry and Biotechnology, 176*(3), 670–699.
2. Abed, R. M. M., Al-Kharusi, S., & Al-Hinai, M., (2015). Effect of biostimulation, temperature and salinity on respiration activities and bacterial community composition in an oil-polluted desert soil. *International Biodeterioration and Biodegradation, 98*, 43–52.
3. Aggarwal, P. K., Means, J. L., & Hinchee, R. E., (1990). *Methods to Select Chemicals for in-situ Biodegradation of Fuel Hydrocarbons* (p. 14). Florida: Tyndall air force base, air force engineering and service center.
4. Aislabie, J., Saul, D., & Foght, J., (2006). Bioremediation of hydrocarbon-contaminated polar soils. *Extremophiles, 10,* 171–179.
5. Applegate, B. M., Kehrmeyer, S. R., & Sayler, G. S., (1998). A chromosomally based *Tod-Luxcdabe* whole-cell reporter for benzene, toluene, ethylbenzene, and xylene (BTEX) sensing. *Applied and Environmental Microbiology, 64*(7), 2730–2735.
6. Atlas, R., & Bragg, J., (2009). Bioremediation of marine oil spills: When and when not-the Exxon Valdez experience. *Microbial Biotechnology, 2*(2), 213–221.
7. Atlas, R. M., (1975). Effect of temperature and crude oil composition on petroleum biodegradation. *Journal Applied Microbiology, 30*(3), 396–403.
8. Atlas, R. M., (1981). Microbial degradation of petroleum hydrocarbons: An environmental perspective. *Microbiology Reviews, 45*(1), 180–209.
9. Atlas, R. M., & Bartha, R., (1998). *Microbial Ecology: Fundamentals and Applications* (4th edn., p. 259). Menlo Park, California: Benjamin/Cummings.
10. Barnes, N. M., Vishwas, B., Khodse, N. P., Lotlikar, R. M. M., & Damare, S. R., (2018). Bioremediation potential of hydrocarbon-utilizing fungi from select marine niches of India. *Biotech, 8*(1), 21–25.
11. Bartha, R., & Bossert, I., (1984). The treatment and disposal of petroleum wastes. In: Atlas, R. M., (ed.), *Petroleum Microbiology* (pp. 553–578). New York: Macmillan.
12. Bento, F. M., Camargo, F. A. O., Okeke, B. C., & Frankenberger, W. T., (2005). Comparative bioremediation of soils contaminated with diesel oil by natural attenuation, biostimulation and bioaugmentation. *Bioresource Technology, 96,* 1049–1055.
13. Bogusławska, E., & Dabrowski, W., (2001). The seasonal variability of yeasts and yeast-like organisms in water and bottom sediment of the Szczecin lagoon. *International Journal of Hygiene and Environmental Health, 203*(5–6), 451–458.
14. Brooijmans, R. J. W., Pastink, M. I., & Siezen, R. J., (2009). Hydrocarbon-degrading bacteria: The oil-spill clean-up crew. *Microbial Biotechnology, 2*(6), 587–594.
15. Brown, D. M., Okoro, S., & Van, G. J., (2017). Comparison of land farming amendments to improve bioremediation of petroleum hydrocarbons in Niger delta soils. *Science of the Total Environment, 596*, 284–292.
16. Campeão, M. E., Reis, L., & Leomil, L., (2017). The deep-sea microbial community from the Amazonian basin associated with oil degradation. *Frontiers in Microbiology, 8*. Article ID: 1019.
17. Catania, V., Cappello, S., & Di Giorgi, V., (2018). Microbial communities of polluted sub-surface marine sediments. *Marine Pollution Bulletin, 131*(A), 396–406.

18. Cerniglia, C. E., Freeman, J. P., Althaus, J. R., & Van, B. C., (1983). Metabolism and toxicity of 1-and 2-methylnaphthalene and their derivatives in cyanobacteria. *Archives of Microbiology, 136,* 177–183.
19. Chaillan, F., Le Fl`eche, A., & Bury, E., (2004). Identification and biodegradation potential of tropical aerobic hydrocarbon-degrading microorganisms. *Research in Microbiology, 155*(7), 587–595.
