Marine Oil-Degrading Microorganisms and Biodegradation Process of Petroleum Hydrocarbon in Marine Environments: A Review

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Abstract Due to the toxicity of petroleum compounds, the increasing accidents of marine oil spills/leakages have had a significant impact on our environment. Recently, different remedial techniques for the treatment of marine petroleum pollution have been proposed, such as bioremediation, controlled burning, skimming, and solidifying. (Hedlund and Staley in *Int J Syst Evol Microbiol* 51:61–66, 2001). This review introduces an important remedial method for marine oil pollution treatment—bioremediation technique—which is considered as a reliable, efficient, cost-effective, and eco-friendly method. First, the necessity of bioremediation for marine oil pollution was discussed. Second, this paper discussed the species of oil-degrading microorganisms, degradation pathways and mechanisms, the degradation rate and reaction model, and the factors affecting the degradation. Last, several suggestions for the further research in the field of marine oil spill bioremediation were proposed.

Introduction

Petroleum is one of the most important raw materials for the production of petroleum fuels (e.g., gasoline and kerosene) and chemical reagents products (e.g., pharmaceuticals, solvents, fertilizers, and plastics) [32]. Due to the increasing global petroleum demand, more and more activities such as exploitation, extraction, refining, and transportation of petroleum have been conducted. At the same time, about half of these petroleum products are transported across the world by sea [56]. Consequently, there is a dramatic increase of the petroleum spill or leakage accidents all over the world, such as spills from oil wells, pipelines, drilling rigs, or transport tankers.

More importantly, these oil spill accidents could cause severe physical, chemical, and biological hazards towards the local marine environment. For example, these accidents (e.g., “Exxon Valdez”, “DeepWater Horizon” oil spill accident in the Gulf of Mexico and “Penglai 19-3” oil spill accident in 2011) have brought serious environmental damage to the local region. For example, comparison with these oil spill accidents in the 21st century, “DeepWater Horizon” oil spill accident in the Gulf of Mexico was the most serious oil accident. The accident did not only lead to the great financial loss, e.g., in the fishing industry, but also damaged wetlands and beaches seriously.

First, oil spill accidents could affect marine meteorological environment via dispersion, dissolution, emulsification, and evaporation of the crude oil [37]. Once oil is spilled into the sea, it could spread over the surface of the seawater. Some research reported that a ton of spilled oil can form 5×10^6 m² of slick on the surface of the sea water. The slick could block the O₂/CO₂ exchange directly and lead to an oxygen depletion and pH change in the sea water. Besides, slick could also influence water evaporation and

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precipitation in marine environment. Thus, some reports indicated that marine desertification was caused by oil spill accidents [51].

In addition, oil spill accidents have a serious impact on the marine/terrestrial ecosystems and human health. For example, oil slick forms an anaerobic condition in the sea water and leads to the death of flora and fauna. Oil spills can cause hypothermia of marine birds and mammals by reducing/destroying the insulating ability of the plumage of birds and the fur of mammals. Meanwhile, the toxic constituents in petroleum could poison or kill birds, mammals, fishes and other marine organisms and damage the fragile underwater ecosystems which lead to a vicious effect on the global food chain, and eventually harm human health by damaging internal organs, such as kidneys, lungs, and liver [21, 46]. Moreover, oil spill accidents could affect marine plants and agricultural production by blocking light and gaseous exchange. It is estimated that half of the total coastal wetland loss was caused by oil spill accidents [46]. At last, the oil pollution in marine environment can cause significant economic losses in tourism and marine resource industries, such as coastal salt industry, marine chemical production, marine aquaculture, and fishery industry.

At present, different cleanup and recovery methods for the oil spills have been developed including physical (e.g., controlled burning, skimming, and absorbing), chemical (e.g., dispersing and solidifying), and bioremediation treatments [2, 8, 38, 50]. Generally, physical and chemical treatments should be taken as emergency measures. For example, at the start of the oil spill accident, the physical and chemical treatments are taken, in order to rapidly control the diffusion and drift of oil. These methods are not suitable for ecological restoration.