20. Chen, M., Xu, P., Zeng, G., Yang, C., Huang, D., & Zhang, J., (2015). Bioremediation of soils contaminated with polycyclic aromatic hydrocarbons, petroleum, pesticides, chlorophenols and heavy metals by composting: Applications, microbes and future research needs. *Biotechnology Advances, 33,* 745–755.
21. Choi, S. C., Kwon, K. K., Sohn, J. H., & Kim, S. J., (2002). Evaluation of fertilizer additions to stimulate oil biodegradation in sand seashore. *Journal of Microbiology and Biotechnol*ogy, *12,* 431–436.
22. Clemente, A. R., Anazawa, T. A., & Durrant, L. R., (2001). Biodegradation of polycyclic aromatic hydrocarbons by soil fungi. *Brazilian Journal of Microbiology, 32*, 255–261.
23. Colwell, R. R., Walker, J. D., & Cooney, J. J., (1977). Ecological aspects of microbial degradation of petroleum in the marine environment. *critical Reviews in Microbiology, 5*(4), 423–445.
24. Cooney, J. J., (1984). The fate of petroleum pollutants in freshwater ecosystems. In: Atlas, R. M., (ed.), *Petroleum Microbiology* (pp. 399–434). New York: Macmillan.
25. Das, N., & Chandran, P., (2011). Microbial degradation of petroleum hydrocarbon contaminants: An overview. *Biotechnology Research International, 2011*, 13. Article ID 941810, doi.org/10.4061/2011/941810.
26. Daugulis, A. J., & McCracken, C. M., (2003). Microbial degradation of high and low molecular weight polyaromatic hydrocarbons in a two-phase partitioning bioreactor by two strains of *Sphingomonas* sp. *Biotechnology Letters, 25*(17), 1441–1444.
27. Dell'Anno, A., Beolchini, F., Rocchetti, L., Luna, G. M., & Danovaro, R., (2012). High bacterial biodiversity increases the degradation performance of hydrocarbons during bioremediation of contaminated harbor marine sediments. *Environment Pollution, 167*, 85–92.
28. Dias, A. C. F., Dini-Andreote, F., & Taketani, R. G., (2011). Archaeal communities in the sediments of three contrasting mangroves. *Journal Soils and Sediments, 11*(8), 1466–1476.
29. Diaz, E., (2004). Bacterial degradation of aromatic pollutants: A paradigm of metabolic versatility. *International. Microbiology, 7,* 173–180.
30. Díez, S., Jover, E., Bayona, J. M., & Albaigés, J., (2007). Prestige oil spill, III: Fate of a heavy oil in the marine environment. *Environmental Science and Technology, 41*, 3075–3082.
31. Dombrowski, N., Donaho, J. A., Gutierrez, T., Seitz, K. W., Teske, A. P., & Baker, B. J., (2016). Reconstructing metabolic pathways of hydrocarbon-degrading bacteria from the deepwater horizon oil spill. *Nature Microbiology, 1.* Article ID: 16057.
32. Dvoˇrák, P., Nikel, P. I., Damborský, J., & De Lorenzo, V., (2017). Bioremediation version 3.0: Engineering pollutant - removing bacteria in times of systemic biology. *Biotechnology Advances, 35*, 845–866.
33. El-Fantroussi, S., & Agathos, S. N., (2005). Is bioaugmentation a feasible strategy for pollutant removal and site remediation? *Current Opinion in Microbiology, 8,* 268–275.

34. Erickson, B. D., & Mondello, F. J., (1993). Enhanced biodegradation of polychlorinated biphenyls after site-directed mutagenesis of a biphenyl dioxygenase gene. *Applied and Environmental Microbiology, 59*(11), 3858–3862.
35. Eugris. (2005). http://www.eugris.info/eugris-soil-water-encyclopedia.asp (accessed on 5 August 2021).
36. Ezekoye, C. C., Chikere, C. B., & Okpokwasili, G. C., (2018). Fungal diversity associated with crude oil impacted soil undergoing *in-situ* bioremediation. *Sustainable Chemistry and Pharmacy*, (2018) *10,* 148–152.
37. Floodgate, G., (1984). The fate of petroleum in marine ecosystems. In: Atlas, R. M., (ed.), *Petroleum Microbiology* (pp. 355–398). New York: Macmillan.