Bioremediation is considered as one of the most important eco-friendly and cost-effective technologies for marine ecological restoration, which leads to a complete decomposition of complex petroleum hydrocarbons of spilled oil into non-toxic compound. In the bioremediation process, appropriate microorganism is essential for the biotransformation/biodegradation of the pollutant. In these accidents, the bioremediation have been used in the Exxon Valdez oil spill. In this article, different species of petroleum degradation microorganism and degradation pathways of biodegradation were discussed. The article could lay a good foundation for the further development of bioremediation technology.

Advantages and Necessity of Bioremediation

Compared with conventional physical and chemical methods, bioremediation technology is less expensive and highly effective for the marine ecological restoration, which has the following advantages [20, 32, 40, 80].

Bioremediation is One of the Most Environmentally Friendly Technologies

The essence of bioremediation technology is that petroleum is degraded into simple harmless inorganic products (e.g., CO_2 and H_2O) during the microbial metabolism process, which could re-enter the biogeochemical cycle easily [80]. However, due to the complex chemical structure, the petroleum compounds are degraded into other chemicals compounds instead of CO_2 and H_2O by conventional physical and chemical methods. At the same time, secondary pollutants could be produced, which have the potential of damaging the marine environment.

Bioremediation is One of the Most Cost-Effective Technologies

Compared with physical and chemical treatments, bioremediation is based on its physical, chemical, and biological processes in the seawater-microorganisms-pollutants system, and the oil pollutant is removed by the metabolism process of microorganisms. According to the survey, compared to the costs of chemicals and physical methods, bioremediation method can save ~50–70 % of the costs [45].

Bioremediation is a Highly Efficient In Situ Technology

Some studies indicated that it is practicable to transfer the specific or genetically engineered oil-degrading microorganisms to the oil contaminated site for in situ bioremediation under favorable environmental conditions.

Species and Distribution of Petroleum Degradation Microorganisms in Marine Environment

Since the middle of the last century, the use of petroleum degradation microorganisms for spilled oil bioremediation has been widely reported [47, 68, 70]. These studies have indicated that different species of petroleum degradation microorganisms are broadly distributed in marine environment. Once other dominant groups of microorganisms are inhibited after oil contamination while these petroleum degradation microorganisms propagate rapidly and become dominant species [9].

In marine environment, more than 100 genera, 200 species of petroleum degradation microorganism (e.g., bacteria, fungi, algae, etc.) have been found, including bacteria (79 genera), cyanobacteria (9 genera), fungi (103 genera), and algae (19 genera) [10, 11, 17, 24, 34, 39, 59].

For example, in marine environment, bacterium plays an important role in petroleum degradation microorganism, e.g., *Achromobacter*, *Acinetobacter*, *Alcaligenes*, *Archrobacter*, *Bacillus*, *Flavobacterium*, *Coryneforms*, *Microbacterium*, *Micrococcus*, *Pseudomonas*, *Actinomycetes*, *Nocardia*, *Aureobasidium*, *Candida*, *Rhodotorula*, and *Sporobolomyces*. In addition, some species of Fungus including *Aspergillus*, *Mucor*, *Fusarium*, and *Penicilium* are also petroleum degradation microorganism. *Gordonia* is widely distributed in land, coastal, and ocean environments, and could degrade various environmental pollutants, including benzothiophene, dibenzothiophene, alkanes, polycyclic aromatic hydrocarbons, and so on [54, 67]. Different types of oil-degrading microorganisms are shown in Table 1.

Degradation of Petroleum by Degrading Microorganisms

Degradation Pathways and Mechanism

Generally, petroleum compounds are biodegraded, followed by three processes. At first, petroleum compounds are absorbed onto microbial surface; Second, these petroleum compounds are transferred to microbial cell membrane; then, these compounds are degraded in the microbial cell. At last, these compounds are degraded into various small molecules by microorganisms [6].

At present, many researches have showed that the degradation way of all sorts of petroleum components (e.g., alkane, polycyclic aromatic hydrocarbons, etc.) is an oxidizing process [6, 13, 61, 78]. However, the degradation pathways of these compounds are different, due to the different structures of petroleum components, such as saturated, aromatic, resin, and asphaltene fractions hydrocarbon.

Degrading Process of Alkane and Cycloalkane

Alkane (general formula: C_nH_{2n+2}) is a typical saturated hydrocarbon with all single bonds in the structure. Cycloalkane (general formula: C_nH_{2n}) is another saturated hydrocarbons with several carbon rings in the structure.

The degrading process of alkane by microorganisms is shown in Fig. 1, which can be classified into three forms: subterminal oxidation, alkyl hydroperoxides, and degradation of cyclohexane [32]. Basically, alkane is catalyzed by some enzymes (e.g., oxidase, dehydroge, etc.) of microorganisms into fatty acids, and then gradually metabolized to acetyl coA and krebs cycle of microbial metabolism, eventually into CO_2 and H_2O [66]. In this process, enzymes (e.g., alkane monooxygenase, fatty alcohol dehydrogenase, fatty aldehyde dehydrogenase, etc.) play an important role in catalyzing the degradation process effectively.

Much like alkane, the biological degradation principle of cycloalkane is also subterminal oxidation. At first, cycloalkane is oxidized to alcohols by kinds of oxidizing enzyme. Then, the alcohols are converted to ketone by dehydroge. Later, the ketone is oxidized to esterase or/and fatty acid. Taking the cyclohexane for example as shown in Fig. 1, cyclohexane is converted to corresponding compound, followed by cyclohexanol, cyclohexanone, dehydroge, and fatty acid. At last, the compound is biodegraded into CO_2 and H_2O .

In addition, cycloalkane with various substituents could be oxidized. The alkyl substituted alicyclic compounds may be two position is in the side chain oxidation and alicyclic compounds, the properties, microbial species, and other factors will influence the initial position of the reaction.

Table 1 The typical offshore oil-degrading microorganisms

	Microorganism colonies	Reference
Bacterium	<i>Achromobacter</i> , <i>Acinetobacter</i> , <i>Alcaligenes</i> , <i>Actinomycetes</i> , <i>Archrobacter</i> , <i>Bacillus</i> , <i>Cycloclasticus</i> , <i>Coryneforms</i> , <i>Chromobacterium</i> , <i>Flavobacterium</i> , <i>Micrococcus</i> , <i>Microbacterium</i> , <i>Mycobacterium</i> , <i>Nocardia</i> , <i>Pseudomonas</i> , <i>Sarcina</i> , <i>Serratia</i> , <i>Streptomyces</i> , <i>Vibrio</i> , <i>Xanthomonas</i> .	[9, 26, 66]
Fungus	Mold: <i>Penicillium</i> , <i>Aspergillus</i> , <i>Fusarium</i> , <i>Geotrichum</i> , <i>Gliocladium</i> , <i>Mucor</i> , Yeast: <i>Acremonium</i> , <i>Aspergillus</i> , <i>Aureobasidium</i> , <i>Pichia</i> <i>Candida maltosa</i> , <i>Candida tropicalis</i> , <i>Candida apicola</i> , <i>Candida</i> , <i>Cladosporium</i> , <i>Debaryomyces</i> , <i>Monilia</i> , <i>Mortierella</i> , <i>Rhodotorula</i> , <i>Saccharomyces</i> , <i>Toruplopsis</i> , <i>Trichoderma</i> , <i>Verticillium</i> . Other fungus: <i>Aureobasidium</i> , <i>Candida</i> , <i>Rhodotorula</i>	[9, 37] [12] [65]
Algae	<i>Agmenellum</i> , <i>Amphora</i> , <i>Anabaena</i> , <i>Aphanocapsa</i> , <i>Chlorella</i> , <i>Chlamydomonas</i> , <i>Coccochlorise</i> , <i>Cylindrotheea</i> , <i>Dunaliella</i> , <i>Microcoleus</i> , <i>Nostoc</i> , <i>Oscillatoria</i> , <i>Petalonema</i> , <i>Porphyridium</i> .	[11, 54]

Fig. 1 Degradation pathway of alkanes and cycloalkane

Degrading Process of Aromatic Hydrocarbon

The degrading process of aromatic hydrocarbon is as follows: at first, aromatic hydrocarbon is oxidized by oxidase to dihydrodiol. Then, dihydrodiol is degraded to o-dihydroxybenzene. O-dihydroxybenzene is degraded following two processes which are ortho-position ring opening reaction and meta-position ring opening reaction, respectively. Then, these compounds are oxidized to long chain compounds and are gradually metabolized to acetyl coA. The degrading process is shown in Fig. 2.