38. Foght, J. M., Westlake, D. W. S., Johnson, W. M., & Ridgway, H. M., (1996). Environmental gasoline utilizing isolates and clinical isolates of *Pseudomonas aeruginosa* are taxonomically indistinguishable by chemotaxonomic and molecular techniques. *Microbiology, 142*(9), 2333–2340.
39. Fritsche, W., & Hofritcher, M., (2000). Aerobic degradation by microorganisms. In: Klein, J., (ed.), *Environmental Processes-Soil Decontamination* (pp. 146–155). Weinheim, Germany: Wiley - VCH.
40. Fuentes, S., Barra, B., Caporaso, J. G., & Seeger, M., (2015). From rare to dominant: Fine-tuned soil bacterial bloom during petroleum hydrocarbon bioremediation. *Applied and Environmental Microbiology, 82*, 888–896.
41. Gogoi, B. K., Dutta, N. N., Goswami, P., & Mohan, T. K., (2003). Case study of bioremediation of petroleum-hydrocarbon contaminated soil at a crude oil spill site. *Advances in Environmental Research, 7,* 767–782.
42. Guerra, A. B., Oliveira, J. S., & Silva-Portela, R. C., (2018). Metagenome enrichment approach used for selection of oil-degrading bacteria consortia for drill cutting residue bioremediation. *Environment Pollution, 235*, 869–880.
43. Hazen, T. C., Dubinsky, E. A., DeSantis, T. Z., & Andersen, G. L., (2010). Deep-sea oil plume enriches indigenous oil-degrading bacteria. *Science, 330*(6001)*,* 204–208.
44. Hazen, T. C., Prince, R. C., & Mahmoudi, N., (2016). Marine oil biodegradation. *Environmental Science and Technology, 50,* 2121–2129.
45. Head, I. M., Jones, D. M., & Röling, W. F., (2006). Marine microorganisms make a meal of oil. *Nature Reviews Microbiology, 4,* 173–178.
46. Heider, J., Spormann, A. M., Beller, H. R., & Widdel, F., (1998). Anaerobic bacterial metabolism of hydrocarbons. FEMS. *Microbiology Reviews, 22*, 459–473.
47. Hou, N., Zhang, N., Jia, T., Sun, Y., Dai, Y., Wang, Q., Li, D., Luo, Z., & Li, C., (2018). Biodegradation of phenanthrene by biodemulsifier - producing strain *Achromobacter* sp. LH-1 and the study on its metabolisms and fermentation kinetics. *Ecotoxicology and Environmental Safety, 163*, 205–214.
48. Jeanbille, M., Gury, J., & Duran, R., (2016). Chronic polyaromatic hydrocarbon contamination is a marginal driver for community diversity and prokaryotic predicted functioning in coastal sediments. *Frontiers in Microbiology, 7,* 1303–1309.
49. Jin, H. M., Kim, J. M., Lee, H. J., Madsen, E. L., & Jeon, C. O., (2012). *Alteromonas* as key agent of polycyclic aromatic hydrocarbon biodegradation in crude oil-contaminated coastal sediment. *Environmental Science and Technology, 46,* 7731–7740.
50. Johnson, O. A., & Affam, A. C., (2019). Petroleum sludge treatment and disposal: A review. *Environmental Engineering Research, 24,* 191–201.

51. Jurelevicius, D., & De Almeida, C. C. R., (2014). Response of the archaeal community to simulated petroleum hydrocarbon contamination in marine and hypersaline ecosystems. *Water, Air and Soil Pollution, 225*(2). Article ID: 1871.
52. Kelly, C. J., Lajoie, C. A., Layton, A. C., & Sayler, G. S., (1999). Bioluminescent reporter bacterium for toxicity monitoring in biological wastewater treatment systems. *Water Environment Research, 71*(1), 31–35.
53. Kleindienst, S., Paul, J. H., & Joye, S. B., (2015). Using dispersants after oil spills: Impacts on the composition and activity of microbial communities. *Nature Reviews Microbiology, 13,* 388–396.
54. Kuiper, I., Lagendijk, E. L., Bloemberg, G. V., & Lugtenberg, J. J., (2004). Rhizoremediation: A beneficial plant-microbe interaction. *Molecular Plant-Microbe Interaction, 17*(1)*,* 6–15.
55. Kumar, A., Bisht, B. S., & Joshi, V. D., (2011). Bioremediation of polluted environment: A management tool. *International Journal of Environmental Sciences, 1*(60), 1079–1093.
56. Labud, V., Garcia, C., & Hernandez, T., (2007). Effect of hydrocarbon pollution on the microbial properties of a sandy and clay soil. *Chemosphere, 66,* 1863–1871.
57. Layton, A. C., Gregory, B., Schultz, T. W., & Sayler, G. S., (1999). Validation of genetically engineered bioluminescent surfactant resistant bacteria as toxicity assessment tools. *Ecotoxicology and Environmental Safety, 43*(2), 222–228,
58. Leahy, J. H., & Colwell, R., (1990). Microbial degradation of hydrocarbons in the environment. *Microbiology Reviews, 54*(3), 305–315.
59. Lea-Smith, D. J., Biller, S. J., & Davey, M. P., (2015). Contribution of cyanobacterial alkane production to the ocean hydrocarbon cycle. *Proceedings National Academy of Science, 112,* 13591–13596.
60. Li, D., Xu, X., Zhai, Z., Yu, H., & Han, X., (2017). Isolation and identification of an N-hexadecane bacterial degrader from soil polluted by petroleum oil in momoge wetlands and its degradation characteristics. *Wetland Science, 15,* 85–91.
61. Ma, Y. L., Lu, W., Wan, L. L., & Luo, N., (2015). Elucidation of fluoranthene degradative characteristics in a newly isolated *Achromobacter xylosoxidans* DN002. *Applied Biochemistry and Biotechnology, 175,* 1294–1305.
62. Margesin, R., Labbé, D., Schinner, F., Greer, C. W., & Whyte, L. G., (2003). Characterization of hydrocarbon-degrading microbial populations in contaminated and pristine alpine soils. *Applied and Environmental Microbiology, 69*, 3085–3092.
63. Mason, O. U., Hazen, T. C., & Borglin, S., (2012). Metagenome, metatranscriptome and single-cell sequencing reveal microbial response to deepwater horizon oil spill. *ISME Journal, 6,* 1715–1727.
64. Masson, L., Tabashnik, B. E., & Mazza, A., (2002). Mutagenic analysis of a conserved region of domain iii in the cry1ac toxin of *Bacillus Thuringiensis*. *Applied and Environmental Microbiology, 68*(1), 194–200.
65. Medina-Bellver, J. I., & Marín, P., (2005). Evidence for *In situ* crude oil biodegradation after the prestige oil spill. *Environmental Microbiology, 7*(6), 773–779.
66. Mesyami, P., & Baheri, M., (2003). Pre-Screening of fungi and bulking agents for contaminated soil bioremediation. *Advances in Environmental Research, 7,* 881–887.
67. Montagnolli, R. N., Matos, L. P. R., & Bidoia, E. D., (2015). Assessing *Bacillus subtilis* biosurfactant effects on the biodegradation of petroleum products. *Environmental Monitoring and Assessment, 187*(4116), 1–17.

68. Nie, Y., Liang, J. L., Fang, H., Tang, Y. Q., & Wu, X. L., (2014). Characterization of a CYP153 alkane hydroxylase gene in a gram-positive *Dietzia* sp. DQ12- 45-1b and its "team role" with alkw1 in alkane degradation. *Applied Microbiology and Biotechnology, 98,* 163–173.
69. Nikolopoulou, M., & Kalogerakis, N., (2008). Enhanced bioremediation of crude oil utilizing lipophilic fertilizers combined with biosurfactant and molasses. *Marine Pollution Bulletin, 56,* 1855–1861.
70. Okoh, A. I., (2006). Biodegradation alternative in the cleanup of petroleum hydrocarbon pollutants. *Biotechnology and Molecular Biology Reviews, 1*(2), 38–50.
71. Overholt, W. A., & Marks, K. P., (2015). Hydrocarbon degrading bacteria exhibit a species specific response to dispersed oil while moderating ecotoxicity. *Applied and Environmental Microbiology, 82,* 518–527.
72. Panke, S., & Sanchez-Romero, J. M., & De Lorenzo, V., (1998). Engineering of quasi-natural *Pseudomonas putida* strains toluene metabolism through an ortho-cleavage degradation pathway. *Applied and Environmental Microbiology, 64*(2), 748–751.