Some of fungus and bacterium could degrade aromatic hydrocarbon, the process is different from each other. Taking the bacterium for example, aromatic hydrocarbon is oxidized by two oxygen atoms, and converted to cis-dihydrodiol. But, aromatic hydrocarbon is oxidized and converted to trans-dihydrodiol by fungus.

Degrading Process of Polycyclic Aromatic Hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAHs) are typically high carcinogenic, mutagenic, and teratogenic substance,

Fig. 2 Degradation pathway of aromatic hydrocarbon **Fig. 3** Degradation pathways of polycyclic aromatic hydrocarbons (PAHs)

which have drawn much attention to its degradation mechanism. It can be degraded under enzymes catalyzing into glycol or catechol groups, then further decomposed into acetyl coA or succinic acid [78]. Generally, the degradation pathway is that PAHs are gradually degraded into epoxide, trans diol, phenol, and trans dihydro 2 phenol by monooxygenase of yeast. Another pathway is that PAHs are gradually degraded by dioxygenase into epoxide, cis diol, cis dihydro 2 phenol, etc. The final metabolites in both pathways are carbon dioxide and water, and the overall steps of biodegradation of PAHs are demonstrated in Fig. 3 [49].

PAHs is different to be degraded, and the degraded level of PAHs should be graded in order of solubility, the number of benzene rings, the species and number of substituent species, the properties of heterocyclic atom, etc.

In addition, the asphalt has the most complicated structure, which is very difficult to be decomposed by biodegradation [62].

However, many researches indicated the PAHs could be degraded in aerobic conditions. While, other researches showed that PAHs also could be degraded in denitrification, sulfate reducing, or methanogenic fermentation under

Table 2 Oil-degrading microorganisms and corresponding degrading substances

Metabolic substances	Species	Reference
Aliphatic hydrocarbon, cyclohexane, alkyl benzene, and dicycloalkane	<i>Pseudomonas</i> ; <i>Corynebacterium</i> ; <i>Bacillus</i> ; <i>Corynebacterium</i>	[77]
Long carbon chain hydrocarbon component of oil and benzo (a) pyrene and other substances	<i>Aspergillus</i> sp. <i>Penicillium</i> sp.	[69]
Naphthalene, 1-methylnaphthalene, 2-methylnaphthalene, 2,6-dimethylnaphthalene, and phenanthrene	<i>Vibrio cyclotrophicus</i> sp.nov.	[35]
Naphthalene, anthracene, phenanthrene, and pyrene	<i>Aeromonas punctata</i> TH	[14, 53]
Phenanthrene and Chrysene	<i>Vibrio</i> , <i>Pseudoalteromonas</i> , <i>Marinomonas</i>	[31]
<i>n</i> -Alkanes aromatic hydrocarbon, naphthalene, phenanthrene and anthracene	<i>Cycloclasticus oligotrophus</i>	[23, 73]
<i>n</i> -Alkanes, branched alkanes and alkylbenzenes	<i>Alcanivorax</i> sp.	[22, 29, 30, 48, 75]
Aliphatic hydrocarbons, alkanols, and alkanolates	<i>Oleiphilus</i> and <i>Oleispira</i>	[28, 74]
Alkanes	<i>Desulfococcus</i>	[1]
PAHs	<i>Cycloclasticus</i>	[36, 42, 43, 73]
Pyrene	<i>Mycobacterium</i>	[25, 41, 72]

anaerobic condition. Compared with the higher rate of aerobic degradation, the anaerobic degradation rate of PAHs is relatively slower. And, the anaerobic degradation pathway of the PAHs is also not clear at present [60].