73. Philip, J. C., Bamforth, S. M., Singleton, I., & Atlas, R. M., (2005). Environmental pollution and restoration: A role for bioremediation. In: Atlas, R. M., & Philip, J., (eds.), *Bioremediation: Applied Microbial Solutions for Real-World Environmental Cleanup* (pp. 1–48). Washington, DC: ASM Press.
74. Piskonen, R., & Itävaara, M., (2009). Evaluation of chemical pretreatment of contaminated soil for improved PAH bioremediation. *Applied Microbiology and Biotechnology, 65,* 627–634.
75. Prenafeta-Boldú, F. X., Andrea, K., & Luykx, D. M., (2011). Isolation and characterization of fungi growing on volatile aromatic hydrocarbons as their sole carbon and energy source. *Mycological Research, 105,* 477–484.
76. Radwan, S., (2008). Microbiology of oil-contaminated desert soils and coastal areas in the Arabian Gulf region. In: Dion, P., & Nautiyal, C. S., (eds.), *Microbiology of Extreme Soils-Soil Biology* (Vol. 13, pp. 275–298). Berlin: Springer.
77. Radwan, S. S., (2009). Phytoremediation for oily desert soils. In: Singh, A., & Kuhad, R. C., & Ward, O. P., (eds.), *Advances in Applied Bioremediation* (pp. 279–298). Berlin: Springer-Verlag.
78. Rahman, K. S. M., & Rahman, T. J., (2003). Enhanced bioremediation of N-alkane in petroleum sludge using bacterial consortium amended with rhamnolipid and micronutrients. *Bioresource Technology, 90*(2), 159–168.
79. Redmond, M. C., & Valentine, D. L., (2012). Natural gas and temperature structured a microbial community response to the deepwater horizon oil spill. *Proceedings of National Academy of Sciences-USA*, *109*(50), 20292–20297.
80. Renou, S., Givaudan, J. G., Poulain, S., Dirassouyan, F., & Moulin, P., (2008). Landfill leachate treatment: Review and opportunity. *Journal of Hazardous Materials, 150,* 468–493.
81. Rivers, A. R., Sharma, S., & Tringe, S. G., (2013). Transcriptional response of bathypelagic marine bacterioplankton to the deepwater horizon oil spill. *ISME Journal, 7*. Article ID: 2315.
82. Röling, W. F., Milner, M. G., & Jones, D. M., (2004). Bacterial community dynamics and hydrocarbon degradation during a field-scale evaluation of bioremediation on a mudflat beach contaminated with buried oil. *Applied and Environmental Microbiology, 70,* 2603–2613.

83. Röling, W. F., & Milner, M. G., (2002). Robust hydrocarbon degradation and dynamics of bacterial communities during nutrient-enhanced oil spill bioremediation. *Applied and Environmental Microbiology, 68,* 5537–5548.
84. Ron, E. Z., & Rosenberg, E., (2014). Enhanced bioremediation of oil spills in the sea. *Current Opinion in Biotechnology, 27,* 191–194.
85. Rosenberg, E., (1993). Exploiting microbial growth on hydrocarbons: New markets. *Trends in Biotechnology, 11,* 419–424.
86. Dos, S. E. O., & Da Rosa, C. C., (2008). Pre-screening of filamentous fungi isolated from a contaminated site in southern Brazil for bioaugmentation purposes. *African Journal of Biotechnology, 7*(9), 1314–1317.
87. Sarkar, P., Roy, A., & Pal, S., (2017). Enrichment and characterization of hydrocarbon-degrading bacteria from petroleum refinery waste as potent bioaugmentation agent for *in situ* bioremediation. *Bioresource Technology, 242,* 15–27.
88. Sayler, G. S., & Ripp, S., (2000). Field applications of genetically engineered microorganisms for bioremediation processes. *Current Opinion in Biotechnology, 11*(3), 286–289,
89. Sebate, J., Vinas, M., & Solanas, A. M., (2004). Laboratory-scale bioremediation experiments on hydrocarbon-contaminated soil. *International Biodeterioration and Biodegradation, 54*, 19–25.
90. Semple, K. T., Doick, K. J., Jones, K. C., Burauel, P., Craven, A., & Harms, H., (2004). Defining bioavailability and bioaccessibility of contaminated soil and sediment is complicated. *Environmental Science and Technology, 38,* 228A-231A.