Specificity of Biodegradation

Marine oil-degrading bacteria strains (e.g., *Alcanivorax*, *Cycloclasticus*, *Marinobacter*, *Neptunomonas*, *Oleiphilus*, etc.) could degrade alkanes or aromatic hydrocarbons [31]. *Alcanivorax* strains have a preference for *n*-alkanes and branched alkanes while *Cycloclasticus* can grow on the aromatic hydrocarbons [31]. Bacteria strains (*Pseudomonas*, *Corynebacterium*, *Bacillus*, and *Corynebacterium*) which were separated from the residual oil of Liaohe oil-field could degrade petroleum compounds in some extent: aromatic hydrocarbon 80 %; bitumen 53 %; aliphatic hydrocarbon 37 %; and nonhydrocarbon 30 % [77]. Several typical oil-degrading microorganism and corresponding substances after degradation are listed in Table 2. Taking PAHs for example, *Tropicibacter naphthalenivorans* gen. nov. sp. could degrade naphthalene, phenanthrene, C1-alkyl naphthalene, and C2-alkyl naphthalene, except for two alkyl benzothiophene, alkyl phenanthrene and alkyl fluorine.

Degradation Efficiency Rate

Theoretically, all the petroleum components can be degraded into inorganic compounds by oil-degrading microorganisms according to the mechanism of degradation

[20]. However, many studies have shown that the degradation efficiency rate of petroleum is different due to the complexity of various petroleum hydrocarbons (e.g., molecular weight and structure, etc.) and the effect of the external environmental parameters (e.g., temperature, oxygen, salinity, pressure, nutrients, etc.).

Molecular Weight of Petroleum Hydrocarbons

Generally, the degradation efficiency rate of petroleum hydrocarbons decreases with the increase of the carbon number in petroleum compounds. Some researchers have indicated that short chain *n*-alkanes are the most easily degradable components followed by branched alkanes, aromatic hydrocarbon, cyclic aromatic hydrocarbon, asphaltene, and lastly heavy crude oil [3]. Peng et al. found that the degradation of alkane was more effective than that of aromatics compounds [55]. By contrast, other researchers separated petroleum degrading microorganism from the strains in marine sediments that could breakdown aromatics hydrocarbons effectively [71].

The Degradation Rate of Branched Hydrocarbons is Significantly Lower than that of *n*-Alkanes Hydrocarbons

The higher the content of branched hydrocarbons, the lower the degradation in the biodegrading branched hydrocarbons process. Thus, the degradation rate of branched hydrocarbons is lower [33]. Shi et al. have found that 91.1 % of *n*-alkane was degraded in 7 days, while the degradation rate of

Table 3 Degradation efficiency of co-metabolism

Metabolic substances	Species	Degradation efficiency
Naphthalene 2-methyl naphthalene phenanthrene phenylbenzene	<i>Vibrio cyclotrophicus</i> sp. nov.	Naphthalene can be degraded. While mix substance of naphthalene, 2-methyl naphthalene, and phenanthrene are degraded in higher degradation efficiency
Fluorine acenaphthene		Part of phenylbenzene, fluorine, and acenaphthene could be degraded. While these are not degraded without co-metabolism
Fluorene, phenanthrene, anthracene	<i>Pseudomonas</i> sp.	Mix substance of fluorene, phenanthrene, anthracene could be degraded, and the fluorene is degraded quickly. While, the other substance is added, the degradation efficiency is improved

one basking alkanes and phytane in 21 days was 47.29 and 41.21 %, respectively [64]. Yuan et al. also found the degradation rate of branched hydrocarbons was nearly two times than that of *n*-alkanes hydrocarbons [77].

Some Petroleum Components Could Affect the Degradation Efficiency Rate

The content of sulfur composition in crude oil could affect the degradation rate. Generally, the low-sulfur petroleum hydrocarbons could be easily degraded by some microorganism [33, 66, 71]. However, saturated hydrocarbon with higher proportion of sulfur still has a higher degradation rate than aromatic compounds [66].