91. Sharma, S., (2012). Bioremediation: Features, strategies and applications. *Asian Journal of Pharmacy and Life Science, 2*(2), 202–13.
92. Sikkema, J., De Bont, J. A., & Poolman, B., (1995). Mechanisms of membrane toxicity of hydrocarbons. *Microbiology Reviews, 59,* 201–222.
93. Singh, H., (2006). *Mycoremediation: Fungal Bioremediation* (p. 256). New York: Wiley- Interscience.
94. Sousa, C., De Lorenzo, V., & Cebolla, A., (1997). Modulation of gene expression through chromosomal positioning in *Escherichia coli*. *Microbiology, 143*(6), 2071–2078.
95. Suyama, A. R., & Iwakiri, N., (1996). Engineering hybrid *Pseudomonads* capable of utilizing a wide range of aromatic hydrocarbons and of efficient degradation of trichloroethylene. *Journal of Bacteriology, 178*(14), 4039–4046.
96. Sverdrup, L. E., Nielsen, T., & Krogh, P. H., (2002). Soil ecotoxicity of polycyclic aromatic hydrocarbons in relation to soil sorption, lipophilicity, and water solubility. *Environmental Science and Technology. Sci. Technol.*, *36*, 2429–2435.
97. Szulc, A., & Ambro˙zewicz, D., (2014). The influence of bioaugmentation and biosurfactant addition on bioremediation efficiency of diesel-oil contaminated soil: Feasibility during field studies. *Journal of Environmental Management, 132,* 121–128.
98. Tao, K., Liu, X., Chen, X., Hu, X., Cao, L., & Yuan, X., (2017). Biodegradation of crude oil by a defined co-culture of indigenous bacterial consortium and exogenous *Bacillus subtilis*. *Bioresource Technology, 224,* 327–332.
99. Tharmer, M., & Al-Kubaisi, A. R., (2013). Biodegradation of Kirkuk light crude oil by *Bacillus thuringiensis*, Northern of Iraq. *Nature Science, 5*(7), 865–873.
100. Thavasi, R., Jayalakshmi, S., Balasubramanian, T., & Banat, I. M., (2006). Biodegradation of crude oil by nitrogen-fixing marine bacteria *Azotobacter chroococcum. Research Journal of Microbiology, 1*, 401–408.

101. Thomas, S. A., (2000). Mushrooms: Higher macrofungi to clean up the environment. *Battelle Environmental Issues*, *Fall*, 1–23.
102. Throne-Holst, M., & Wentzel, A., (2007). Identification of novel genes involved in long-chain n-alkane degradation by *Acinetobacter* sp. strain DSM 17874. *Applied and Environmental Microbiology, 73*(10), 3327–3332.
103. Tremblay, J., & Yergeau, E., (2017). Chemical dispersants enhance the activity of oil and gas condensate - degrading marine bacteria. *ISME Journal, 11,* 2793–2808.
104. Van, D. J., Siciliano, S. D., Winsley, T., Snape, I., & Ferrari, B. C., (2014). Bacterial targets as potential indicators of diesel fuel toxicity in sub-antarctic soils. *Applied and Environmental Microbiology, 80,* 4021–4033.
105. Van, D. M. I., Lee, H., & Trevors, J. T., (1996). Survival of lux AB marked *Alcaligenes eutrophus* H850 in PCB-contaminated soil and sediment. *Journal of Chemical Technology and Biotechnology, 65*(2), 115–122.
106. Van, L. H., Top, E. M., & Verstraete, W., (1998). Bioaugmentation in activated sludge: Current features and future perspectives. *Applied Microbiology and Biotechnology, 50,* 16–23.
107. Varjani, S. J., (2017). Microbial degradation of petroleum hydrocarbons. *Bioresource Technology, 223,* 277–286.
108. Varjani, S. J., & Gnansounou, E., (2017). Microbial dynamics in petroleum oilfields and their relationship with physiological properties of petroleum oil reservoirs. *Bioresource Technology, 245*, 1258–1265.
109. Varjani, S. J., Rana, D. P., Jain, A. K., Bateja, S., & Upasani, V. N., (2015). Synergistic *Ex-situ* biodegradation of crude oil by halotolerant bacterial consortium of indigenous strains isolated from onshore sites of Gujarat - India. *International Biodeterioration and Biodegradation, 103,* 116–124.