Co-metabolism

Generally, due to the complicated structure of petroleum compounds, the degradation efficiency rate is lower [63]. But, the degradation efficiency rate could be improved with other co-metabolism compounds. In this process, the simple compounds are favor to improve the ability of degradation. Taking PAHs for example, a variety of microorganisms (e.g., Bacteria, fungi, and prokaryotic algae) are able to degrade the PAHs through co-metabolism. For example, the degradation efficiency of pyrene could be improved and be up to 98.2 % by adding 1 % Osmocote and 0.1 % Chitosan. Table 3 shows the degradation efficiency of PAHs was improved with co-metabolism. Some report also indicated that the degradation efficiency rate was shortened two months by co-metabolism compounds adding co-metabolism compounds. [58].

Degradation Rate and Model

In marine environment, type of petroleum hydrocarbons [19], temperature [4], species of microorganisms [31], and nutrients [15, 16] can affect the degradation rate of

petroleum hydrocarbon. Different microorganisms have different tendencies to attack various types of petroleum hydrocarbons. Generally, the susceptibilities of hydrocarbons that can be degraded by microorganisms are as follows: *n*-alkane > branched alkane > small aromatics hydrocarbon > polycyclic aromatic hydrocarbon (PAHs) [7, 20]. Temperature is another important parameter that determines the biodegradation rate of hydrocarbons by affecting the metabolic activity and the diversity of the microorganisms [57]. The biodegradation rate increases with increasing temperature and maximum rate occurs in the range of 15–20 °C in marine environment [5, 20]. Nutrients (such as nitrogen and phosphorus) can be the limiting factor that enhances the biodegradation rate of hydrocarbons [5, 44]. However, excessive nutrient concentration can also decrease the biodegradation rate of oil pollutant [18, 52].

Degradation Rate

Some researchers have considered that degradation rate could be inferred by establishing degradation model. And, some models were established to describe the biodegradation process [27, 76, 79, 81], such as the Michaelis–Menten equation, shown in Eq. 1:

$$v_c = \frac{v_{c,\max} \rho_s}{K_c + \rho_s}, \quad (1)$$

where v_c is the degradation rate (g/dL); ρ_s is the mass concentration of oil (g/L), $v_{c,\max}$ is the maximum degradation rate (g/dL), and K_c is the K_s saturation constant, g/d.

Zhang et al. have found that [79] speed coefficient of degradation of dynamic plastic bacteria, $v_{c,\max}$ and K_c , was 0.27 and 1.04 respectively, under the condition of rich nutrition, but, under the condition of poor nutrition, $v_{c,\max}$ and K_c , was only 0.0034 and 0.41, respectively. Similarly, under the condition of rich nutrition, speed coefficient of degradation of *Pseudomonas* genus, $v_{c,\max}$ and K_c , was 0.25 and 1.22, respectively. And, under the condition of poor nutrition, $v_{c,\max}$ and K_c , was 0.0039 and 0.32, respectively.

Conclusion and Future Prospects

The low-cost, environmentally friendly bioremediation technology is considered as one of the best approaches for cleaning up the petroleum polluted area. Some studies have testified that petroleum-contaminated shoreline could be restored by biodegradation technology within 2–5 years. In the paper, the paper introduced that the species of oil-degrading microorganisms, degradation pathways and mechanisms, the degradation rate and reaction model, and the factors affecting the degradation.

With the increase of marine oil pollution accidents, it is necessary to solve some key issues about biodegradation in marine environment.

After Bioremediation, the Risk Should be Assessed and Solved

Risk of producing secondary contamination from the metabolites of hydrocarbon to the local environment should be identified. And the impact of cultivating petroleum degrading microorganisms to the local ecological system should be assessed.

The Development of Mixed Local Microorganisms

The studies indicated that the degradation rate is low for the remediation of complex mixture of contaminants by one species of petroleum degrading microorganisms. However, this rate could be improved using mixed local microorganisms, as each microorganism could degrade specific hydrocarbon compound by special active enzymes in themselves.

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