110. Varjani, S. J., & Upasani, V. N., (2016). Biodegradation of petroleum hydrocarbons by oleophilic strain of *Pseudomonas aeruginosa* NCIM 5514. *Bioresource Technology, 222,* 195–201.
111. Varjani, S. J., & Upasani, V. N., (2012). Characterization of hydrocarbon utilizing *Pseudomonas* strains from crude oil contaminated samples. *International Journal Science and Computer, 6*(2), 120–127.
112. Varjani, S. J., & Upasani, V. N., (2017). Critical review on biosurfactant analysis, purification, and characterization using rhamnolipid as a model biosurfactant. *Bioresource Technology, 232*, 389–397.
113. Varjani, S. J., & Upasani, V. N., (2017). New look on factors affecting microbial degradation of petroleum hydrocarbon pollutants. *International Biodeterioration and Biodegradation, 120,* 71–83.
114. Wang, J., Zhang, Z. Z., Su, Y. M., He, W., He, F., & Song, H. G., (2008). Phytoremediation of petroleum polluted soil. *Petroleum Science, 5*(2), 167.
115. Wang, C., Liu, X., Guo, J., Lv, Y., & Li, Y., (2018). Biodegradation of marine oil spill residues using aboriginal bacterial consortium based on Penglai 19-3 oil spill accident, China. *Ecotoxicology and Environmental Safety, 159,* 20–27.
116. Wang, L., Huang, X., & Zheng, T. L., (2016). Responses of bacterial and archaeal communities to nitrate stimulation after oil pollution in mangrove sediment revealed by Illumina sequencing. *Marine Pollution Bulletin, 109*(1), 281–289.

117. Wang, Q., Zhang, S., Li, Y., & Klassen, W., (2011). Potential approaches to improving biodegradation of hydrocarbons for bioremediation of crude oil pollution. *Journal of Environmental Protection, 2,* 47–55.
118. Wang, X. B., Chi, C. Q., Nie, Y., Tang, Y. Q., Tan, Y., Wu, G., & Wu, X. L., (2011). Degradation of petroleum hydrocarbons (C6–C40) and crude oil by a novel *Dietzia* strain. *Bioresource Technology, 102,* 7755–7761.
119. Xu, X., Zhai, Z., Li, H., Wang, Q., Han, X., & Yu, H., (2017). Synergetic effect of bio-photocatalytic hybrid system: G-C3N4, and *Acinetobacter*, sp. JLS1 for enhanced degradation of C16 alkane. *Chemical Engineering Journal, 323,* 520–529.
120. Xue, J., Yu, Y., Bai, Y., Wang, L., & Wu, Y., (2015). Marine oil-degrading microorganisms and biodegradation process of petroleum hydrocarbon in marine environments: A review. *Current Microbiology.* (2015), *71*, 220–228.
121. Yakimov, M. M., Timmis, K. N., & Golyshin, P. N., (2007). Obligate oil-degrading marine bacteria. *Current Opinion in Biotechnology*, *18,* 257–266.
122. Yamada, K., Mukumoto, H., Katsuyama, Y., & Tani, Y., (2002). Degradation of long-chain alkanes by a polyethylene-degrading fungus, *Penicillium simplicissimum* YK. *Enzyme and Microbial Technology, 30,* 828–831.
123. Yan, L., Yu, D., Hui, N., & Naanuri, E., (2018). Distribution of archaeal communities along the coast of the gulf of Finland and their response to oil contamination. *Frontiers in Microbiology, 1*(9), 15–20.
124. Yang, Y., Wang, J., Liao, J., Xie, S., & Huang, Y., (2015). Abundance and diversity of soil petroleum hydrocarbon-degrading microbial communities in oil exploring areas. *Applied Microbiology and Biotechnology, 99,* 1935–1946.
125. Zedelius, J., Rabus, R., & Grundmann, O., (2011). Alkane degradation under anoxic conditions by a nitrate-reducing bacterium with possible involvement of the electron acceptor in substrate activation. *Environmental Microbiology Reports, 3,* 125–135.
126. Zhang, Z., & Lo, I. M., (2015). Biostimulation of petroleum hydrocarbon- contaminated marine sediment with co-substrate: Involved metabolic process and microbial community. *Applied Microbiology and Biotechnology, 99*(13), 5683–5696.